

Expert Systems in the Steel Making Industry

Jürgen Dorn

Christian Doppler Laboratory for Expert Systems
Vienna University of Technology
Paniglgasse 16, A-1040 Vienna, Austria

Tel: ++43-1-58801-6123

Fax: ++43-1-5055304

E-mail: dorn@vexpert.dbai.tuwien.at.ac

Abstract

This paper presents three prototypical expert systems that were developed in different fields of the steel making industry. It is described which kind of knowledge has to be represented, what are the techniques required for intelligent reasoning, and why expert systems offer better solutions to the described problems than traditional programming approaches. From the given applications the main functions of expert systems in steel making industry are concluded.

As a goal for further developments, a network of expert systems is proposed to achieve the full benefits of expert systems in the steel making industry. This is illustrated by means of a group of expert systems in an Austrian company. Finally, task-oriented design is recommended in order to achieve a better reusability for software artefacts in expert systems.

Key Words: steel making, reasoning with uncertainties, scheduling, control, classification

Expert Systems in the Steel Industry

Jürgen Dorn

Introduction

Artificial Intelligence (AI) is a research field between psychology, cognitive science and computer science with the common goal to improve reasoning capabilities of computers. Some researchers aim at artificial systems as intelligent as humans – other only try to improve existing techniques as far as possible by decreasing the cognitive distance between human thinking and the knowledge representation used to program computer systems. The latter is typical for industrial automation projects in the steel industry.

The Christian Doppler Laboratory for Expert Systems funded by the Austrian Industries is concerned with the research and introduction of expert systems into the Austrian steel making industry. Expert systems are a subfield of AI concerned with specialized knowledge-intensive domains like medicine or in our case steel making. The success of expert systems is based on the restriction to narrow domains. There is no expert system for the whole steel making process but for subareas. Typically, in an expert system the decision process of one or more human experts in one of the steel making plants is modeled. Such a decision process depends on much domain knowledge, but does not necessarily rely on commonsense reasoning.

Expert systems are used because it is not so easy to formalize the expert's knowledge with procedural programming. There are three main difficulties:

- (1) The human expert applies general physical models to support his reasoning that cannot be described as a deterministic algorithm.
- (2) The human expert uses incomplete, vague, and uncertain knowledge to decide a problem.
- (3) The human expert uses heuristics or rules of thumb to cope with the complexity that is inherent in many problems of his domain.

Expert system technology offer mechanisms to represent and process such kinds of knowledge. We demonstrate this on three case studies in different subareas of the steel making industry in the next section. These systems are all well published.

Since there are usually different expert systems desirable in a steel making plant that use partly the same knowledge, we propose a communicating network of expert systems and illustrate this by means of four experts systems in an Austrian plant.

The aspect of reuse and maintenance of expert systems in the existing environment will be our third point. The expert systems' success comes from the idea to separate knowledge representation and processing. The idea is to represent explicitly the whole expertise consisting of physical models, uncertain knowledge, and rules of thumb. If this is carefully considered and the knowledge base well structured, the system may be transferred easily from one application to another. The knowledge base should be readable like a book. For every piece of knowledge an expert should be able to decide its relevance for the new application. Of course, this separation with an explicit representation of knowledge also supports the modification and maintenance of the knowledge. If single pieces of knowledge as e.g. rules, predicates, or objects are represented independently from other parts, these can be modified easily. Although expert system facilitate the reuse of knowledge structures, the actual practise in knowledge engineering is different. With task-oriented design we propose a methodology that could overcome the existing difficulties.

Case Studies of Expert Systems in the Steel Industry

We describe three subdomains to give readers unfamiliar with the steel making process an impression of the problems occurring in steel making industry. For each subdomain we describe an expert system and stress the problems that favor the application of expert systems. Furthermore, for readers unfamiliar with expert system techniques we want to give a stimulus what are expert systems good for in this domain. Sometimes we reference other expert systems aiming at the same functionality. However, readers that are interested in a more comprehensive overview on existing expert systems in steel making industry are referred to (Eiter 1990), (Slany 1991) or (Dorn 1993b).

Classification

The international steel market demands an ever increasing diversity of products in size, form, surface, and quality. The customer requirements differ in physical characteristics (e.g., compression, impact, yield, or tensile strength), application domain (e.g., structural steel, tool steel, steel for power plants or turbine blades), and qualities (e.g., stainless or heat-resistant steel). The different requirements are achieved by different alloying metals and by special treatments. Steel or metallurgical grades are specifications on different ingredients that are given as lower and upper bounds. For high-grade steel these specifications are very restrictive. Actually, it is very difficult to produce a constant quality. Due to several uncertainties in the production, the quality aimed at is therefore always better than that asked from the customer due to the uncertainties.

Since the main steelmaking operations are performed on the same units for the different steel grades, the production sequence of different grades is strongly constrained:

- (1) If the hot steel is treated in a unit as e.g., in an electric arc furnace residuals remain in the furnace wall and will be assimilated by the subsequent heat.
- (2) To achieve a maximal throughput the casting sequence on the continuous casters should not break. However, if two heats with different steel grades will be cast after another they will be mixed in the tundish.

To avoid these difficulties one can try to reduce the variety of steel grades for a collection of customer orders. This problem has been addressed through the development of an expert system by Bethlehem Steel, USA (Vasko et al. 1989) and (Woodyatt et al. 1992). Ordered lists of possible steel grades for incoming customers orders were generated. As we have yet described, these steel grades are usually better than the ordered quality. Although the first steel grade in the list is the best grade for the customer's demand, it is also possible to take one of the others in the list. With these sets of potential grades for each order, one grade is selected that would be required to produce all orders. The likelihood of a grade meeting the customer's specifications without difficulty is described by fuzzy sets. The selection of one grade for a collection of customer orders is performed by a set covering approach. It is reported that this set covering algorithm with 2,500 orders and 1,500 grades is performed in less than 3 CPU seconds.

Since the demands of the steel market change and new steel grades and products will be developed, a classification system will never be complete. An expert system approach promise in the described case the possibility to have a living classification system that is maintained easily.

Scheduling of Production Processes

Scheduling is the task of allocating jobs or operations to resources. In most applications the number of available resources is restricted and usually one resource can process only one operation at a time. If several resources are regarded in a scheduling application, the problem to find a feasible schedule, i.e. a feasible allocation of all operations to resources under temporal constraints, is an NP-hard problem. Due to this complexity, mathematical algorithms from Operations Research fail. Furthermore, there are so many uncertainties in the production process that scheduling operations with an integer programming approach seems not to be adequate. Expert systems promise a remedy to this problem since it is easier to represent domain dependent strategies and to represent fuzziness than with OR techniques.

The REPLAN system supports the human experts in constructing a schedule for high-grade steel making at Böhler in Kapfenberg, Austria (Dorn & Shams 1990). The plant consists of four production lines each starting with an electric arc furnace. The molten steel is poured into ladles, refined in special aggregates, and finally cast either by cranes into ingots or on a horizontal continuous caster into slabs. The greatest problem is the variety of metallurgical grades. As yet described before, these form considerable constraints on the sequence of heats. Fortunately, only a small amount of heats are produced on the caster. Otherwise, it would be impossible to find legal schedules. Besides chemical constraints, spatial and temporal constraints have to be regarded. The intention is usually not to generate optimal schedules since it is not describable which schedule is optimal. Instead it is tried to optimize local constraints.

The approach to solve the problem is as follows: The scheduling system first analyses all orders for one week and determines what are the problems or bottlenecks in this week. Then each order gets a value that describes the difficulty to schedule this order in the actual week. The important orders and those that were classified very difficult will be scheduled first. To be scheduled means the best time for this order in the schedule is looked for. Iteratively the remaining orders will be scheduled afterwards. For some orders this can result in constraint violations. Finally, the achieved schedule is analyzed for weak points and is iteratively repaired. This means, constraint violations are looked for and it is tried to replace some jobs by others to avoid the violation.

The system is now in operational use. However, to set the applied methodology on firmer ground and to improve its reusability we have developed the methodology further (Dorn & Slany 1993). The importance and difficulty of jobs and the grade of constraint satisfaction is represented by fuzzy sets. To achieve the ability to compare schedules, we define evaluation functions by combining the fuzzy values of single constraints. With this evaluation function we can apply the repair-based strategy in a more general fashion. For example, now it is possible to modify penalties for constraint violations without changing the scheduling algorithm. Thus we achieve an architecture that is easier transferable to another application. At the moment we transfer it to a steel plant with different characteristics.

There are lot of other scheduling expert systems in the steel industry. We want to reference only one of them. SCHEPLAN was the first published system (as far as I know) implemented by IBM Tokyo for the Keihin plant of NKK (Numao & Morishita 1989). The plant produces mass steel and the scheduling objective was to reduce waiting times before the casting units and a maximization of the casting sequence. It was reported that the required daily scheduling time was reduced from three hours to less than thirty minutes and the average waiting times are reduced from sixteen minutes to eight minutes. For the second reduction a saving of about one million dollars was derived by the authors.

Control of Blast Furnaces

A blast furnace is a huge steel stack, lined with refractory brick, where iron ore, coke and limestone are charged into the top, and preheated air is blown into the bottom. Steam and fuel, such as oil or natural gas, are also injected with the hot blast to control the energy input into the furnace. Inside the furnace, the iron ore is heated and goes through numerous chemical reactions which reduce the oxides, resulting in an impure molten iron. Coke generates heat and gases which drive these chemical reactions. The ratio of ore to coke quantity can be adjusted to control heat levels in the furnace. The lime from the limestone forms a slag which helps remove impurities from the liquid iron. The molten iron and slag are drained from the hearth of the blast furnace several times a day. The hot metal temperature and chemistry is measured each cast to determine the physical and chemical balance within the furnace.

Iron making in the blast furnace is a continual process. Raw materials are continually charged into the furnace top and take several hours to accumulate as iron and slag in the furnace hearth bottom. The molten iron is “cast” into ladles by drilling a hole into the bottom.

The main focus of the blast furnace quality improvement effort is hot metal silicon variability reduction. It is controlled by the heat levels inside of the furnace. If it is too hot in the furnace, the silicon will increase and if it is too cool it will decrease. Unfortunately, it is not possible to take the temperature inside of the furnace. The hot metal temperature is only known indirectly. Two problems are addressed by existing expert systems:

- (1) Prediction of abnormal situation such as slip (abnormal and sudden descending of the raw materials charged in the furnace) and channeling (the heated gas reaches the top of the furnace without reaction) and
- (2) To keep the thermal condition stable.

Furnace heat levels and hot metal temperature can be adjusted by variables such as ore-to-coke ratio, hot blast temperature, fuel injection level, and blast moisture level. If the hot metal silicon is below the aimed value, the hot metal temperature will also be below its aim and the heat level needs to be increased. The problem in controlling this process are the long reaction times and the different reactions of human operators. They use different actions, start them at different times, and the magnitude of changes is also different. Furthermore, old data of previous casts is used to decide reactions. The goal of most managers of blast furnaces is therefore not an optimization but to achieve a standardization of this control on a high quality. Due to the uncertainty of many data it is difficult to find a simple control algorithm. Many companies use now or intend to use expert systems for the supervision and control of blast furnaces. The advantage of an expert system is the possibility to build a model of the physical and chemical process in the furnace with symbolic values. Rules allow the specification of certain standards, when and how an operator should react.

The ALIS system of Nippon Steel that is used for several blast furnaces is described in several publications (Amano et al. 1990) or (Atsumi et al. 1989). Comparison between human and expert system performance were made saying that in 25% the expert system had performed better and only in 7% the human had decided better. Furthermore, the system is continually adapted to improve the competence of the system.

A system developed by NKK (Inaba et al. 1991) is coupled directly with the blast furnace via a process computer. In order to reason efficiently, the sensor data is preprocessed and only symbolic and trend data are delivered to the expert system. By using certainty factors and three-dimensional membership functions the number of required rules is reduced.

Integration of Expert Systems in the Steelmaking Industry

At the moment expert systems in the steelmaking industry are single-user front-end computer systems dedicated to one function. The integration with the existing organization is very simple. There exist some systems that are coupled with a process computer or with a production planning system. However, most benefits from expert systems can be gained, if a stronger coupling is achieved. We demonstrate this by means of our experience made in the steel works at Linz. The following four expert systems are partly in operational use:

- (1) In the rolling mill an expert system was developed to generate casting schedules for the steel plant. This schedules are lists of orders that are send to the steel making plant. The expert system applies knowledge about possible rolling sequences in the mill and abstract knowledge about the capabilities of the steel making plant and its objective is to minimise inventories between both plants (Kelemis et al. 1993).
- (2) In the steelmaking plant an scheduling expert system was developed to support the dispatchers in fine planning. The objective is reactive scheduling, i.e. the reaction on malfunctions like violated steel grades or the breakdown of machines (Stohl et al. 1991).
- (3) A computer aided quality control (CAQC) system produces dependent on customer orders and steel grades prescriptions to achieve the desired steel quality. These are not complete in aspects like process routings and settings of process parameters for heats in the steelmaking plant. To have guidelines which possibility to choose, an expert system was developed (Blümelhuber 1990).
- (4) An expert system for the diagnosis of the blast furnace was developed with the characteristics as described before. The system works interactively and does not control the furnace directly (Blümelhuber 1990).

These systems are not coupled, although some produce knowledge that is used by others. One aspect that influences the scheduling strategy in the scheduling system is the amount of hot iron. If enough iron is available, a maximal throughput is the optimization goal. Otherwise, the dispatcher prefers to produce difficult steel qualities. To support this strategic decision in the steelmaking plant, it would be desirable to have estimations about the time and amount of the next delivery of hot iron which could be given by the diagnosis system.

The potential process routings generated by the third expert system are stored together with the CAQC prescriptions in a data base. The second expert system has access to this data base. However, it cannot use the knowledge to decide whether exceptions to this process routings can be made to react on disturbances in the production process.

The first expert system delivers lists of heats to the second expert system. However, information like the amount of available hot iron or breakdowns of machines are not considered. A kind of negotiation between both expert systems seems to be a promising approach to minimize the stored slabs and to be flexible on irregularities in the production process.

We believe that the future of expert systems in the steel making industry rely on a network of expert systems. Since it is not advisable to develop one big system, several small expert systems that have great competence in a narrow domain should be developed. However, to improve the productive power, these systems should be able to communicate with each other. The classification system described in the second section would be most effective, if it would get knowledge from other expert systems that describe the difficulty to produce certain steel grades. Since the characteristics will change over time due to aspects like the steel market, new production technologies, and new products, it is preferable to get the knowledge from these systems that have the relevant competence.

We distinguish several kinds of communication between expert systems. The simplest way is the passive communication via a data base. A master-slave communication could be applied between scheduling and diagnosis system. The first (master) asks the blast furnace system (slave), when the next delivery of hot steel takes place. The most powerful communication however, is the negotiation between two expert systems. In this case, the two expert systems of the steel making plant and the rolling mill negotiate about certain orders with several offers and demands. The kind and the extend of communication should be designed before the development of single expert systems starts.

Despite this communication, the human expert will still be necessary. The network of expert systems can only be an assistance for an expert. To get the acceptance from this expert, the systems should support him with many things, not only with their competence. These expert systems should have a user friendly interface that helps the expert also in things like information retrieval, documentation, ordering, printing, faxing, and many more. The utilization of these tools should be as easy as possible and it would be of great benefit for a whole company if a standardized user interface could be defined. The most promising approach seems to us an object-oriented designed user interface where the user can handle objects of his domain. Objects like heats, slabs, or orders and collections of them should be manipulatable easily. We are on the way to make an overall object-oriented design for an expert system and its user interface for scheduling applications in the steel making industry. However, a more general approach should model consistently all objects of the steelmaking industry.

Knowledge Engineering

Although knowledge-based systems exist since the early seventies, there are still some problems with the professional construction of knowledge-based systems. A great number of different knowledge-based techniques, methods, and tools were developed in recent years. However, a new application in a real production environment is usually developed from scratch because the reuse of them is too costly. Expert systems tools for diagnosis or scheduling were developed with the intention to reuse them in new applications. This intention failed because they are restricted to too specific domains. Most often a mixture of different techniques and existing tools would be appropriate. Furthermore, these tools and techniques must be able to be interfaced to other soft- and hardware systems.

Expert systems for a certain application are often developed in an ad hoc manner and rapid prototyping is used as an excuse for not formally specifying the design and documenting the implemented system. However, for many experienced knowledge engineers rapid prototyping is only a technique for analyzing a problem instead of an overall technique for system development. As a consequence, for the development of large expert systems a design methodology is looked for that supports the analysis, design, maintenance and the reuse of software.

In the late sixties the need for a methodological approach was recognized in traditional programming. The discipline Software Engineering was founded with the intention to cope with the so called software crisis and to stimulate the research for a better understanding of the software production process. Software life cycle models were created in order to formalize the different phases of the development of software. An actual and promising approach to reuse software in traditional software engineering is the object-oriented paradigm where a problem is structured into objects that have their own data structure and methods to manipulate these data. Single objects or classes of objects are the granularity of reuse.

For knowledge-based systems this paradigm appears not to be sufficient since not objects are in the focus of the problem solving competence of knowledge-based systems. One of their

strong points is the explicit representation of reasoning. In first knowledge-based systems the representation of reasoning through production rules was stressed. Today it is known that most reasoning processes are more complex than a simple combination of such rules. Nevertheless, also in the new generation of expert systems the reasoning capabilities are central for problem solving. This accentuation of the reasoning capability distinguishes them from data base systems.

Since in knowledge-based systems we generate abstractions from the reasoning process, we should try to model reusable entities that describe the reasoning process. Consequently, many researchers demand a task-oriented model for *knowledge acquisition* (analysis), design, and maintenance of expert systems. In the analysis phase a task model is developed that describes how the expert solves a problem. This model may contain several tasks. The design of the expert system may be different from the expert's view of the solution since the system cannot imitate the expert in all aspects. Nevertheless, the same tasks exist and this should be transparent to facilitate the maintenance. After deciding which tasks must be performed, we choose from different reasoning methods one or more to achieve a task. Besides the advantage of a professional construction, it is expected that tasks designed for one application may be reused easier in another one. If a new system is developed whose domain consists of other objects and other strategies, the tasks may be reused. This is achieved by describing tasks in such a generic way that the differences are not visible on the abstract reasoning level.

In (Dorn 1993a) we have described in more detail the task-oriented design for a scheduling system in a steel making plant.

Conclusions

One of the main motivations for the application of expert systems in the steel making industry is the objective to standardize existing knowledge. Since much of this knowledge exists in rule-based form, expert systems seems to be adequate. However, for a general approach of improving the automation, methods for coping with complexity and uncertainty are necessary, too. We favor an object-oriented design approach to develop supporting tools for experts. However, this design must stress also the reasoning and task-oriented knowledge since this is a central point for expert systems.

We have motivated the development of networks of expert systems to obtain the full effectiveness of expert systems, since the different expert systems share a lot of knowledge and often one expert system is the producer of knowledge for another expert system.

Furthermore, we have argued that the phase of trial and error approaches for the development of expert systems must be overcome. What is needed is a more professional development of expert systems. Usually, expert systems like those for control of blast furnaces, scheduling of steel treatments, and others cannot be transferred easily from one application to another. We neither believe in expert system tools supporting, e.g., all blast furnaces. Several aspects especially strategic issues will always differ that will make it impossible to design one general tool. However, an approach of designing reusable components for such applications looks promisingly to me. These can be composed by experienced programmers.

To our opinion another aspect is important. Not every steelmaking plant should try to develop its own expert system. Some companies specialized in the development of expert systems should make dedicated solutions. These companies must also be responsible for the maintenance of these expert systems. Although the maintenance of expert systems is easier than that for other software systems it must be made and we assume that it must be done also more often, since the used knowledge changes more regularly.

References

- Amano, S., Takarabe, T., Nakamori, T. Oda, H., Taira, M., Watanabe, S. and Seki, T. (1990) Expert System for Blast Furnace Operation at Kimitsu Works, *Journal of the Iron and Steel Institute of Japan* 30 (2), pp. 105–110.
- Atsumi, T. (1989) Artificial Intelligence in the Japanese Steel Industry, *Proceedings of the Technical Exchange Session on the Use and Application of Expert Systems and Artificial Intelligence*, Chicago, Belgium: International Iron and Steel Institute, pp. 31–42.
- Blümelhuber, F. (1990) Expert System Application in the VA Stahl Linz GmbH, *Proceedings of the International Workshop on Expert Systems in Engineering*, G. Gottlob, W. Nejdl (eds), *Lecture Notes in Artificial Intelligence* 462, Springer Verlag, pp. 249–250.
- Dorn, J. and Shams, R. (1991) An Expert System for Scheduling in a Steelmaking Plant, *Proceedings of the 1st World Congress on Expert Systems*, Orlando Fla., pp. 395–404.
- Dorn, J. and Slany, W. (1993) A Flow Shop with Compatibility Constraints in a Steelmaking Plant, *Intelligent Scheduling*, Morgan Kaufmann (to be published).
- Dorn, J. (1993a) Task-oriented Design for Scheduling Applications, in *Scheduling of Production Processes*, J. Dorn and K.A.Froeschl (eds), Chichester: Ellis Horwood, pp. 163–178.
- Dorn, J. (1993b) Expert Systems in the Steel Industry. (Invited paper) To be published in the *Proceedings of the International Conference on Computerized Production Control in Steel Plant (CPC'93)* Seoul, Korea, November 1–5.
- Eiter, Th. (1990) Knowledge-based Systems for Metal-Related Technology – A Bibliography, Technical Report CD-S 90/3, Christian Doppler Laboratory for Expert Systems, Vienna.
- Inaba, M.; Aoki, T.; Sumigama, T. and Sakurai, M. (1991) Application of an Expert System to a Blast Furnace Operation, *Proceedings of the 1st World Congress on Expert Systems*, Orlando Fla., pp. 30–37.
- Kelemis, A.; Siebert, V.; Böhler, A. and Himmelbauer, F. (1993) Potentielle Anwendungsgebiete für CAPS, ein wissensbasiertes System zur integrierten Anlagenprogrammerstellung für Stahl- und Walzwerk, *CIM Management*.
- Minami, E. and Hirata, T. (1991) An Expert System for Large Scale Fault Diagnosis in Steel Manufacturing, *Proceedings of the 1st World Congress on Expert Systems*, Orlando Fla., pp. 1311–1318.
- Numao, M.; Morishita, S. (1989) A Scheduling Environment for Steel-Making Processes, *Proceedings of the 5th International Conference on Artificial Intelligence for Industrial Applications*, Miami, pp. 279–286.
- Stohl, K.; Snopek, W.; Weigert, T.; Moritz, T. (1991) Development of a Scheduling Expert System for a Steelplant, *Proceedings of the IFIP Conference on Experts Systems in Mineral and Metallurgy*, Finnland.
- Vasko, F.J.; Scott, K.L.; Wolf, F.E. and Woodyatt, L.R. (1989) A Fuzzy Approach to Optimal Metallurgical Grade Assignment, in *Applications of Fuzzy Set Methodologies in Industrial Engineering*, G.W. Evans, W. Karwowski, M.R. Wilhelm, Elsevier, pp. 285–298.
- Woodyatt, L.R.; Stott, K.L.; Wolf, F.E. and Vasko, F.J. (1992) Using Fuzzy Sets to Assign Metallurgical Grades to Steel, *Journal of Metallurgy*, February.