Faculté d'Économie, de Gestion et de Sciences Sociales

Design and Implementation of Decision Making Checkers for Industrial Production Scheduling, Control and Maintenance

Thèse de Doctorat
présentée
par

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Année Académique
2001-2002

Jury de thèse

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Design and implementation of decision making checkers for industrial production scheduling, control and maintenance

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June 6, 2002

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Preface

This document gathers research results obtained during the last years in the domain of human centred decision aid. Our focus, stimulated by the contact with Jean-Pierre Barthélemy, was concentrated on the design and the implementation of decision making checkers in the domain of industrial production.

The beginning of our work in decision aid goes back to the late eighties, when the freshly founded Centre de Recherche Public – Centre Universitaire in Luxembourg decided to start some Operations Research projects[1]. The projects concerned mainly a girders disposing problem proposed by the Luxembourg Steel Industry ARBED (Bisdorff, 1992). As the appointed head of research, I could bring some professional competence in, on the one hand, multicriteria decision aid techniques through my work at the LAMSADE (University Paris–Dauphine) and, on the other hand, artificial intelligence and, more specifically, constraint logic programming, on which I had recently started to work (Bisdorff, 1993). Unfortunately, these early projects did not achieve *real* practical results despite convincing scientific and technical results[2].

It was in this mood that I met Jean-Pierre Barthélemy in Spring 1993 at a EURO MCDA working group meeting in Chania (Greece). We discussed my difficulties in *really* applying our research work in OR and he convinced me to try a new project about the application of Cognitive Sciences in industry, the SYSCOG project (see Chapter **3**), with the aim of showing that a human expertise centred decision aid (HECDA) approach could greatly enhance practical application of such kind of research work. The practical success of this first project led us to start a second project, this time at the European level: the Brite-EURAM COMAPS project (see Chapter **4**). In parallel, Sàndor Jenei, a young Hungarian mathematician appointed with the help of Marc Roubens, joined our research group and worked independently on a third project, the ADAC project (see Chapter **5**).

In the following pages it is our intention to try to convince, in a similar way, our reader that the paradigm switch from a general decision aid approach to a human expertise centred one may seriously enhance practical application of OR techniques as

[1] «Optimisation Dynamique de la Production»(ODGP and ODGPII).

[2] Not really convinced by the practical application, I started instead a successful parallel research activity in applied statistics and symbolic data analysis (Bisdorff,2000), with the intention not to work on OR projects anymore.

all these three projects have indeed had some real industrial impact. The latter two were even followed by important industrial software developments (see Chapter **6**).

This work is largely based on previously written texts, mainly elaborated from 1994 to 1999 by the involved PhD students and myself in the context of these OR projects. That is why the reader may find some repetitions and evolving concepts throughout the pages. Indeed, we have more or less kept the original wordings in order to make apparent the evolution of our ideas during this crucial period. As a consequence the reader will find some interesting ideas only cursorily presented, whereas others may reappear recurrently in the presentation of our applications. A third poart (see Chapters **7** and **6**) therefore tries to make a scientific point from multiple disciplines' points of view, such as Psychology, Cognitive Sciences and Metahistory.

The overall work is organized in three parts.

- Part **A** (Chapters **1** and **2**) presents a general introduction to the subject and delimits our work. Indeed, we are mostly interested in decision making in the presence of practical decision expertise and this first part develops an innovative methodological framework for designing and implementing HECDA methods and tools. The methodological discussion brings in concepts and methods from several scientific fields such as cognitive psychology, multi-criteria decision aid and advanced computer science.

- Part **B** (Chapters **3** to **5**) presents in detail three industrial case studies. Chapter **3** presents the SysCog case study: a general cognitive decision aid laboratory. In Chapter 4, a second case study, the Comaps case, presents the design and implementation of a guarded decision making through a Check as You Decide device. The third case study, the Adac case is presented in Chapter **5**. It concerns the design of a guarded fault diagnostic and repairing process through an incremental operator assistance system.

- Finally, Part **C** (Chapters **6** and **7**) concerns validation of our methodological approach. Chapter **6** discusses practical (ecological) validation issues whereas Chapter **7** is finally devoted to the overall scientific validation of our approach.

Our main editorial idea was to make each chapter and especially the three illustrative case studies presented in Part **B** (Chapters **3** to **5**) more or less self-contained texts, that may be read independently on their own. Therefore also, we decided to give a separate list of bibliographic references at the end of each Chapter.

I wish to express my thanks to the Centre de Recherche Public – Gabriel Lippmann[3], who gave me the material support throughout the years for conducting the above mentioned OR projects. Special thanks are due to Fernand Reinig, the managing director, who supported a.o. in 1993 the creation of our "Statistics and Decision" Department.

[3]Formerly Centre de Recherche – Cenre Universitaire.

My special thanks are also due to Jean-Pierre Barthélemy, for his fruitful and friendly collaboration during all these years. His positive scientific impact on the research work presented hereafter may not be stressed enough.

Many thanks are naturally due to my collaborators in the three projects mentioned before: Sophie Laurent and Emanuel Pichon (SysCog), Nathalie Lépy and Pierre Saunier (Comaps) and Sàndor Jenei (Adac), to the TrefilARBED Bettembourg team working on the SysCog project, but also to the whole Comaps team and especially Laurette Maquet and Michel Streel, the R&D managers at Circuit Foil Luxembourg S.A.

Finally, I wish to express my deep appreciation and warmest thanks to Marc Roubens, Yves Crama and Gerard Colson, who criticized some draft versions of this work and always encouraged me to continue working on it.

R. B.

Luxembourg, March 2002

Part A

Decision aid for experienced decision-makers

Part A : Decision aid for experienced decision-maker

Abstract

In this first part, we present the motivation and delimit the purpose of our work. Our main interest is turned towards the design and the implementation of decision aid systems that specifically address the experienced decision maker. Indeed, complex repetitive decision making problems appearing in the context of industrial production scheduling, controlling and maintaining, are generally solved by experienced decision makers.

We start the discussion (see Chapter **1**) by recalling the classic Operations Research approach to decision aid by mathematical optimization techniques, thereby illustrating the lack of effective involvement of the actual decision maker in the problem solving process. The paradigm switch from mathematical optimization techniques to multicriteria decision aid, as introduced by the French School of OR around B. Roy, is then presented. Yet this approach, even if quite consequently addressing the effective decision making process and indeed positively involving the actual decision maker, appears not adapted, from a cognitive point of view, to situations where this decision maker might show a considerable amount of decision expertise (a case we commonly meet with our industrial schedulers and controllers for instance).

A second chapter (see Chapter **2**) introduces the cognitive principles that underly our methodological approach for decision aid addressing the experienced decision maker. It is mainly the refined consideration of a given decision making history, where the decision expertise is presumably reflected, that makes up the distinguishing feature of our cognitive approach to decision aid. The Moving Basis Heuristics (MBH) is introduced as major alternative for modelling cognitive solving strategies of experienced decision makers.

Chapter 1

Classical approach to decision aid

> "*...the term* operations research *means a scientific approach to decision making, which seeks to determine how best to design and operate a system, usually under conditions requiring the allocation of scare resources.*"
>
> WAYNE L. WINSTON (1994)

Contents

1.1 What decisions to consider ? Who to assist in his/her decision practice and how?

In this introductory chapter we review the methodological approach to decision aid from classic Operations Research (OR) and from the French School of Multi-criteria Decision Aid (MCDA) in order to illustrate their practical difficulty in tackling the kind of decision problems in which we are interested, namely highly repetitive and, thereby, experienced decision making, such as scheduling, controlling and maintaining within an industrial context.

Very often such decision practice (re)appears recurrently in time, as for instance in case of planning or scheduling problems, but also in case of production control and maintenance, and is generally embodied either in an individual person or in a clearly defined board with recognizable individual participants.

It is our main claim, that in such kind of decision problems, the repetitively involved human decision makers acquire a lot of experience, i.e. knowledge about admissible, satisfactory and sometimes even optimal decision actions. In this work we would therefore like to focus exclusively on such decision making problems where a human decision expertise apparently exists. Our concern is motivated by the fact that we mostly discover such kind of decision problem in practice, be it in industry or business and finance.

What are the necessary scientific requirements on which a decision aid methodology must rely to be efficient for such an experienced decision maker?

We proceed by presenting, in a first section (Section 1.2), classic linear optimization techniques from Operations Research. Noticing the pure technical orientation of this approach, we briefly introduce, in a second section (Section 1.3 on page 19), the Multi-criteria Decision Aid (MCDA) approach as promoted by the French OR School following the seminal work of Bernard Roy (1985).

Although much more decision-maker oriented, this approach does not explicitly take into account any specific cognitive decision expertise as observed in our industrial decision problems. A last section (Section 1.4 on page 25) therefore emphasizes the operational limitation of the MCDA approach when confronted with such experienced decision making.

1.2 Classic Operations Research approach to decision aid

Applied science, as is all scientific decision aid, needs methods and tools to understand, to decide and to act in coherence with some underlying (generally numerical) values embodying symbolic coding of all relevant aspects to the proposed decision aid (see Figure 1.1). For classic OR , a given decision problem is therefore formu-

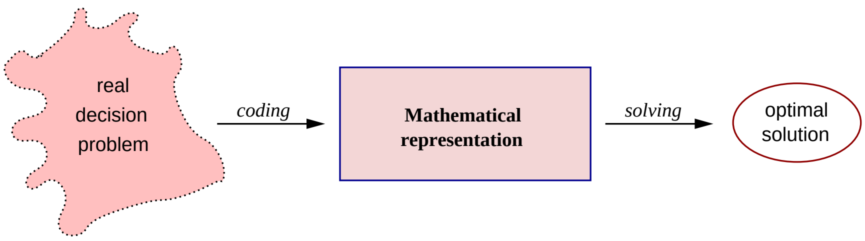

Figure 1.1: Modelling the optimal decision

lated in mathematical (analytical) terms and, algebraic solving methods, for instance from linear algebra, are used in order to extract from the once formulated problem a mathematical object designated as the *optimal*, i.e. the *best or correct rational* decision.

In this sense, Operations Research is seen as a "*natural*" or "*engineering science*" and standard mathematical tools are used to solve a given decision problem without any direct intervention of the actual decision maker, at least during the solving phase.

In order to assess methodological implications of this decision aid approach, let us consider a small didactic example taken from Vidal Cohen (1995).

Example 1.2.1. The baker's decision problem.

A baker is producing every day a quantity x of cakes and a quantity y of Vienna breads from three ingredients: flour (A) in a quantity 80, butter (B) in a quantity 24 and sugar (C) in a quantity 36.

resource allocation	cake	Vienna bread
A (flour)	5	4
B (butter)	1	2
C (sugar)	3	2

Table 1.1: Resource allocation example

Table 1.1 shows the resource allocation for the production of a unit of each product and a linear assumption on the production process allows to write the following inequations describing the global limitations of the production:

$$5x + 4y \leq 80, \tag{1.1}$$

$$1x + 2y \leq 24, \tag{1.2}$$

$$3x + 2y \leq 36, \tag{1.3}$$

$$x \geq 0, \tag{1.4}$$

$$y \geq 0. \tag{1.5}$$

Furthermore, if we suppose that these products are sold with following prices: a cake is sold 40 F and a Vienna bread is sold 50 F (independently of the quantities x and y produced) then the expected income for the baker is representable by a linear objective function I:

$$I = 40x + 50y. \tag{1.6}$$

The set of possible productions is confined to the interior and the frontier of the polygon OMNP shown in Figure 1.2 on the next page.

Solving this problem consists in shifting as high as possible the objective function I such that there exists an intersection point with OMNP. Graphical inspection shows that I is indeed maximal for point N, i.e. an optimal production of $x = 6$ units of

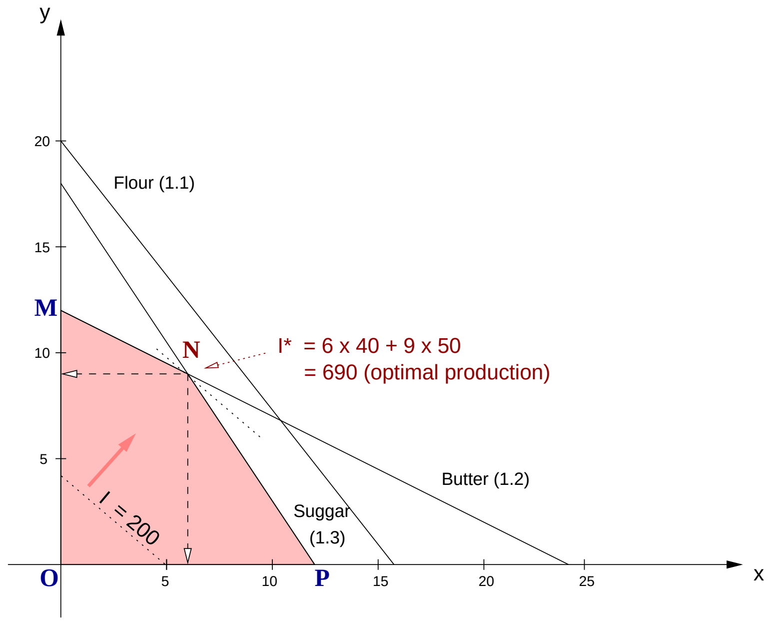

Figure 1.2: Linear Programming example

cakes and $y = 9$ units of Vienna bread. Optimal income of 690 F is achieved for this decision vector.

The baker is hereafter invited to produce every day 6 cakes and 9 Vienna breads. These quantities will maximize his income under the condition that the mathematical description of the decision problem corresponds effectively to the really given decision problem of the baker. Hence, apart from validating the initial specification of the decision problem, the baker, i.e. the decision maker in this example, is in fact not needed to solve it.

In the classic OR approach to decision aid the decision maker is only intervening during a first identification step – for delimiting that part of some "real world" that will be formulated mathematically as a decision problem. The subsequent modelling and solving steps are solely depending on mathematical skill. Eventually, the decision maker is again needed for validating the extracted optimal decision in practice.

This kind of decision aid is most relevant in the field of technical optimization problems where the origin of classic OR is situated. When OR researchers tried to tackle more strategic decision problems, apart from the original technically oriented application field, practical acceptance problems soon appeared[1] with real life decision makers. Indeed, effectiveness of the decision aid was often contested for such strategic decision making where decision makers, often general managers, assume a greater part

[1] Already in the sixties there appears a first crisis in classic OR with respect to practical application outside the traditional field of technical applications (see Cohen, 1995, p. 111).

of subjective responsibility for the actual outcome of the decision process; generally with the argument, that the classic OR approach is not able to cope effectively with the decision maker's real pragmatic problem.

This practical difficulty for applying classic OR decision aid led the French and Belgian OR schools to develop, during the seventies and the early eighties, a new methodological framework for decision aid now generally called *multi-criteria aid for decision* (MCDA)[2].

1.3 The French school of multi-criteria aid for decision

The main paradigmatic shift[3] of the MCDA approach consists in explicitly addressing the decision maker's pragmatic preferences by a set of concepts and methods we will briefly pass in review[4].

Solving a decision problem consists no longer in showing some optimal solution, as was the case in the classic OR approach, but instead consists in correctly modelling the actual preferences of a well identified and effectively involved decision maker (see Figure 1.3 on the following page).

First, we have to identify "conscious" *decision actions*[5]. Indeed, a potential decision action is not simply some abstract point in a geometric space as assumed in the previous example (see Figure 1.2 on the preceding page), but a logic denotation, (*yes*, *no*), applied on a discrete set A of recognized *reasonable* points, indicating possible, i.e. intelligible and reasonable choice candidates called *potential decision actions* for the decision to be taken. It is naturally the decision maker's first task to explicitly validate this set A.

Example 1.3.1. Coming back to the baker's decision problem (see Example 1.2.1 on page 17), the decision aid now starts with the identification of such a discrete set $A = \{M, N, N', P\}$ of potential candidates for decision (see Figure 1.4 on page 21). Decision action M consists in producing solely Vienna breads whereas decision action P consists in making only cakes. Decision actions N and N' appear to be rather close to each other as both produce a mixture of cakes and breads. The first proposes more cakes and fewer breads and the second, just on the contrary, proposes more breads and fewer cakes.

[2]As the author is more familiar with the work proposed by the Lamsade (Laboratoire d'Analyse et de Modélisation pour l'Aide à la Décision, directeur B. Roy (1970-1998),Université Paris-Dauphine) around Bernard Roy, than with the work around the PROMETHEE methods (see Brans et al., 1984) for instance, we limit our discussion in the sequel exclusively to the former one. But the same argumentation could be produced with respect to the PROMETHEE methods.

[3]«*Aider à décider, c'est, en tout premier lieu, aider à clarifier la formation, la transformation et l'argumentation des* préférences.» (Roy and Bouyssou, 1993, p.46).

[4]For a detailed presentation of the methodology see Roy (1985) and more concise (Roy and Bouyssou, 1993).

[5](see Roy, 1985, chapter 5, p.53).

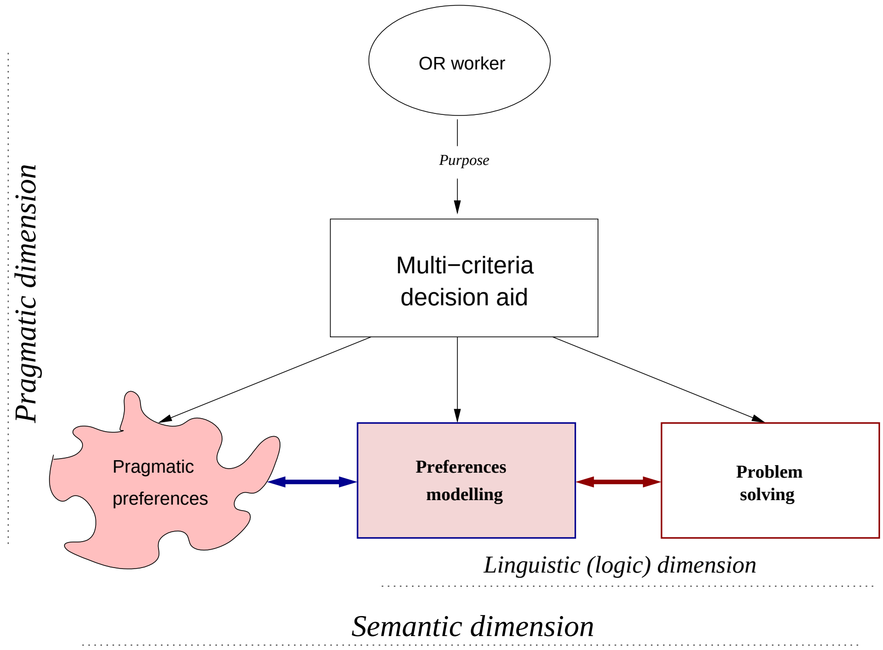

Figure 1.3: Multi-criteria Decision Aid Modelling

Consequently MCDA shifts from the mathematical (geometrical) representation of the decision space towards discrete relational preference representations[6], the main focus of the formal construction being now concentrated on a correct *logical modelling* of the apparent decision maker's pragmatic preferences as we might observe on the set A of potential decision actions (see Figure 1.4 on the facing page). Solving the decision aid problem means here not modelling the decision problem and extracting the optimal solution as in the classic OR approach but rather modelling correctly the pragmatic preferences of the decision maker. The solution of the actual decision problem depends here eventually on the underlying decision problematic, i.e. choice, ranking or sorting[7].

In order to uncover such preferences on the set A of potential decision actions, we have to *evaluate* the practical consequences of these actions, again with the help of the decision maker, with respect to *multiple preference dimensions* which allows us to qualify or *evaluate* each potential decision action with respect to the "*conscious*" assumption that this action is precisely the actual decision to be taken.

Example 1.3.2. In the case of the baker (Example 1.3.1 on the page before), we might choose two such preference dimensions: daily income and daily balance of the product offer.

[6](see Roy, 1985, chapter 8, p 170).
[7](see Roy, 1985, chapter 6, p.73).

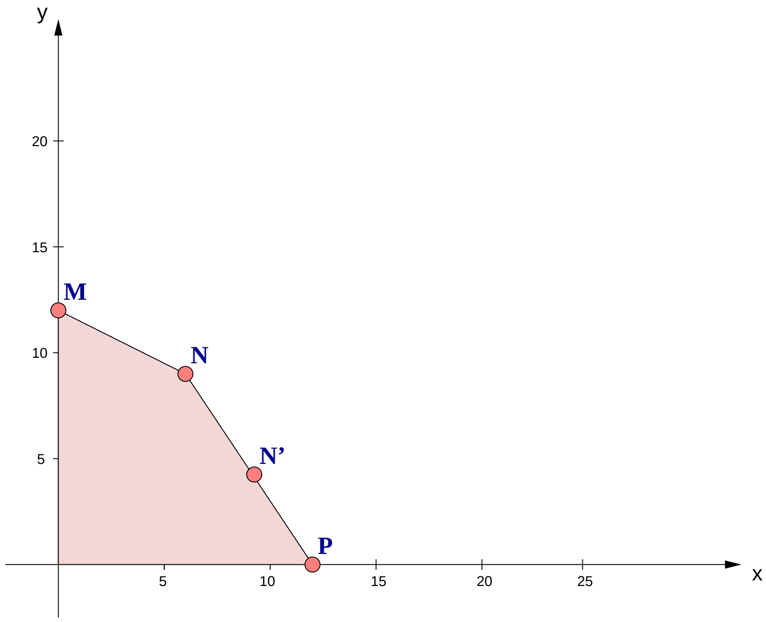

Figure 1.4: MCDA approach: Potential decision actions

But, in contrast to the classic OR approach as described above, here the main interest does not go to directly model each potential decision action, but instead to model the pairwise preference relation we observe between these potential decision actions. Multiple preference dimensions are therefore operationally organized in a *coherent family* F of preference judgment functions called *criteria*[8] defined on the set A of admissible decision actions. Coherent[9] means here essentially that all preference dimensions are indeed covered by F; that each criteria is consistently comparing all potential decision actions (the criteria models generally a complete ordering structure on A) and that each criteria is independent in a preferential sense from each other[10].

Example 1.3.3. In the baker's decision problem (Example 1.3.1 on page 19 and 1.3.2 on the preceding page) let us consider the following criterion-functions:

- We may take a simple income sum as a criteria I for the first preference dimension and

- An ordinal preference scale with five linguistic grades : "*very weak, weak, medium, good, very good*" for the second preference dimension, numerically

[8](see Roy, 1985, chapter 9, p. 224) is most insisting on the importance of this concept of formal criteria for constructing pairwise comparisons of decision actions.

[9](see Roy, 1985, p.310).

[10]A thorough discussion on the semiotical foundation of this approach may be found in Bisdorff (2001).

coded as shown in Table 1.2, may give a criterion Q modelling preferences according to the balance of the product offer.

linguistic grade	*numerical code*
very weak	−2
weak	−1
medium	0
good	1
very good	2

Table 1.2: Ordinal criterion for a qualitative preference dimension

The first criterion is a pure numerical construction whereas the second represents an ordinal preference scale with 5 levels.

With the help of such a coherent family of criteria we are able to present a global performance tableau of the potential decision actions on each criteria, as shown for instance in Table 1.3. Concentrating on preference modelling we are now able to

A	I	Q
M	480	−2
N	690	1
N′	620	2
P	600	−1

Table 1.3: Sample evaluation matrix

construct on the set A a pairwise comparison based on an *outranking relation*[11] with semantics: *"at least as good as"* on each preference criteria (see Tables 1.4 and 1.5 on the next page). Following the tradition of the *Electre* methods[12], these outrankings

S_I	M	N	N′	P
M	1	0	0	0
N	1	1	1	1
N′	1	0	1	1
P	1	0	1	1

Table 1.4: Outranking relation defined on criteria I

per criterion may be additively aggregated into a general fuzzy outranking index based on *concordance* and *non discordance* of the individual outranking relations.

[11](see Roy, 1973).
[12](see Roy and Bouyssou, 1993, chapter 6, p. 331).

S_Q	M	N	N′	P
M	1	0	0	0
N	1	1	0	1
N′	1	1	1	1
P	1	0	0	1

Table 1.5: Outranking relation defined on criteria Q

We have here to associate with each criterion a relative *importance coefficient* somehow balancing out each criterion with respect to the others.

Example 1.3.4. For instance, if we consider in the baker's problem (Examples 1.3.2 on page 20 and 1.3.3 on page 21) the following relative importance weights: I(75%), Q(25%), i.e. income is considered as three times as important as the balance of the product offer, then we obtain the global outranking index shown in Table 1.6.

S	M	N	N′	P
M	1	0	0	0
N	1	1	.75	1
N′	1	.25	1	1
P	1	0	.75	1

Table 1.6: Global fuzzy outranking index

Depending on the *decision problematic*[13]: best choice, ranking, preference descriptions etc several techniques may be used for actually solving the decision making problem, i.e. to show the corresponding solution of the decision problem. For instance, in case a unique best choice is searched for in the given decision problem, a bipolar kernel extraction (Bisdorff, 1997, 1999; Bisdorff and Roubens, 1996a,b) may be used to solve the problem (see Figure 1.5 on the next page).

Example 1.3.5. For the global outranking index elaborated in Example 1.3.4 (see Table 1.6) this technique would associate following credibilities with each potential action's quality to figure as best decision candidate:

$$\{M(0.25), N(\mathbf{0.75}), N'(0.25), P(0.25)\}$$

so that the point N appears indeed as best decision candidate with a credibility of 75%, whereas all other equally get very low credibility (25%) for the same potentiality.

Symmetrically, we could also compute fuzzy worst choice recommendations from the outranking index shown in Table 1.6:

$$\{M(\mathbf{1}), N(0), N'(0), P(0)\}$$

[13](see Roy and Bouyssou, 1993, chapter 6, p. 332).

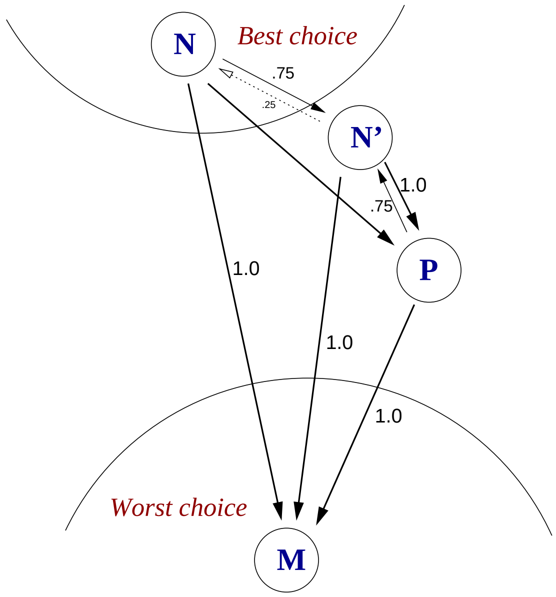

Figure 1.5: Exploiting a fuzzy global outranking relation

Here we may notice that the point M appears with certainty as the worst decision candidate (see Figure 1.5) whereas neither of the three others appears with certainty as a worst candidate.

It is worth noticing that the decision maker is returned a fuzzy logical denotation on all potential decision actions. The actual decision to be eventually taken as a result of the decision aid process relies now completely in the hands of the actual decision maker.[14]

Example 1.3.6. Following the results proposed in Example 1.3.5 on the preceding page, the baker could accept decision action N as best candidate if he accepts recommendations with 75% of credibility. If, however, he were to require a credibility of more than 75% in order to accept a recommendation then no clear unique best choice appears to him. All three actions N, N′ and P are identically not credible enough candidates, whereas the worst choice M is once for all given with certainty as may be easily confirmed in Figure 1.5.

This detailed development of Roy & Bouyssou's approach to multi-criteria decision aid illustrates the paradigmatic shift from a mathematical towards a logical or semiotical problem, i.e. constructing formal criteria supporting the decision makers's preferences and induce a credible recommendation. In the original classic OR

[14] This feature represents our main original contribution to the decision aid methodology of the French OR school (Bisdorff, 2000).

approach, main focus is given to the solution of the actual decision problem, for instance, the optimal decision. In this latter approach the pragmatic preferences gain major attention. In this approach the decision maker is therefore significantly more present, as he is requested to validate progressively and in a constructive way all the four levels of decision aid constructs:

- the delimitation of a set A of potential decision actions;
- the modelling of the consequences of the potential decision actions within multiple preference dimensions;
- the performance tableau with the help of a coherent family of criteria and,
- finally, depending on the given decision problematic (choice, ranking, sorting, etc) the eventually fuzzy decision recommendation depending on the relative importance that the decision maker attributes to each individual criteria.

Therefore, MCDA methodology appears a more pertinent approach to the new application domain for decision aid methodology, as given by such higher level strategic decisions; A domain where classic OR decision aid, with its more technology oriented approach, could not easily propose acceptable tools and methods.

Nevertheless, there remain some important cognitive limitations for acceptance of this methodological approach to decision problems where a human decision maker has acquired some decision expertise.

1.4 Practical limitation of MCDA approach

An important limitation for acceptance of MCDA in practice comes precisely from the very constructive nature of the methodology. The methodology requires a potential decision maker to follow and accept all progressive modelling steps.

In practice however, it often appears that these methodological requirements are somehow in conflict with occasionally existing "intuitive" solving strategies which an experienced decision maker may have acquired through a repetitive decision making process.

This may lead such experienced decision makers to reject the necessarily completeness of the modelled consequences of the potential decision actions. They generally consider the MCDA approach, from the point of view of their current decision practice, as being outmost heavy and unadapted to effectively assist them in their recurrent decision making practice.

We may claim that from a cognitive point of view, the more a decision maker appears as an expert with respect to a recurrent decision practice, the more (s)he will show aversion to such exhaustive modelling of the decision problem. Indeed decision expertise, as we will see in the Chapter **2**, is precisely given when a decision maker can, in a reliable way, immediately concentrate himself on essential features of each decision situation, without being otherwise bothered by what he knows being irrelevant considerations.

A further difficulty for applying MCDA methods and tools may come from the always present necessity of modelling the relative importance of the criteria in order to be able to aggregate the individual preferences modelled by each criteria. Uniform static global weights of importance for each preference criteria over the whole set A of potential decision actions, as requested in the MCDA approach, appear indeed in concurrence with the intuitive criteria weights a decision maker selectss for achieving his intuitive preferences.

We will indeed see in the next chapter that, from a cognitive point of view, local preferences (in the sense of the set A) are normally based on a specific local weighing of the underlying relevant preference dimensions. Some other preferences may rely on other weighings of otherwise relevant dimensions, so that assuming static global weights makes no cognitive sense in general to an experienced decision maker.

1.5 Moving on

Both classic OR and MCDA decision aid methodology clearly only address such kinds of decision problems where the decision maker generally does not know, even intuitively, in advance the final solution of the decision problem with which he is confronted. In other words, the decision problem generally concerns a unique large and complex decision process where no repetitive decision practice may have led in the past to efficient solving strategies before the actual decision aid is starting.

Under this restrictive assumption, both approaches the MCDA naturally more than the classic OR ones, are able to convince potential decision makers[15] of the usefulness of their decision aid.

The methodological approaches to decision aid presented in this first chapter lack specific support for a whole class of practical decision problems, namely those where a human experienced decision maker is acting. In industrial settings, however, we are very often confronted with such kind of decision problems. Thus we shall propose in the next chapter a new methodological framework for addressing just this kind of decision problems.

[15]These decision makers appear generally as complex institutional bodies, such as state agencies, large companies etc. so that a particular decision practice may not be effectively embodied in specific human persons.

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Chapter 2

Assisting the experienced decision maker

"*We think in clichés because clichés are ideas which have so to speak proved their Darwinian* fitness *over time* (*I say nothing, here, of truthfulness*)"

THE BIOGRAPHER'S TALE, A.S. BYATT (2000)

Contents

2.1 The experienced decision maker

Having illustrated in the previous chapter, how classic decision aid methodology, be it from classic OR or from MCDA, may fail to address decision problems involving an experienced decision maker, we are now going to investigate in greater detail the all important concept of *experienced decision maker*. Further sections will then introduce our conception of the cognitive supports we would like to develop for such a kind of decision problems.

Let us start by setting up some basic definitions:

2.1.1 Basic definitions

Definition 2.1.1 (cognitician and decision maker).
We call *cognitician*, the person or institutional body in charge of the design and implementation of a decision aid system. We call *decision maker* the person or the institutional body effectively taking formal decisions, i.e. *decision acts* that are clearly recognizable and may be formally described in a model of the decision making. Finally, we call *decision situation* the clearly identified moment where the decision maker is taking his/her decisions.

As already mentioned in Chapter 1, we are mainly interested in experienced decision making, i.e. decision-making that is based on repetitive (re)solving in time of similar decision problems. Our main focus in this work goes indeed to production scheduling, control and maintenance problems, i.e. decision problems that are normally of a highly repetitive nature.

Furthermore, we are interested in decision problems where the complexity of the task prevents any easy automation approach and where experienced decision makers have developed instead own "*wild*", i.e. intuitive practical solving strategies.

Definition 2.1.2 (experienced decision maker).
We call *experienced* decision maker, a person or an institutional body, composed of a limited number of recognized human participants, who has acquired during past decision experiences, through a more or less formal "learning–by–doing" process, non–trivial problem–solving strategies that lead to a socially recognized human decision expertise concerning a given repetitive decision problem.

One of the major critics we address to both the classic OR and the MCDA decision aid methodology when trying to assist experienced decision makers concerns the under-estimation and/or the ignorance of the specifically human decision making expertise.

Integrating efficiently such cognitive capacities of experienced decision makers into a decision aid purpose needs to address more precisely the concept of *human decision making expertise*.

What makes up human decision expertise?

How are the ideas organized in the mind of such an experienced decision maker so as to make him competent for complex problem solving tasks?

2.1.2 The nature of human decision expertise

Recent work in artificial intelligence[1], where researchers tried to develop non-human systems that mimic intelligent human task performance in a variety of domains, have supported the idea that human decision expertise is not based on the availability of a general problem-solving method or algorithm (Feigenbaum, 1989) .

The general problem solver (GPS)(Ernst and Newell, 1969), designed to translate and then represent internally the components of a certain problem and then to solve it by applying certain problem-solving heuristics, based on the idea of means-end analysis, did not show a concluding result. Indeed, early failures to write programs that could compete with human decision expertise (particular in the area of chess) have led to the conclusion that domain-independent expert systems do not exist because the nature and structure of knowledge differs from domain to domain.

Instead of trying now to identify any stable domain-general individual characteristics to model human problem solving expertise, cognitive science research has turned rather to domain-specific explanations of skill-related differences within certain expertise domains such as chess playing, physics, electronics, and so on.

Let us concentrate here on the results obtained when studying chess playing expertise for instance. Early work by De Groot (1965) showed that, although chess grandmasters choose better moves than less experienced players, they do not apparently process much more information than the latter ones, i.e. both consider apparently roughly the same number of potential moves before choosing their actual move. Also they apparently don't differ in how far they look ahead to find the best move.

A major conclusion was that a grandmaster simply does not waste time by exploring moves and move constellations that do not lead anywhere, instead concentrates his time and effort on the exploration of promising moves. De Groot hypothesized that the expert's larger knowledge base guides his better selection of moves.

[1] This section is inspired by the article of Frensch and Buchner on Domain-generality versus domain-specificity in cognition (Frensch and Buchner, 1999).

What distinguishes a master, i.e. experienced chess player, from a class A or a novice one has also been investigated by Chase and Simon (1973). They studied three chess players (a master, a class-A player and a novice, i.e. an unexperienced player) in a variety of experimental situations. The master's ability to recall briefly presented, meaningful chess positions is better than the class A player's or the novice's. Furthermore, the master reproduced the chess board perfectly in three or four trials, whereas the class A player typically required a few more trials than the master. The novice needed up to 14 trials to reproduce the entire board configuration.

Howeve, when random configurations were recalled, the results changed dramatically. Now there were no more performance differences between the three type of players. The overall first-trial performance for all three of them was even worse than the first-trial of the novice in case of a meaningful board.

Chase and Simon (1973) interpreted these results in the following way, roughly confirming de Groot's results: the superior ability of experienced players over less experienced players to recall briefly presented positions cannot be explained by a superior memory storage capacity, i.e. masters cannot keep in their short term working memory more chess pieces than lesser experienced players. Their superiority in this task is based on a vast number of basic, meaningful chess patterns, called chunks, that are stored in long-term memory. Each of these pattern can be quickly identified and accessed in long-term memory through some kind of hashing table mechanism. This hypothesis can also explain why random generated chess patterns, being generally not meaningful and so not present in the hashing mechanism, are not significantly better recalled by the master than by the novice players. Their short-term working memories are not different one from another.

Translated in the context of our experienced decision making, the preceeding theories might well explain why an experienced decision maker feels uneasy and unconvinced by both classic OR and MCDA methodology.

First, a given human decision expertise, is not relying on any particular general intuitive algorithmic approach as for instance linear algebra or problem-solving heuristics as proposed by the GPS (General Problem Solver) program. This makes classic OR decision aid rather un-appropriate for dealing effectively with human decision expertise.

Working Hypothesis 2.1.3 (decision expertise). Decision expertise relies on the storage in long-term memory of a large number of meaningful, ie. exemplary decision situations, that can be quickly identified and accessed if necessary through a specific hashing key or label. This knowledge organization is dependent on the actual decision making practice the decision maker has had the opportunity to tackle, i.e. his(her) practical decision experience. The more (s)he has experienced different and contrasted decision situations, the more the decision maker is likely to be able to describe precisely his pragmatic preferences.

Decision expertise is therefore necessarily partial, biased and incomplete. Sometimes the decision maker is very confident about his decision-making. Sometimes (s)he is rather hesitating and unable to clearly express his preferences. This fact would explain why experienced decision makers may find the MCDA approach too heavy and inappropriate. Necessary completeness in all formal specifications, i.e. the complete set of potential decision actions, all possible preferential aspects to be taken into account for all decision actions, the complete ordering of all actions on all criteria etc, is generally not matching the otherwise uneven distributed knowledge the experienced decision maker has acquired with time.

Having gained some insight in the nature of human decision expertise, we are now confronted with the operational problem of how to observe and formally describe a specific decision expertise.

2.2 How to observe a decision expertise

When observing an experienced decision maker, the cognitician will make a careful distinction between the observable "embodied" decision extension, i.e. the actually observed on-site decision practice, and the possibly communicated conscious decision intention, i.e. the strategic discourse the decision maker utters to explain, to legitimate or comment his/her decision practice[2].

It is imperative to point out that our approach does not intend to replace the actual decision maker by an artificial formal decision system as is usually the objective in classic OR and/or Artificial Intelligence. Rather we will try to uncover and enhance the existing decision practice by supporting the decision maker in his/her attempt to formalize his/her decision intention (see Figure 2.1 on the following page).

Definition 2.2.1 (purpose of the decision aid).
The purpose of a human expertise centred decision aid (HECDA) is to support the experienced decision maker: first, in his/her decision practice and secondly, in communicating his decision intention. This latter support is essentially based on pragmatic considerations that should enhance the decision maker's choice, on the one hand, of the decision domain and, on the other hand, of the decision model. The first choice allows the decision maker to delimit the decision problem in such a way that it supports the pragmatic solving strategies and/or the decision outcome.

It is worthwhile noticing that there exists a strong cognitive double bind between the pragmatic solving strategies and the formal delimitation of the problem as shown in Figure 2.1 on the next page. Problem delimitation and problem solving are opposite sides of a same semantic construct, i.e. precisely the decision expertise we want to take into account and enhance. Indeed, as we shall see further on (see Part **B**), decision

[2] This section is largely based upon Bisdorff (1999).

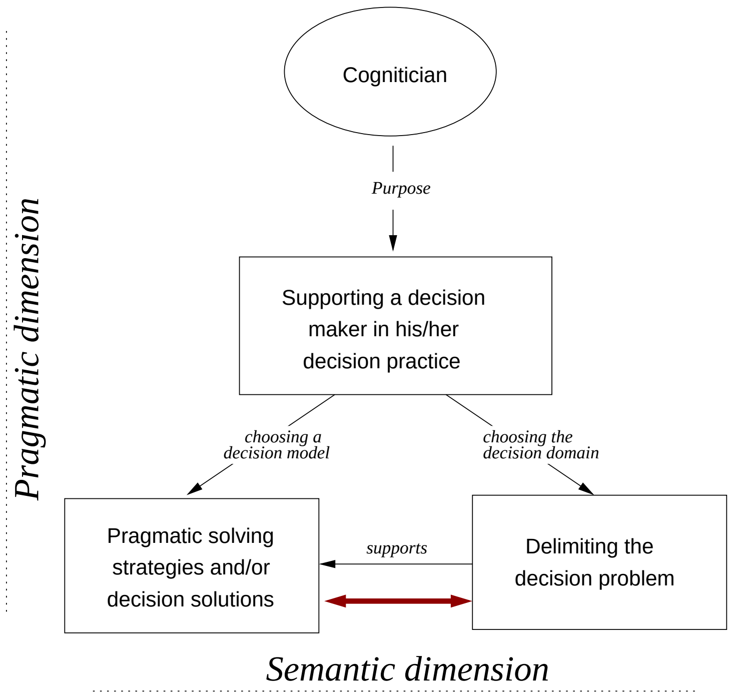

Figure 2.1: How to support a decision maker
source: *Bisdorff* (1999)

expertise also appears in the pertinent delimitation of the decision problem as in the proper solving strategies and their corresponding decision solutions.

Therefore, we cannot simply formally translate the intentional discourse of the decision maker. Indeed, if we accept as such the proposed delimitation of the problem, the problem delimitation will be too firmly linked to the actual solving strategies. On the other hand, if we accept as such the intentional solving strategies, the delimitation of the decision problem is *subjectively* pre-conditioned, so that it appears difficult for the cognitician to model the global decision problem in an *objective* way.

To avoid such a subjective bias in the modelling phase of the decision aid, we rely on a behaviouristic approach gathering the effectively observable decision acts with their respective consequences. From such an objective decision history, we try to induce, on the one hand. an adequate decision problem formulation and delimitation and, on the other hand, the apparent cognitive problem-solving strategies that the decision maker might have used to take his/her decision.

2.2.1 Constructing a cognitive artifact of the decision problem

Our operational purpose is to construct a formal model or representation of the decision problem and of corresponding solving strategies by symbolic coding and application of inductive and algebraic closure operations (see Figure 2.2).

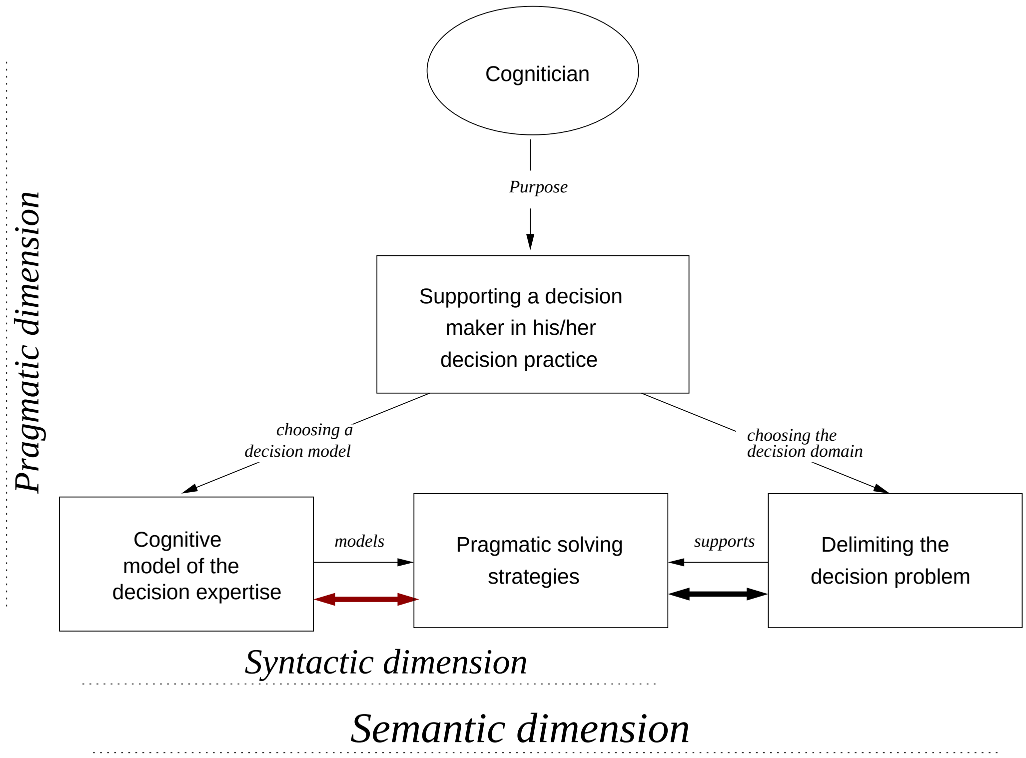

Figure 2.2: Cognitive modelling of the decision problem
source: *Bisdorff* (1999)

Definition 2.2.2 (model of the decision expertise).
We call *model of the decision expertise*, the formal (syntactic) representation of the decision problem, the cognitician elaborates from the objective observation of a given experienced decision maker. Again, the formulation involves two structural choices:

- the choice of the decision model, allowing in fact to operationally formulate the expert solving strategies the experienced decision maker is showing;
- the choice of the decision domain. This choice induces consequent problem delimitations that support in fact the cognitive solving strategies of the decision maker.

This formal model may be seen as a *cognitive artifact*[3] to be used as discussion support in order to simulate, evaluate and compare observed and declared decision extensions with declared decision intentions.

[3]In the French community, the term *artifact* has a negative connotation. Here this term is to be taken in a positive sense as is common in the Anglo-Saxon community, and it denotes a formal construction supposed to enhance the cognitive abilities of the decision maker

It is important to stress, on one hand, the essentially communicative purpose of this cognitive model or artifact. It is mainly used to communicate between actors around the decision problem; to define the problem and to formulate possible solving strategies. The importance of this symbolic production comes indeed from the fact that it effectively only instantiates the actual experienced decision maker[4].

On the other hand, this artifact consists essentially in a symbolic linguistic construction generally based on elementary first–order predicate logic calculus as we shall see in the next section. In our practical implementations as shown in the second part (see Part **B**) of this work we use for operational purposes the sub-model of this logic handled by the constraint logic programming languages. This sub–model is better suited for immediate computation of logical specifications. Concurrent propagation as operationally implemented with the help of these systems allows indeed to efficiently study and simulate such decision expertise.

Finally, we must notice a second cognitive double bind between the cognitive model and the solving strategies that appears beside the one already discussed before (see Figure 2.2 on the page before). This time, the double bind is embedded in the syntactic dimension. The formal richness of the model of the decision expertise naturally determines expressivity of potential solving strategies and problem delimitations, but also conversely, the intentional formulation of the problem and of the pragmatic solving strategies determine strongly the choice of the formulation of the decision expertise. A critical analysis will be necessary, in order to lift this model out of its embedding in the subjective intentional discourse of the decision maker.

In order to cope with this methodological difficulty when constructing a cognitive model of a given decision expertise, we proceed in three steps:

1. describe first the empirical decision practice under *extensional* form, i.e. a set of observable real cases of solved decision situations,

2. extract by logic induction, in a second step, from this formal historic description an apparent decision *intension*[5], that is a set of decision strategies or rules apparently underlying the decision extension, and

3. *reflect* in a third step this *artificial* decision intension towards the decision maker's decision intention.

[4]«... *On peut dire que ce que nous appelons* je , *nous-mêmes, naît des capacités linguistiques récursives de l'homme et de sa capacité unique d'autodescription et de narration. ... la fonction langagière est elle aussi une capacité modulaire qui cohabite avec toutes les autres choses que nous sommes sur le plan cognitif. Nous pouvons concevoir notre sentiment d'un* je *personnel comme le récit interprètatif continuel de certains aspects des activités parallèles dans notre vie quotidienne ...* », (Varela, 1996).

[5]We use the technical term '*intension*' for artificial, computed decision rules in order to distinguish them from the experienced decision maker's '*intention*', i.e. his intentional discourse.

It is precisely the third step, that installs the methodological possibility for a critical comparison of the *artificial* decision expertise, generated at step two of our procedure, and the *natural*, subjective decision expertise as intentionally communicated by the experienced decision maker. Such a *conscious* confrontation should ideally result in a stable, formal model of the decision expertise, both accepted and validated by the cognitician and the decision maker.

We claim that this will generally be the case, if the expertise's cognitive artifact is constructed with the objective to *mimic* as closely as possible the natural decision making practice and this in a dynamic system setting.

2.2.2 Implementing a mimic decision making model

Installing a formal engine between the experienced decision maker and the information return from the repetitive decision practice involves creating a mimic[6] formal model of the decision expertise shown by the operator in his real practical activity (see Figure 2.3).

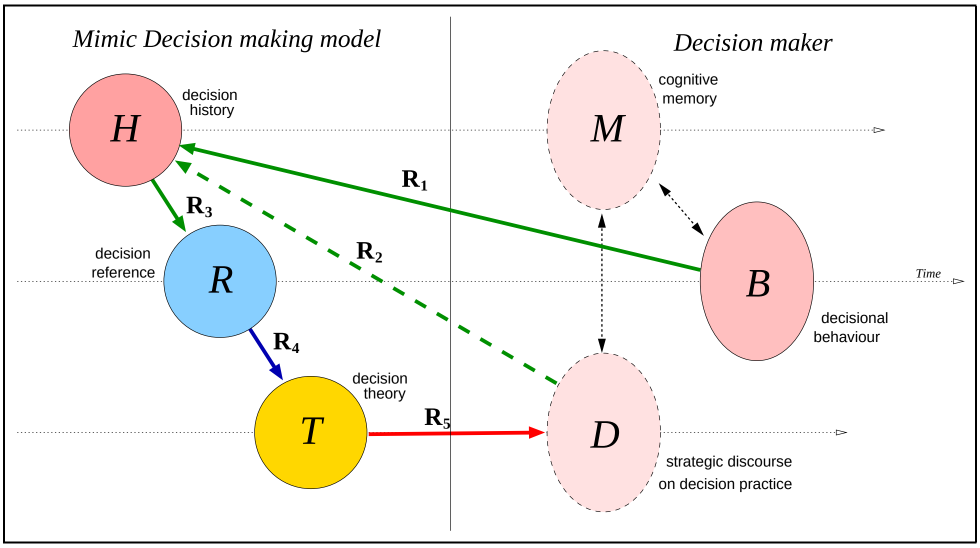

Figure 2.3: Describing the decision practice

Implementing such a formal model involves three *mimic* steps:

- a *symbolic coding* step (see arrow R_1 in Figure 2.3), capturing the semiotics of the decision process description, i.e. installing a symbolic universe of discourse allowing to formally (that is from a syntactic point of view) express the behavior of the decision maker;

[6]Distinguishing three mimic steps in the historical (re)construction of a decision practice is based on the corresponding work of P. Ricœur 1983.

- a *configuration* step: First, qualifying the decision practice (see arrows R_2 and R_3 in Figure 2.3 on the preceding page) and secondly, capturing or computing the cognitive strategies (see arrow R_4 in Figure 2.3 on the page before) allowing to understand the decision maker's behavior and

- a most important last *cognitive validation* step (see arrow R_5 in Figure 2.3 on the preceding page), installing the *reflexive mirror* towards the decision maker in order to initiate a *hermeneutic circle* needed for validating and make positively evolve the mimic decision model.

Trying to collect historical data H on a given decision practice, necessarily involves capturing physical measurements and/or qualitative assessments from the empiric context B in which the decision practice takes place. For instance, in the COMAPS project (see Chapter 4 in Part **B**), the involvement of a human expert controller allows us to rely on his expertise for gathering all relevant figures and data for describing the control practice. Without this symbolic representation no decision practice is assessable and no behavior and discourse may be gathered and represented.

Experienced decision makers show in general good or satisfactory practical performance. In order to be able to support and eventually enhance this performance, we must understand the apparently underlying decision strategies. Therefore the cognitician now inductively constructs, on the basis of a given decision reference R, i.e. a set of good qualified control decisions taken out of the decision history H, the apparently underlying control strategies T. This problem is in general a computationally non trivial job envolving a large amount of data and computational power (see Section 4.4.3 on page 128 in Chapter 4).

But it is not sufficient to exhibit such possible decision strategies T (computed on the basis of the decision reference R). We eventually must reflect these results towards the decision maker's strategic discourse D on his decision expertise. And, here appears the specific difference we want to install between traditional OR or Artificial Intelligence (AI) approaches and ours.

In order to directly validate this configuring part of the decision support, traditional OR or AI approaches have to focus the communicative dialogue on their artifact (see Section 1.4 on page 25). But, as their configuration step and following their artifact, are not necessarily compatible with the cognitive model of the decision maker, it is difficult in practice, if not impossible, to get reliable and robust feedback. Natural and artificial decision expertise will be in competition and, in case the decision-aid is accepted, the natural decision expertise, generally less well–uttered in a formal, scientific discourse, looses its value and eventually vanishes in front of the artificial ones. The decision makers gets, in fact, dispossessed of his original decision expertise.

In our approach, however, knowing the cognitive limitations of the human mind and considering the very nature of human decision expertise (see Working Hypothesis 2.1.3 on page 32), we shall try to configure the apparent decision theory in accordance with the cognitive capacities of the decision maker, which are essentially of an heuristic nature. In order to avoid the risk of loosing the decision maker's own natural expertise, we try to put the person effectively in the loop, in the sense that he/she will be an essential element of conscious validation of the cognitive artifact, i.e. the formal mirror of his/her own real decision expertise.

To represent the solving strategies in accordance with these cognitive requirements, we will, therefore, rely on the well formalized psychological model described by the Moving Basis Heuristics (MBH) paradigm.

2.3 Formulating the decision expertise

In this section, we introduce very briefly the main aspects of the MBH as promoted by Jean-Pierre Barthélemy and Etienne Mullet[7].

2.3.1 The Moving Basis Heuristics

The MBH concern experts, riskless multi-attribute choices and deterministic models for various choice tasks. An expert is someone familiar with a given decision task. In this kind of situation, it can be assumed that the decision maker is able to expand his/her strategy at a high level of complexity (strategies are supposed to be searched in long-term memory, while in a particular decision task, the short-term memory is at work). In multi-attribute decision, actions (or objects, or alternatives, or stimuli) are supposed to be described by several attributes (or features, or variables, or criteria). Since these attributes usually range conflictingly the objects, there is no (objective) way to express any, cognitively relevant, notion of optimality. Multi-attribute decision making is a good example of where notions relative to bounded rationality (Simon, 1979) can be expressed: other things than utilities may be considered as to be optimized. For instance, the cognitive effort involved in a judgmental process may be considered as to be minimized under constraints like social justifiability and flexibility of the process, etc.

The notion of minimization itself may be weakened into parsimony principles. A *local* utilitarian-like point of view may be introduced as the search for a dominance structure (Montgomery, 1983) . Consider, for example, the task of choosing one alternative among two. Despite the fact that no alternative is *better* than the other on every attribute, the decision maker may represent the situation by a limited number of aspects (subjective evaluations of alternatives on attributes), in such way that, according to these aspects, one alternative will dominate the other. So, by restriction to this set of aspects, the chosen alternative appears as the best one (local utilitarianism).

[7]The following text is extracted from a communication by Barthélemy, Bisdorff, Laurent and Pichon at the Second International Conference on Practical Application of Prolog, London (1994).

The judgmental process becomes essentially a search for such a dominance structure and hence involves abductive reasoning.

The deterministic case is concerned mainly with the study of decision rules that may account for the decision process in terms of the selection of information and the integration of selected information. Moreover, to consider that a subject produces *errors* relatively to given rules no longer makes any sense, since these errors themselves are issues from the cognitive decision process performed by the subject and have to be explained by it as well.

2.3.2 Application domains

Many kinds of tasks require the use of a judgmental process. Some of them are listed below:

- *Choices and preferences*:
  - *Paired comparisons* (or binary choices) where pairs of stimuli are presented to the subject (who has to select one stimulus out of each pair). When the choice of one stimulus in each pair is imposed the task is called a forced choice.
  - *Ranking* where the subject has to rank object according to some order of preference. Selections where the subject has to select one, or several, objects out of many. Eliminations where the subject has to eliminate some objects out of several.
- *Similarity and dissimilarity*:
  - Pairs of stimuli are presented to the subject who must then declare them *similar* (dissimilar) or not.
- *Categorization*:

  The subjects have to sort objects into several clusters (or classes, or categories). Two cases may occur:
  - *Non-supervised* categorization: the subjects are free in terms of the number of clusters they constitute and the meaning of each of them.
  - *Supervised* categorization: the categories (as empty boxes) are explicitly given to the subject at the beginning of the experiment.

  Such categorizations may be ordered, or not (for instance if the given categories are labeled by *very good*, *good*, *medium*, *bad*, *very bad*, then they are linearly ordered). Notice that the order on the classes may be a partial one and is not necessarily explicitly given (Barthélemy and Mullet, 1987) .

2.3.3 Principles

Applying the MBH model relies on three basic principles:

- A *parsimony principle.* Due to his/her inability to process the whole data set, the expert extracts some subsets whose size is small enough to be compatible both with human short-range storage abilities (there is no intermediate storage in a long term memory) and with human computational abilities.

- A *reliability/warrantability principle.* This principle works, in some sense, as the opposite of the preceding one. Concerned by reliability (socially as well as personally), the expert extracts from the data set a subset large enough and composed in such a way as to appear meaningful (comparisons on several attributes, conjunctive rules). For instance in case of binary choices a decision is made if and only if the gap between the two alternatives is large enough (threshold rules).

- A *decidability (flexibility) principle.* Concerned with the necessity to achieve choice in almost all cases, the expert extracts subsets of data in a manner flexible enough to achieve, almost all the time, a decision on relatively short notice. Minimal conflict corresponds to such a decision.

The MBH (see Figure 2.4 on the following page) pre-supposes a co-ordinated use of four types of rules, corresponding to the three principles above: lexicography (parsimony), threshold (reliability), conjunction (reliability) and disjunction.(decidability).

In Figure 2.4 on the next page (Box 1) represents the subprocess of selection of one or more attributes and thresholds at a given time. The set A of attributes and thresholds will be used to perform the judgmental task. The nature of these thresholds will depend on the task. For instance, in the case of binary choices and similarity (or dissimilarity) judgments, they are difference thresholds; in the case of a selection task, they are absolute thresholds. Boxes 2 and 3 show the subprocess of performing the task on the basis of A attributes (dominance testing phase). For instance, in case of binary choices (or similarity judgments), the Subject compares the relative superiority of one alternative over the other (the superiority of one stimulus over the thresholds for A, in case of a selection task); if at least one difference is lower - greater in the case of similarity judgment -, then no decision is taken. In case of a selection task, if at least one aspect is lower than the corresponding threshold, no decision is taken. In case of no decision, the decidability principle works and another set of attributes and thresholds can be taken into account (boxes 5 and 7, dominance structuring phase). After several iterations, the subject may decide or not (boxes 4 and 6). To illustrate the model we will discuss further the case of selection judgments.

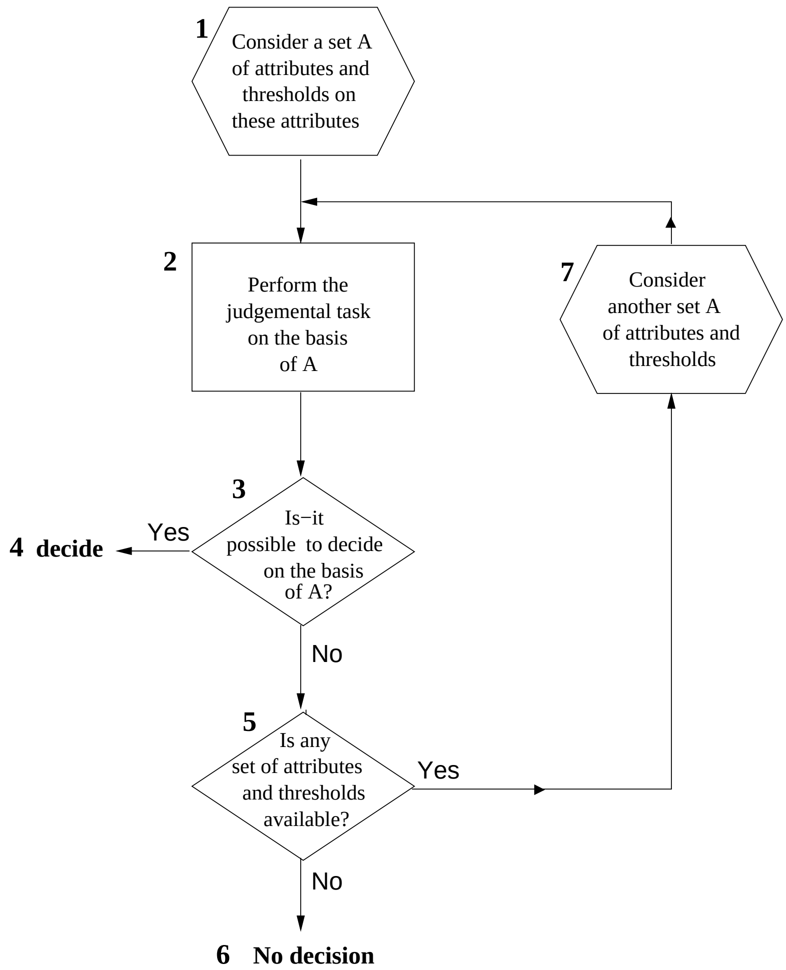

Figure 2.4: Moving Basis Heuristics: general model
source: *Barthélemy and al.* (1994)

2.3.4 MBH for a selection task

The implementation of the MBH for a selection task is shown in Figure 2.5 on the facing page. Two final issues are possible for a given stimulus: select (box 4) or eliminate (box 6).

Example 2.3.1. As an example, consider some hotels with restaurants described by several attributes in some specialized guide (like price of the menu, price of the rooms, quality of the reception, noise, quality of the accommodation, etc).

According to the MBH, the subject first examines all the alternatives under consideration and makes selections (or eliminations) on the basis of aspects considered as favourable (or unfavourable). For example, a hotel may be selected because its menu is inexpensive or because the quality of the reception is very good and the rooms are

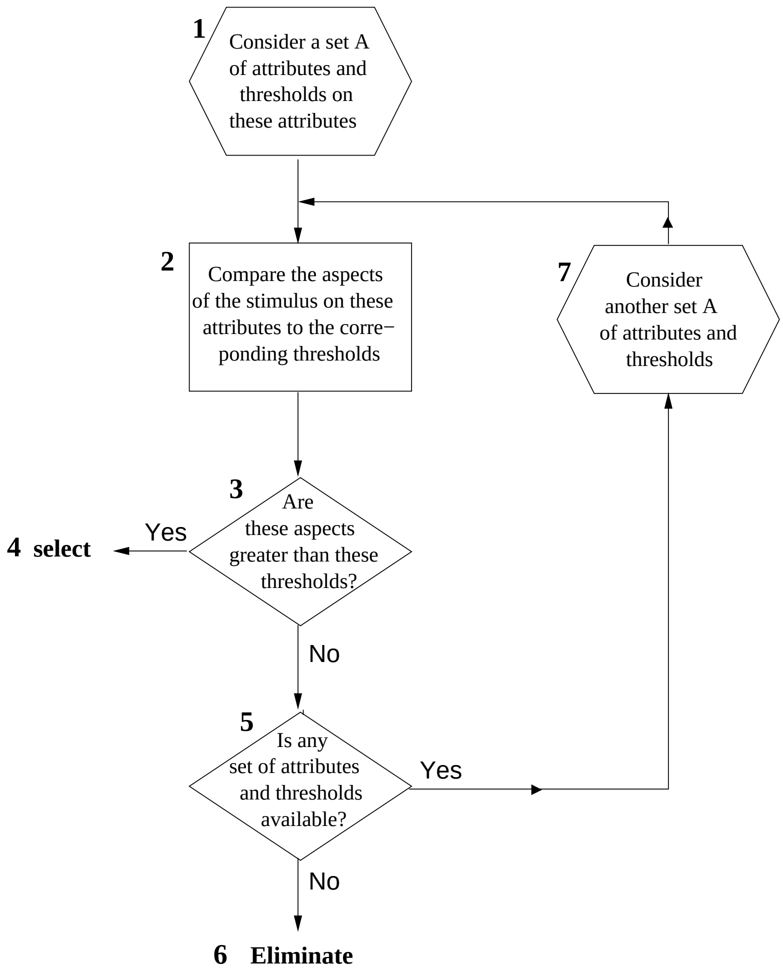

Figure 2.5: MBH for a selection task
source: *Barthélemy and al.* (1994)

inexpensive. Figure 2.6 on the next page shows a realization of the heuristics that may be expressed as follows:

$$H6 + B4D6 + B4H4 + C6D4 + C4H5$$

H, B, C, D, E represent attributes and these rules are to be interpreted in the following way: Each hotel having a value on attribute H that is at least 6 has been selected, as well as the hotel whose value is at least 4 on B and 6 on D, etc. In this 'polynomial' representation, 'monoms' like B4D6, may be understood as decision rules (conjunctive rules) and the addition as an articulation of these rule (disjunction). Moreover, in such a formula, each 'monom' represents what is generally conceived as a production rule and the whole formula may be viewed as a production system. This expression may also be called an equation of the selection.

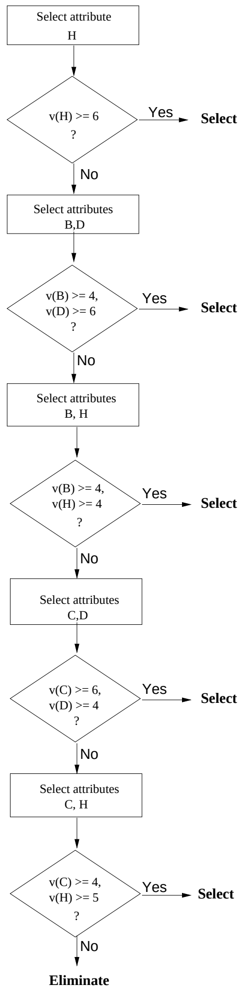

Figure 2.6: A realization of the MBH
source: *Barthélemy and al.* (1994)

An interesting feature of the MBH, and the one we will extensively refer to in Part **B**, is that the decision situations, where it applies, can be mathematically characterized and (as a consequence) its abilities to explain 100% of the choices of a sample can be experimentally validated (without any computation of equations). Such a characterization is given in Barthélemy and Mullet (1986); Barthélemy and Mullet (1987, 1989) for respectively, binary choices, ordered supervised categorization, selections and multi-stages selections and similarity judgments. It is precisely this feature of the MBH, that will implicitly and explicitly underly most of the design choices of the decision aid methods and tools we propose to offer the experienced decision maker.

This concludes our short presentation of the MBH in the perspective of the practical applications we have made with this cognitive decision model in mind. Let us now come back more to our problem, i.e. defining a methodology for decision aid in case we are faced with an experienced decision maker.

2.4 Human expertise centred decision aid

Definition 2.4.1 (human expertise centred decision aid).
We understand under the concept *human expertise centred decision aid* (HECDA), a general methodology for supporting the experienced decision maker:

- in the formulation of his decision problem and his cognitive problem solving strategies and,
- in his recurrent resolving process without disturbing his natural decision expertise.

The general outcome of such a human expertise centred decision aid, is a cognitive artifact, mimicking the natural decision expertise.

In the HECDA approach, we observe a further paradigm shift of the concept of *decision aid*. After the first shift from the classic OR concept, i.e. solving a mathematical optimization problem, to MCDA, i.e. modelling the actual preferences of the decision maker, we now propose that the decision aid get focused on the cognitive model of the decision expertise, i.e. on the formulation of some observed decision expertise in accordance with a psycho-cognitive model of the decision maker.

The general characterization of the nature of human decision expertise, as exposed in the previous sections, gives us a hint towards the design of new decision aid methods and tools that fit with the above definition of an HECDA, in the sense that they appear better adapted to the cognitive specificity of an experienced decision maker.

A first set of methods and tools concerns the assistance for symbolic delimitation.

2.4.1 Assistance for formal decision problem delimitation

From a cognitive psychological view point it is important to notice that the intentional discourse concerning a given decision expertise, as revealed and eventually formulated with the help of the MBH model, will generally produce two different typical descriptions of the underlying decision expertise.

On one hand, regarding the decision extension, typical occurrences or representatives in the sense of prototypes (Rosch, 1973) will be evoked. On the other hand, concerning the intentional side, this evocation will produce typical properties, family resemblances (Rosch and Mervis, 1975) or promising aspect combinations (Barthélemy and Mullet, 1986) which characterize given satisfactory decision acts. These cognitive biases, resulting from common underlying cognitive mechanisms such as dominance structures and anchoring phenomena, fragmentation of the discourse and uncheckable inductive closures, will produce a natural divergence between these two evocations. There will be a small set of prototypes opposed to a small set of abusively generalized intentional sentences.

Repetitive confrontation of both these representations with an actually observable decision practice will generally create a converganceof the decision problem formulation and resolution towards a consistent and stable symbolic formulation.

The SysCog case study presented in Chapter **3** discusses a practical application of such kind of decision aid.

2.4.2 Maintaining a decision expertise over time

A second type of methods and tools concerns maintaining a given decision expertise over time. This general problem will be illustrated in the second application: The Comaps case study presented in Chapter 4.

Main attention will here be given to the construction of a *factual decision history* recorded from past decision practice, revealing an underlying *objective decision reference*, i.e. exemplary decision situations embodying the effective past decision expertise.

Official subjective decision strategies embodying the intentional decision theory of the decision maker may then be critically checked against the objective decision reference. This cognitive confrontation allows to adjust the official decision strategies to the really observed, i.e. objective decision expertise.

2.4.3 "*Check as you decide*" assistance

In the continuation of the previous problem, once a stable formal HECDA model of the decision expertise is given, a Check as You Decide device may be developed in order to provide *on-line passive assistance* to the decision maker.

This device similar to the "*check as you type* feature offered by modern office writing tools is presented at the end of Chapter 4. This device may serve for instance the experienced decision maker for avoiding inattention faults or revealing potentially weak knowledge 'regions' in the decision practice.

But it may also serve as a more active guidance device for unexperienced or novice decision makers. In the Comaps case, it becomes apparent that most poorly qualified decision situations are observed in industry during a weekend where the normal experienced operators are replaced by less experienced ones. Here such a Check as You Decide device may be rendered more compulsory in its advice function, but under the condition that the artificial decision expertise, underlying the Check as You Decide device, is cognitively validated with the experienced decision maker.

2.4.4 Solidifying decision making expertise

During the SysCog project (see Chapter 3) we noticed that the decision expertise knowledge is generally organized into three levels of consistency, analog to the three physical states: solid, liquid and gaseous.

- "*Solid*" decision expertise often appears as official, *regular* knowledge, well identified and easily formulated without any apparent cognitive difficulty;

- "*Liquid*" decision expertise appears directly embodied in the experienced decision practice, but there exist formal difficulties to precisely model this decision expertise in a stable way. In one situation, the decision strategy is this one, in the next similar situation, a different strategy appears. In fact, the decision maker hesitates, makes trials and is undecided etc. Eventually, this *critical* behaviour will converge with the recurrent decision practice to a *solid* behaviour, revealing thereby a new *solid* regular decision expertise.

- A "*gaseous*" decision expertise will not possibly be formulated. One may even question that in this case a slightest decision expertise may exist. But similar to the wind, who reveals the nevertheless existing consistency of the air, the on-going decision process with its more or less animated rhythm, may reveal the existence of such *furtive* decision expertise.

In the SysCog project we developed a cognitive decision aid laboratory (see Chapter 3) in order to help the experienced decision maker to reinforce his regular, i.e. "solid", expertise and to reduce the part of his "liquid" expertise.

The essential idea was to install an artificial decision making process, augmenting the frequence in time of the natural decision making sessions and thereby multiplying the experience space of the expert in order to precisely explore the effective cognitive frontiers between solid and liquid or gaseous expertise and reduce the second in favour of the first type.

2.4.5 Operator guidance for regular and critical decision situations

In the ADAC case (see Chapter 5) we present a cognitive decision aid system which directly operates on the distinction between regular or solid and critical or liquid and even gaseous decision expertise.

Indeed, the ADAC project proposes a compulsory guiding assistance for regular decision situations based on a underlying regular and official decision expertise and a probabilist learning assistance for critical situations, where no solid, i.e. regular, decision expertise is available.

2.5 Conclusion

In this chapter we have presented the main methodological developments of this work. After defining what we call an experienced decision maker, and how to observe a given decision expertise, we introduced a formal model, the Moving Basis Heuristics, in order to properly formulate it. A last part of this chapter introduces the Human Expertise Centred Decision Aid (HECDA), a methodology especially designed for assisting the exeperienced decision maker. A list of specific HECDA problems such as assistance for formal decision problem delimitation, maintanance of decision expertise, 'Check as You Decide' assistance a.o., is proposed.

In the next part three industrial case studies are presented which illustrate these HECDA methods and tools in real industrial application contexts.

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Part B

Applications of human expertise centred decision aid

Part B : Applications of human expertise centred decision aid

Abstract

In this second part of our document, we present in detail three illustrative applications of Human Expertise Centred Decision Aid (HECDA).

- The SysCog case study (Chapter **3**): a cognitive decision aid laboratory designed for uncovering and checking the solving strategies of an experienced human operator confronted with a complex production scheduling problem;
- The Comaps case study (Chapter **4**): a guarded production control system based upon the exploitation of a large history of expert production control;
- Finally, the Adac case study (Chapter **5**): a guided production fault diagnosis and repairing system.

Every case study is presented as a self-contained chapter. However, a common structure has been adopted:

- First a *quick summary* of the case study is proposed;
- Then follows a detailed *formal description* of the decision problem in question;
- A *critical study* of this description leads to the design of methods and tools that illustrate the reflexive cognitive confrontation at the heart of our HECDA methodology.

Chapter 3

The SYSCOG Case: Checking a Production Scheduler

« *Le travail de délimitation relatif à la classe de phénomènes, compte tenu du champ de questions, implique [...] une foule d'options qui, pour découper le fragment approprié, relèvent avant tout de l'observation, de l'imagination et du savoir-faire. C'est pourquoi nous parlons de l'*art de la découpe. »

Bernard Roy (1985)

Contents

3.1 Summary of the SYSCOG case

This case study gathers research work conducted in the context of the SysCog «Systèmes Cognitifs en Industrie» project executed for TrefilARBED Bettembourg in collaboration with Jean-Pierre Barthélemy, Sophie Laurent[1] and Emanuel Pichon[2]. from October 1992 to October 1995.

At the TrefilARBED side we worked mainly with Fernand Grosber, responsible production engineer, and Daniel Schmit, chemical engineer, responsible for the specific part of the TrefilARBED production process we have studied in this project.

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[1] With S. Laurent we were working since 1992 on finite decision problems proposed by the Luxembourg steel industry. In a common paper, published in EJOR (Bisdorff and Laurent, 1995), we discussed the usefulness of constraint logic programming compared to traditional mathematical programming for solving such kind of problems.

[2] E. Pichon was engaged as PhD student under the scientific direction of J.-P. Barthélemy

3.1.1 Description of the scheduling problem

The application concerns the scheduling of an important patenting/plating installation in a wire drawing industry. The raw steel wire is mechanically drawn, thermically patented and plated to be eventually refined in refining drawing step. This kind of plated steel wire is commonly used in the automobile tire production. The plating of the wire enhances there the adherence of the gum on the steel. The actual production

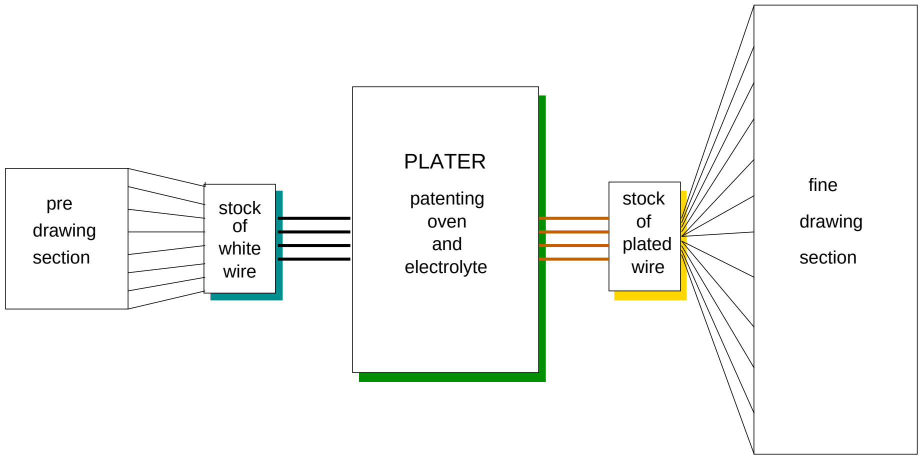

Figure 3.1: The TREFILARBED wire drawing production line
source: *Pichon* (1966)

line may be split into three main steps (see Figure 3.1):

1. A pre-drawing is operated on several parallel devices to obtain an initial stock of raw or so-called "white" wires;

2. A plater installation is used for patenting and plating the white wires resulting in a stock of plated wires;

3. And finally, a last step refines the drawing of the plated wires to achieve final customer specifications.

In the production line, the plater installation appears as a bottle-neck which explains the origin of a difficult scheduling problem for the plant manager to be solved on a fortnight basis.

Economic considerations impose the plating of several types of wire in a same production step, thus giving raise to the concept of *production campaign*. Such a campaign is characterized by its overall duration and by the type and the number of associated wires. Richness of the product catalog potentially gives origin to quite a lot of possible production campaigns. But strong physical and chemical constraints at the level of the plater installation only allow a small subset of admissible campaigns.

A *production plan* now constitutes a satisfactory succession of such admissible production campaigns.

To be efficient, the scheduling of the production plan must respect technical constraints like wire type association and sequence as well as organizational constraints like available input stocks, customer orders, etc.

3.1.2 The experienced decision-maker

The production plan is established by the plater operator, long time responsible for the installation, with great empirical and practical knowledge of the installation. With continuous measures and technical experiments, this operator had gained a deep technical understanding of the physical and chemical constraints underlying the constitution of admissible production campaigns. This technical knowledge, coupled with a charismatic ability to solve organizational problems, appears as our scheduling expertise. The actual establishment and updating of the weekly schedule took him two to three hours time every Monday morning. All work was done by hand without the use of any computerized support.

3.1.3 Institutional context

At the time when the SysCog project started, the plant manager commissioned, parallel to this external study, an internal audit in order to evaluate and enhance the efficiency of the actual plater schedule.

Both these studies, to some extent concurrent and certainly first experienced as controversial by the plater operator, helped us greatly to get accurate knowledge regarding the plater scheduling problem.

It took the SysCog team until the end of the project to understand that their external study was in fact aimed to support the plant manager against the apparently efficient arguments of the plater operator. Indeed, the manager's feeling was that the scheduling bottle-neck experienced at the plater level was artificially provoked by the overly rigid minded plater operator. The SysCog team was hence commissioned to study his scheduling procedure and strategies and to develop a new, and hopefully more efficient, production scheduling procedure, eventually completely automated and push-button driven, with the purpose being to gain back for the plant manager overall control over the production plan.

Contrary to the SysCog team, the plater operator naturally suspected this hidden purpose of the external study and did everything to convince the external auditors of the pertinence of his arguments. This way he implicitly enhanced the knowledge extraction process we will describe in the sequel.

3.1.4 The results of the SYSCOG project

Results of the SysCog project may be analyzed along three arguments:

- First, the enhancing of the production outcome. Indeed, from the beginning to the end of the project, a reduction of 50% of the overall production scrap was observed;
- Secondly, the audit of the decision expertise of the plater operator. The human scheduler, a chemical engineer, showed an impressive mastering of the complex problem. A complete precise and stable formulation of the scheduling problem with corresponding subtle solving strategies could be achieved;
- And finally, one of the outcome and certainly not the least consisted in an executable specification of these expert scheduling strategies. This software tool, programmed in a constraint logic programming environment allowed to implement the actual solving strategies, thus providing the operator with different decision checking tools, for instance for checking if a possible production campaign satisfies or not the admissibility constraints.

We shall now present in detail the SysCog production scheduling problem[3].

3.2 The SYSCOG case

This section presents in some detail the organization, the industrial production context and the corresponding scheduling problem of the SysCog case.

3.2.1 Organization of the SYSCOG study

The SysCog study lasted roughly 21 months, from April 1993 to December 1994. and involved two full time computer scientists: Emanuel Pichon, doctoral student in Brest under the direction of Jean-Pierre Barthélemy and Sophie Laurent, our research assistant who was specialized in constraint logic programming. In this section we will heavily rely on the numerous technical reports which were produced in the context of the SysCog project (see Bisdorff et al., 1994a,b,c, 1995b).

The SysCog study was organized in three subsequent steps:

1. The first was concerned with gathering in a rather literary and informal way the detailed description of the production scheduling from the refined view point of the production scheduling expert;

[3]We are going to use two sources for this part of our work. First, some technical reports produced for TrefilARBED (Bisdorff et al., 1994a,b,c, 1995b) and naturally Pichon's PhD dissertation (Pichon, 1996). And secondly, numerous lecture notes we produced during the SysCog project, where we discussed and refined the methodological approach we promoted under the name of "*L'art de la découpe*", a terminology suggested by Bernard Roy (1985).

2. A second step consisted in formulating in mathematical terms the given production scheduling problem with all variables, parameters, constraints etc ;
3. Finally, a third step was concerned with the precise acquisition of the human scheduler's cognitive strategies for solving the apparently quite complex planning and scheduling problem.

The overall time schedule of the SysCog project is shown in Table 3.1.

Year	Period	Work Package
1993	April – June	groundwork
	July – September	formal specification of the scheduling problem
	October – December	delimitation of potential production campaigns
1994	January – February	Recording an industrial context evolution
	March – July	Delimitation of potential campaign transitions
	August – December	Global solving strategy elicitation

Table 3.1: SysCog project schedule and work packages

It was especially the main working phase dedicated to the knowledge extraction from October 1993 to December 1994 that revealed the exceptional expertise that our human operator showed in his weekly scheduling practice. The highly qualified person, a chemical engineer, could most of the time provide refined technical arguments for all his cognitive artifacts and solving strategies.

The knowledge extraction was divided into three main periods:

1. Delimitation of potential production campaigns, i.e. simultaneous plating of different types of wire;
2. Identification of all admissible production campaign successions and
3. And formal study of the global scheduling strategies.

3.2.2 The industrial production context

After the pre-drawing step (see Figure 3.1 on page 57), the white steel wire cannot be further drawn as the physical structure of the steel has been too much modified by the drawing action. The patenting phase is therefore used to recover the initial properties of the steel. In Figure 3.2 on the next page are shown the technical details of the plater installation. The steel wires are passed in parallel on Line I (up to 52 winders) and Line II (up to 20 winders) through two patenting processes to be first red–heated and then shock–cooled in a liquid lead bath. After a chlorhydric acid cleaning, the wire is finally plated in a common electrolytic bath for the two separated patenting lines. The plated wire after the plater step may be characterized in three ways:

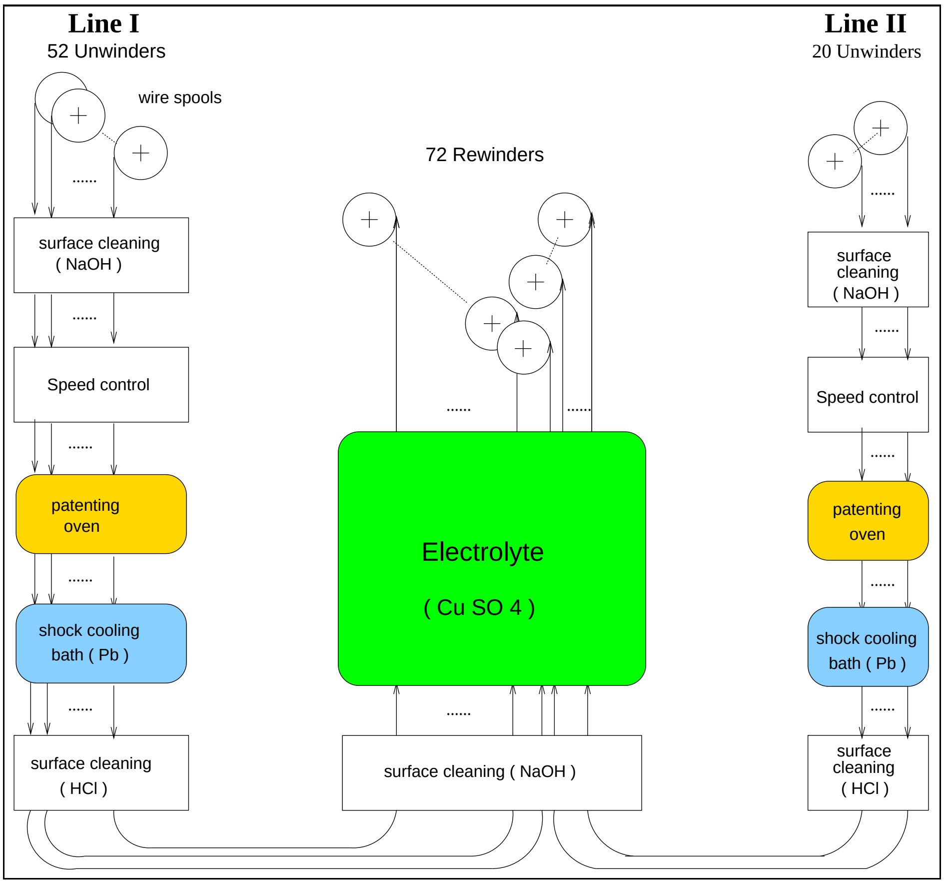

Figure 3.2: The plater installation at TrefilARBED Bettembourg

- Its diameter (from 0.94 to 2.18 mm);
- Its plating characteristics (% of copper versus % of zinc). Four plating qualities are distinguished as shown in Table 3.2 on the following page;
- And the underlying steel specifications. Three qualities of raw steel wire are used: MK70, SKD70 and SKD80 and two families of plated steel wire may be distinguished as:
  - Steel cord wires with a generally low copper percentage (see Table 3.3 on the next page);
  - And hose wires with a high copper percentage (see Table 3.4 on page 63).

% Cu	Name
63	low
65	medium
66	r.d.a.
67	normal

Table 3.2: The plating qualities

diameter (mm)	Cu (%)	deposit (g/kg)	steel quality
0.94	medium	5.0	SDK70
1.08	medium	5.0	SDK70
1.17	low	4.0–3.5	SDK70
1.17	low	4.3	SDK80
1.22	low	4.0	SDK70
1.28	low	3.4	SDK70
1.28	low	3.8	SDK70
1.28	low	4.3	SDK80
1.35	low	3.6	SDK70
1.35	low	5.0	MK70
1.36	low	3.4	SDK80
1.55	low	2.7	SDK70
1.55	low	3.2	MK70
1.55	low	3.5	MK70
1.62	low	3.5	SDK80
1.65	low	3.0	SDK80
1.65	low	3.5	SDK80

Table 3.3: TREFILARBED steel cord wires

3.2.3 Description of the scheduling problem

The production at the plater step is organized on the level of *production campaigns*. Such a campaign is defined as follows: a certain wire type, with its associated characteristics is passed on each of the two plating lines. A campaign may concern up to 52 spools on Line I and up to 20 spools on Line II (see Figure 3.2 on the page before).

Several wire types may be plated together in a same campaign, but the maximum difference in plater deposit weight must not exceed 1.5 g/kg.

Normally, production campaigns with different diameters follow each other without stopping the plater lines. At the end of a spool a new spool is fixed on-line to the end of the preceeding one. This is done for all 52 spools on Line I and all 20 spools on Line II.

Campaigns with same wire diameter, but different copper and deposit characteristics are obtained by modifying either the chemical composition of the electrolyte or the electrical density of the bath.

diameter (mm)	Cu (%)	deposit (g/kg)	steel quality
1.17	normal	5.0	SDK70
1.17	normal	6.0	SDK70
1.28	rda	3.8	SDK70
1.33	normal	5.0	SDK80
1.35	normal	4.0	MK70
1.35	normal	5.0	MK70
1.35	normal	5.0	SDK70
1.45	normal	5.0	SDK70
1.45	normal	5.0	SDK80
1.55	normal	5.0	SDK80
1.62	normal	5.0	MK70
1.62	normal	5.0	SDK70
1.62	normal	5.0	SDK80
1.95	normal	5.0	SDK70
1.95	normal	5.0	SDK80
2.18	normal	5.0	SDK80

Table 3.4: TREFILARBED hose wire types

On the plater, two types of production phases are distinguished:

1. An *established phase*: Line I is running with all 52 wires, Line II may be running with up to 20 wires and the electrolyte has reached stable depositting characteristics for all wires;

2. A *transitory phase*: every restart of the lines and each campaign transition produce for some time an unstable production outcome.

It is evident that such transitory phases have to be kept as small as possible. Therefore, production campaigns with very different characteristics in diameters or copper concentration and deposit may not follow each other.

The production capacity of the plater in terms of number of wires to be plated together, as shown in Table 3.5 on the following page, is dependent on the diameter of the wires and on the required speed of the plating. As each plater line uses a different speed controller, both lines may be run with a same speed, but also with different speeds. For a same given copper concentration, Line II may run slower than Line I, thus producing different deposit weights. However, the difference in plating speeds must be confined within 34 m/min.

Finally, raw wire input stocks and plated wire output stocks at the plater level (see Figure 3.1 on page 57) are maintained at a rather high level in order to avoid any out of stock situation. For each wire type, the minimum plated stock must equal the number of fine drawing machines following the plater step. Due to space limitations, stocks are confined to a maximum of 300 tons for white wires and to a maximum of 850 tons for plated ones.

diameter (mm)	speed (m/min)	wires on Line I	wires on Line II
0.94; 1.08	78–80	52	0
1.17	78–80	52	0
1.22	73–75	52	0
1.28	70–72	52	20
1.33; 1.35; 1.36	62–64	52	20
1.45	50–52	52	20
1.55	50–52	40	15
1.62; 1.65	49–51	40	15
1.95; 1.98	40–42	0	12
2.18	38–40	0	8

Table 3.5: Production capacity of the plater lines

In order to minimize scrap production during transitory phases, it is important to minimize the number of restarts of the plater as well as the number of campaign transitions. The normal number of production stops in a month is two, so that generally a production period covers 12 to 14 days of continuous operation. Production stops, apart from rare production faults, generally correspond to pre-established maintenance and cleaning operations of the installation.

Minimizing the number of campaign transitions is achieved by scheduling complete campaigns (72 wires) with more or less similar characteristics in subsequent periods. Mixing different types of wires within a same campaign represents a compromise with the required quality of the product. Furthermore, due to a risk of wire rupture during transition to a new campaign, plating of low wire types necessitates a freshly cleaned installation, so that they may only be scheduled at the beginning of a new production period.

3.2.4 Formal specification of the scheduling problem

The SysCog production scheduling problem appears as a classic planning problem driven by the necessity to provide at each moment the fine drawing section with sufficient quantities of plated wires as requested by their production plan.

3.2.4.1 Scheduling variables and parameters

Let $I = \{1, 2, \ldots n\}$ represent the set of of wire types produced by TrefilARBED . Let $B^T = \{1, 2, \ldots, T-1\}$ represent a set of $T-1$ production days (called the *temporal base* of the production scheduling). Indeed, as charged wire spools are of a comomn weight of around 1.5 tons, unwinding and rewinding a given spool takes around 24 hours for any type of wires.

For each plated wire type i we define in the context of this temporal base:

- A daily consumption required by the fine-drawing section (in number of spools for each plated wire type);
- A global quantity of spools to be produced;
- A possible deadline for the preceding production;
- And a requested and a minimum security quantity of plated wire on stock at the end of the production period (in number of spools).

Let c_i^t with $t \in B^T$ represent the requested consumption of wire type i during day t of the fine-drawing sector. The matrix C represents the daily consumptions of all given wire types over the whole temporal base:

$$C = \begin{bmatrix} c_1^1 & \dots & c_1^{T-1} \\ \dots & c_i^t & \dots \\ c_n^1 & \dots & c_n^{T-1} \end{bmatrix} \tag{3.1}$$

Our decision variables concern the daily production q_i^t of each wire type i during each day t. The matrix Q gathers all the individual decisions over the whole temporal base B^T.

$$Q = \begin{bmatrix} q_1^1 & \dots & q_1^{T-1} \\ \dots & q_i^t & \dots \\ q_n^1 & \dots & q_n^{T-1} \end{bmatrix} \tag{3.2}$$

Each such daily production vector q^t for $t = 1..T-1$ is called a *production campaign.*

Let s_i^t represent the stock of wire type i available on day t. We denote $s^0 = \{s_i^o : i \in I\}$ initial stocks and $s^t = \{s_i^t : i \in I\}$, final stocks. Assuming that $s_i^t \geq 0$ for all $i \in I, t \in B^T$, final stocks may be computed as follows:

$$\forall t \in B^T, \forall k \leq t, \forall i \in I,\ s_i^t = s_i^o + \sum_{k=1}^{t} (q_i^t - c_i^t). \tag{3.3}$$

We may again represent final stocks under matrix form:

$$S = \begin{bmatrix} s_1^1 & \dots & s_1^{T-1} \\ \dots & s_i^t & \dots \\ s_n^1 & \dots & s_n^{T-1} \end{bmatrix} \tag{3.4}$$

Finally, let $r^T = \{r_i^T : i \in I\}$ denote the reserve stocks requested on the last day of the considered production period.

3.2.4.2 Scheduling constraints

The decision constraints working on the choice of the daily production vector $q^t = \{q_i^t / i \in I\}$ may now be formulated as follows. The daily production is limited to the overall capacity q_{max} of the plater, i.e.

$$\forall t \in B^T, \sum_{i \in I} q_i^t \leq q_{max}. \tag{3.5}$$

Avoiding shortage of plated wire with respect to the daily consumption of the fine-drawing sector may be achieved by non-negativity constraints:

$$\forall t \in B^T, \forall i \in I, \ s_i^t \geq 0. \tag{3.6}$$

Let P denote the technically and physically admissible daily production campaigns, i.e. possible association of different types of wires to be plated simultaneously. In order to achieve a satisfactory production outcome, we must choose each daily production vector q^T within these potential production campaigns P.

$$\forall t \in B^T, q^t \in P. \tag{3.7}$$

This constraint takes a combinatorial form.

Finally, in order to avoid difficult and long lasting transitions between succeeding production campaigns, it is necessary to choose a satisfactory sequence of daily campaigns. Let S denote the set of satisfactory campaign transitions. This constraint may be formulated as follows:

$$\forall t \in B^{T-1}, (q^t, q^{t+1}) \in S. \tag{3.8}$$

Again we observe here a combinatorial constraint.

3.2.4.3 Multiple objectives scheduling

Four overall objectives appear to play a role in the scheduling problem:

1. In time delivery of the customer orders, i.e. avoid out of stock situations with respect to the daily production schedule of the fine drawing sector;

2. Minimize the number and length of the transitions between subsequent production campaigns, i.e. reduce the unavoidable transitional scrap;

3. Optimize final plated stocks;

4. Maximize capacity utilization of the plater.

The first objective is achieved through constraint 3.6. The second objective is implicitly taken into account by constraint 3.7. The fourth objective is taken into account within the definition of admissible production campaigns, so that constraint

3.8 implicitly introduces this objective in the decision problem formulation. Only the optimal stock management remains to be considered here. Indeed, the optimal production schedule Q^* minimizes the absolute difference between requested (r^T) and final produced stocks (s^T), i.e.

$$Q^* = \min_Q\left(\sum_{i \in I} \mid s_i^T - r_i^T \mid\right), \tag{3.9}$$

under the previous four constraints 3.5 to 3.8.

Both objectives 2 and 4 are not easy to put into analytical form and the problem appears under the form of a highly combinatorial decision problem. Despite some evident limitations of admissible production campaigns and satisfactory sequences, the estimated number of possible instantiations of the Q matrix in the real TREFILARBED problem turned around 10^{500}. Integrating human expert solving strategies in the effective resolution of the scheduling problem appeared inevitable.

The study of the cognitive artifacts used by the experienced production scheduler was therefore our next phase in the SYSCOG study. Four steps may be distinguished in this study. The delimitation of the set P of admissible daily production vectors q^t was the first real-world test of our cognitive decision aid approach.

3.2.5 Delimitation of admissible production campaigns and transitions

A first intensive interaction with the scheduling expert was concentrated on the precise formulation of the set P of potential daily production vectors q^t. The knowledge extraction mainly relied upon a written interaction between the cognitician and the experienced scheduler through specifically elaborated questionnaires. The expert initially provided 49 potential production vectors associated with corresponding formal combination rules that apparently underly his selection.

We translated these rules into CHIP[4], a constraint logic programming (CLP) system and checked the corresponding extension (see Bisdorff et al., 1994b). Here we obtained over 3000 potential production campaigns. This result is not astonishing in the sense that a *typical extension* is naturally parcimonous if compared to the extension covered by a *typical intention*[5].

In order to reduce the gap between both typical descriptions, i.e. the initially communicated admissible production campaigns and the corresponding intentional discourse around the selection criteria of these campaigns, we developed a strictly controlled information exchange protocol between the cognitician, i.e. E. Pichon, and the experienced production scheduler (see Figure 3.11 on page 84).

[4] Constraint Handling in Prolog, a CLP system from Cosytec, France (Aggoun and Beldiceanu, 1991).

[5] From a cognitive point of view, typical cases are generally not covering exactly all possible cases, and typical strategies generally don't consider otherwise known exceptions. See Chapter 7 Section 3.

A written questionnaire with 30 questions was addressed to the expert who gave his written answers without any supplementary intervention of the cognitician. A subsequent interview was necessary in order to clearly state and confirm all written answers through oral interaction. The thorough study of all written material and audio recordings gave rise to some 20 further questions that were handled by direct phone calls.

The delimitation of the set S of admissible campaign transitions necessitated the further elaboration of three successive and refining questionnaires; a first with 31, a second with 23 and a last one with 15 questions. Considering the large amount of campaign series to be envisaged, the organization of these questionnaires tried to minimize the cognitive effort of our scheduling expert.

The main contribution of Pichon to the SysCog study lies in the fascinating discussion of the effective cognitive interaction he had with the scheduling expert and in the presentation of a systematic and quasi-automatic approach for compiling these questionnaires (Pichon et al., 1994). We shall come back more formally to this topic in Section 3.4 on page 77.

3.2.6 Solving the production scheduling problem

Finally, the cognitive solving strategies of the expert could be elicitated to a great part. A main part of the solving expertise appeared to lie in the cognitive construction of the set P of admissible production campaigns and of the corresponding set S of satisfactory campaign transitions. Considering that, at most, three different types of wires may compose an admissible production campaign, and that the satisfactory campaign transitions induce a stable, repetitive global outlay of admissible production campaign series, the set of potential decision actions, actually the domain of matrix Q, reduces to a quasi-diagonal organization:

$$Q = \begin{bmatrix} \boxed{q_1^1} & \boxed{\cdots} & 0 & \cdots & 0 \\ \cdots & \boxed{\cdots} & \cdots & \cdots & \cdots \\ 0 & \cdots & \boxed{q_i^t} & \boxed{\cdots} & 0 \\ \cdots & \cdots & \cdots & \boxed{\cdots} & \cdots \\ 0 & \cdots & 0 & \cdots & \boxed{q_n^{T-1}} \end{bmatrix} \tag{3.10}$$

Indeed, this diagonal structure, which limits the production of each wire type to a single interval in the temporal horizon of the schedule, minimizes the necessary campain transition to a strict minimum.

The main scheduling expertise appears to lie in this reduction of complexity where different formal delimitations, such as those defining the sets P and S, conduct to a decomposition of the scheduling problem based on the integration of the necessary highly repetitive nature of the weekly scheduling problem (see Figure 3.3 on the facing page).

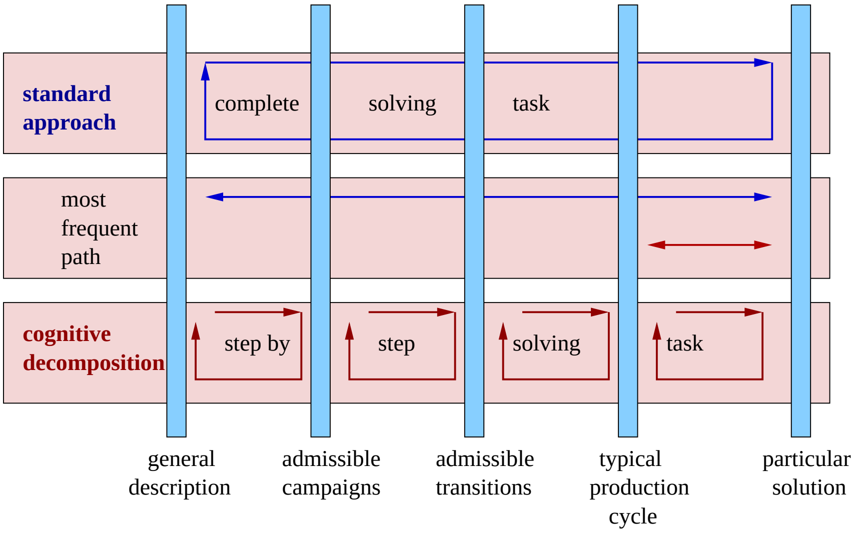

Figure 3.3: Cognitive decomposition of the solving strategy

It is natural not to recompute each week the given set of admissible production campaigns, and not to recompute every week the set S of admissible campaign transitions. Pre-solving these two sets allows for concentrating on the weekly cognitive solving effort on the satisfaction of the actual order-book as presented by the fine-drawing section. Indeed, changes in the delimitation of admissible production campaigns are essentially triggered by the actual production catalogue, i.e. the types of wire to be produced. Whereas admissible transitions mainly rely on stable quality control requirements, so that again, only explicit changes in customer quality requirements may, the case given, trigger a necessary revision of the set S.

In the next section we will analyze in greater detail these cognitive delimitation and decomposition strategies of our scheduling expert.

3.3 Critical study of the "*art of cutting*"

In order to evaluate the cognitive decomposition and simplification strategies of the expert scheduler, we shall reformulate the scheduling problem in the context of a constraint logic programming system[6]. This reformulation of the decision problem gives us an operational specification, i.e executable programs with which we can compute practical results comparable with the outcome produced by the human expert scheduler. The corresponding solving strategies we need to introduce, allow us to evaluate, on the one hand, the operational pertinence of the cognitive delimitation and decomposition of the overall scheduling problem we have observed and, on the

[6]The CHIP (Constraint Handling in Logic Programming) system from Cosytec, France.

other hand, the computational performance of the human scheduler compared with such an automatic computing device.

In this section we shall concentrate on the first aspect, i.e. the evaluation of the very repetitive nature of the scheduling problem and its consequence on the design of efficient solving strategies. The second aspect, i.e. evaluating the computational performance, will be tackled in the next section.

We shall first present a general formal framework, inspired by B. Roy (1985), for delimiting a set of potential decision actions. In a second part, the delimitation of the set of potential production campaigns, as well as the set of satisfactory campaign transitions, will be cast in this framework and finally, formal conditions for observing a given modelling expertise are presented.

3.3.1 Pragmatic modelling approach

Following B. Roy in his methodological considerations (Roy, 1985)[7], we define a finite decision model as a cognitive construct (generally under the form of diagrams or mathematical formulas) which, for a given domain of pragmatic questions, is taken as the representation of a class of phenomenons, more or less smartly detached from their context by an human observator, in order to support either investigation or communication in the decision making process.

Definition 3.3.1 (finite decision problem (FDP)).
Let X denote a finite set of n decision variables and S_X a semantic description associated with the decision variables X. The couple (X, S_X) is called the *decision domain*. Let Y denote the union of n finite value domains associated with the set of decision variables. S_Y denotes the semantic description associated with Y and the couple (Y, S_Y) is called the *co-domain* of the decision. We denote R a bi-partite graph defined on X and Y. $\nu : R \rightarrow V$ represents a valuation of the graph where V represents the domain of valuation.

We call *finite decision problem* the following structure $P = \langle X, S_X, Y, S_Y, R, V, \nu \rangle$.

Following Roy again (Roy, 1985, pp 55–56), a *decision action* a is seen as a potential contribution to a global decision which may be considered per se and which may serve as support to a decision aid application. And a *potential* decision action consists in a real or fictious action accepted as being realistic as candidate for the decision aid recommendation. Formally:

---

[7]"*Le modèle ne porte évidemment que sur un fragment de la réalité. Celui-ci peut, d'une façon générale, être regardé comme un système apte à fonctionner et qu'il est raisonnable d'isoler eu égard aux finalités recherchées. Le fragment de réalité est donc identifié en tant que système, tout autant par rapport à la classe de phénomènes qu'il appréhende qu'en fonction du champ de questions qui contribue à en fixer les limites.*" (Roy, 1985, p. 12).

Definition 3.3.2 (decision action).
A valued correspondence $\phi = (X, Y, R, \nu)$ between decision domain X and co-domain Y is called a *decision action*, or a contribution to the decision.

Potential actions are determined through the specification of the sets X and Y, the type of the graph R, as well as the associated valuation ν.

Definition 3.3.3 (potential decision action).
We denote C_s a set of *structural static*[8] constraints imposed on the generation of decision actions, such as domain or co-domain restrictions.

C_d denotes a set of *dynamic*[9] constraints imposed on the instantiation of the graph R and its associated valuation ν.

Now, Φ_p denotes the set of all possible correspondences under the constraints C_s and C_d. This set is called the set of *potential decision actions*.

Finally, we may define in a similar way optimal, or at least satisfactory decision actions.

Definition 3.3.4 (optimal decision action).
Let us denote C_o a set of global optimization constraints. Then Φ_o, the set representing all possible correspondences ϕ verifying constraints C_s, C_d and C_o is called the set of optimal decision actions.

In our critical investigation we restrain our formulation to such decision problems, where a single decision action, i.e. a valued correspondence $\phi = (X, Y, R, \nu)$, is to be selected as final decision outcome.

Within this general framework, we may now reformulate the particular SysCog scheduling problem.

3.3.2 Reformulating the repetitive scheduling problem

In the context of the repetitive scheduling of the plater, X denotes a set of n production slots covering approximately a monthly period and S_X represents the positioning of the slots on a temporal line with associated production characteristics and human resources availability.

Y denotes a finite set of production campaigns defined by the association of several wire types and S_Y represents physical, chemical, technical and organizational characteristics of the production campaigns.

R represents the allocation of a production slot to a given production campaign.

[8] *structural static* is taken here in a compiler design sense, i.e. *non changeable and compile time defined and instantiated.*

[9] *dynamic* is taken again in a compiler design sense. These constraints are indeed introduced at run time and thereby may induce computational simplicactions and relaxations of the overall solutions space through appropriate propagation algorithms.

Finally, V denotes the number of concurrent spools of wire making up a given campaign such that ν represents the quantification of the scheduled production campaigns.

We call $\phi = (X, Y, R, \nu)$ a *production plan.*

In order to formulate the set Φ_p of potential production plans, we require as global, static constraints C_s, a single production campaign per production slot, pre-scheduled maintenance periods for the plater and restricted sequencing of the campaigns.

Dynamical constraints C_d are mainly derived from technical and organizational constraints depending on given customer requirements.

We may thus define Φ_p as the set of potential production plans that verify constraints C_s and C_d.

An optimal production plan ϕ_o is finally achieved through following constraints C_o:

- The number of production campaign in a given plan are minimized;
- Input and output stocks are minimized;
- Maximize the use of the plater installation;
- – etc.

Such a decision problem, at the time of the SysCog study, is repetitively solved by a human expert scheduler each Monday in approximately two hours work. Let us now formulate the repetitive nature of the decision problem.

3.3.3 Decision expertise and formal specification stability

Definition 3.3.5 (sequence of FDPs).
$T = \{0, \ldots, t, \ldots,\}$ denotes an open end temporal horizon, where 0 represents the initial and t the current time point. To each such time point t corresponds the specification of a given decision problem $P^t = \langle X^t, S_X^t, Y^t, S_Y^t, V^t, C_s^t, C_d^t, C_o\rangle$ where each component may vary in time.

Let $\phi^t = (X^t, Y^t, R^t, \nu^t)$ describe the decision solution at time point t. We denote $\Pi = \langle (P^0, \phi^0), (P^1, \phi^1), \ldots, (P^t, \phi^t) \ldots$ a sequence of decision problems and solutions indexed in time.

We may distinguish two limit situations:

- A sequence of constant problems:
$$P^t = P^0 \quad \forall t \in T;$$
- And completely independent problems in time:
$$P^t \neq P^{t'} \quad \forall t, t' \in T : t \neq t'.$$

Between the constant case and the ever changing case, there exists a lot of repetitive decision problems presenting a partly evolving specification. In this general case, a refined distinction between stable and evolutive aspects in the specification of the problem may lead to specific stable constraints delimiting the set of potential but also optimal decision actions.

In practice, the precise knowledge of such stable delimiting constraints appears as authentic decision expertise. Furthermore, it characterizes the cognitive pertinence of the decision expert.

Working Hypothesis 3.3.6.
Cognitive decision aid aims at uncovering and enhancing the actual decision practice of the decision maker. It will be effective only if it takes into account and is based upon his/her cognitive decision expertise.

In the pragmatic approach of B. Roy, the set of potential decision actions is considered to be stable if two conditions are fulfilled:

- *Interior stability*: The actual decision aid study, in its internal design, is not supposed to update (except perhaps marginally) the initial definition of the set of potential decision actions;
- *Exterior stability*: The prescription, i.e. the definition of optimal decision actions, relies on a set of potential decision actions that shows some persistence with respect to the exterior context of the decision problem.

Translated into our repetitive context, we may globally state that a family of repetitive decision problems is characterized by a constant decision co-domain $\overline{Y}$, i.e.

$$Y^t \approx Y^0 = \overline{Y} \quad \forall t \in T.$$

Working Hypothesis 3.3.7.
A stable decision co-domain $\overline{Y}$ in a repetitive decision problem is a cognitive construct, i.e. a result of a cognitive information treatment in the mind of the decision maker.

As example of such cognitive constructs in the SysCog study, we may consider the concept of production campaign and the set of potential production campaigns, but also the set of admissible campaign transitions.

Working Hypothesis 3.3.8.
The stable decision co-domain $\overline{Y}$ appears in the mind of the decision maker under a double identity:

- first, an identity in *extension* revealed by those potential decision actions that are declared as being typical and

- secondly, an identity in *comprehension* expressed under the form of typical formal generation rules.

Definition 3.3.9 (Working Hypothesis 4).
The co-domain Y of a repetitive decision problem is stable (in the pragmatic sense of Roy) if and only if the extensional and comprehensional definitions of Y correspond and may be supposed constant in the limit of time covered by the decision aid.

In our scheduling problem, as mentioned in Section 3.2.6 on page 68, the scheduler has apparently achieved such a stable delimitation of the decision's co-domain.

3.3.4 Decomposition w.r.t. repetitive aspects of the problem

Careful observation of a human decision maker facing a sequence of FDPs shows that the "lazy solver" metaphor is most adequate to describe the cognitive solving approach, naturally taken by expert decision makers. Indeed, if a given FDP does not change over time the same satisfactory solution, once found, is re-exhibited unchanged all the time. On the other hand, if the problem specification is essentially changing in time (the problems are semantically not linked), no specific knowledge can improve general solving algorithms and human decision makers may find a solution only with great difficulty and only with the help of sophisticated systems like traditional mathematical programming tools or the above mentioned constraint logic programming systems. Now, between these two extreme cases, we find problem sequences where the FDP specification is only slightly changing over time. Careful distinction between changing and non-changing aspects of the problem leads to partial solutions or special constraints on the local admissible solutions set. In practice this knowledge appears as real decision expert knowledge and it characterizes essentially what we may call a decision maker's expertise.

In order to illustrate such human decision expertise for repetitively solving FDPs, we may consider the human approach for solving a simple clownery puzzle (Bisdorff and Mousel, 1990).

Example 3.3.10 (The clowns' puzzle game).
The puzzle (see Figure 3.4 on the facing page) is composed of nine pieces. Each side of these square elements is characterized by the head or the feet of a clown with a specific colour (red, blue, yellow, green). Therefore, the problem consists in combining these nine pieces in order to connect heads and feet of the same colour to obtain a single possible image. The search space of this game includes $9! \times 49 = 17781120$ possibilities for only four final solutions; In fact a unique solution that may be rotated clockwise.

Through a small sample we have observed human behaviour facing the solving of this puzzle in order to analyze the corresponding cognitive strategies (Bisdorff et al., 1995a; Laurent et al., 1994). At the beginning of the game, the player randomly

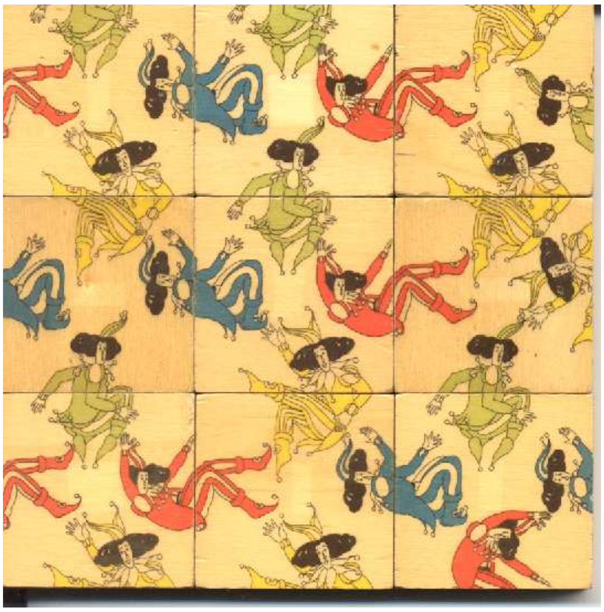

Figure 3.4: The clowns' puzzle game

takes pieces and tries to assemble them correctly. This first stage shows a «generate and test» strategy, where all the possibilities are considered. The main operational difficulty for solving the game comes from the necessary backtracking. Nevertheless, after some time, the player's trials generally lead to solutions where all pieces are correctly assembled except one. This incites him/her to look more closely at the description of the individual pieces. Intuitively, (s)he eventually discovers that all the elements may be considered in one and the same orientation. This simplification restricts the problem to disposing nine pieces on a grid of nine squares while respecting the heads/feet and colours connections. The search space is now reduced to $9! = 362880$ possibilities.

Because necessary backtrack still exceeds his/her cognitive capacities, the player tries again to find new interesting simplifications. Then, (s)he generally notices that there are three particular pieces. They all possess a side with a figure for which there does not exist a complement piece of same colour. (S)He may also discover that two pieces have four different colours. Most of the time, (s)he tries to put one of them at the centre. Therefore, the search space is automatically reduced because the possible places for these special elements are restricted to two sides and the centre of the grid. These intuitive strategies quickly lead the player to the solution. One can notice that, after some more games, the player is now able to exhibit the final solution at once, from his visual memory of the grid. This is the fastest possible instantiation of the decision variables.

Real industrial planning and scheduling FDPs do not present this constant specification in time. Nevertheless, different levels of relatively time independent imbricate specifications allow an expert decision maker to acquire corresponding efficient solving heuristics. Figure 3.5 shows the observed cognitive decomposition of the global scheduling problem as operated by the expert scheduler. Clearly, the two initial problem solving phases serve as stable problem delimitation for the subsequent refined decision problems.

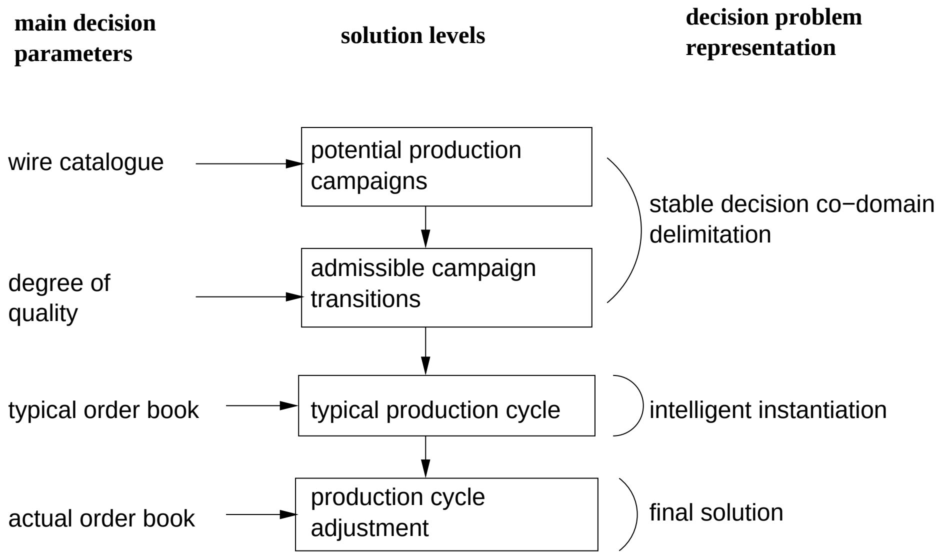

Figure 3.5: The expert's approach: decomposition w.r.t the repetitive aspects of the problem

But the abstraction of a typical production cycle, in fact a stable sequence of production campaigns, also appears as such a cognitive construct that produces a stable representation of the decision co-domain.

Finally, solely the last residual adjustment, taking into account anecdotical and unstable information from the actual order book, i.e. changing from week to week, appears to represent the essential decision problem tackled during the weekly scheduling activity.

In a last section we shall now present in some detail, the specific decision aid tools that we developed in the SysCog study, in order to provide a cognitive decision aid to the expert scheduler.

3.4 Designing a cognitive decision aid laboratory

In this Section we present the cognitive decision support system[10] we designed in order to solve the practical problem as given in the SysCog study. First, we present the general design of a cognitive decision aid laboratory. A second part is devoted to the design of a general algorithm for constructing stable cognitive delimitations of the co-domain of the decision problem. A last part is concerned with the overall system design of our approach.

3.4.1 Validating cognitive artifacts

As shown in Figure 3.6, the experienced decision maker is not working in a social desert. Indeed, his decision practice, and hence his decision expertise is embedded in a social environment. Generally, the decision maker has to comment, explain or justify his decision practice towards working colleagues, but also to his hierarchical supervisors.

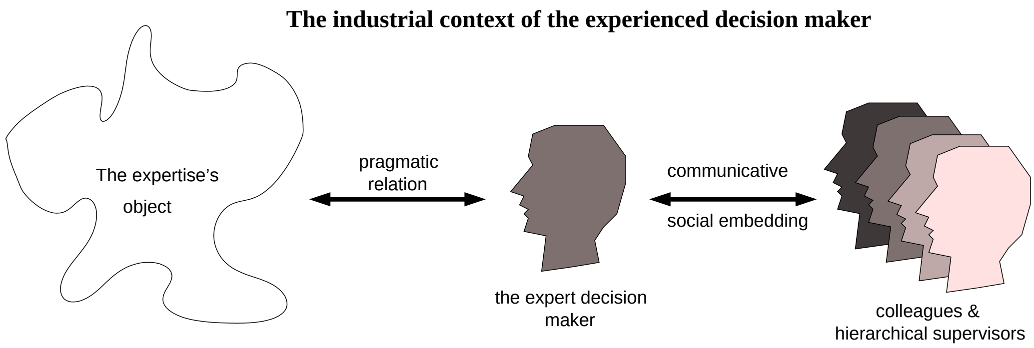

Figure 3.6: The social and pragmatic embedding of the decision maker
source: *Pichon* (1996)

Again we may notice that stable persistent cognitive constructs may appear about which the decision maker may provide a strategical discourse. By adding a professional cognitician to the social environment of the decision maker (see Figure 3.7 on the next page), our cognitive decision aid will precisely work in this context. This person aims at installing a validating circle between real observed decision practice and formal discourse on the corresponding decision strategies .

The original object of expertise is thus replaced by a formal representation, obtained from coding the decision problem and from formal closure operators. It is precisely this representation or model of the decision problem and the corresponding

[10] This section is based on a communication held at the First Conference on Cognitive Science in September 1994 in Luxembourg, (Laurent et al., 1994).

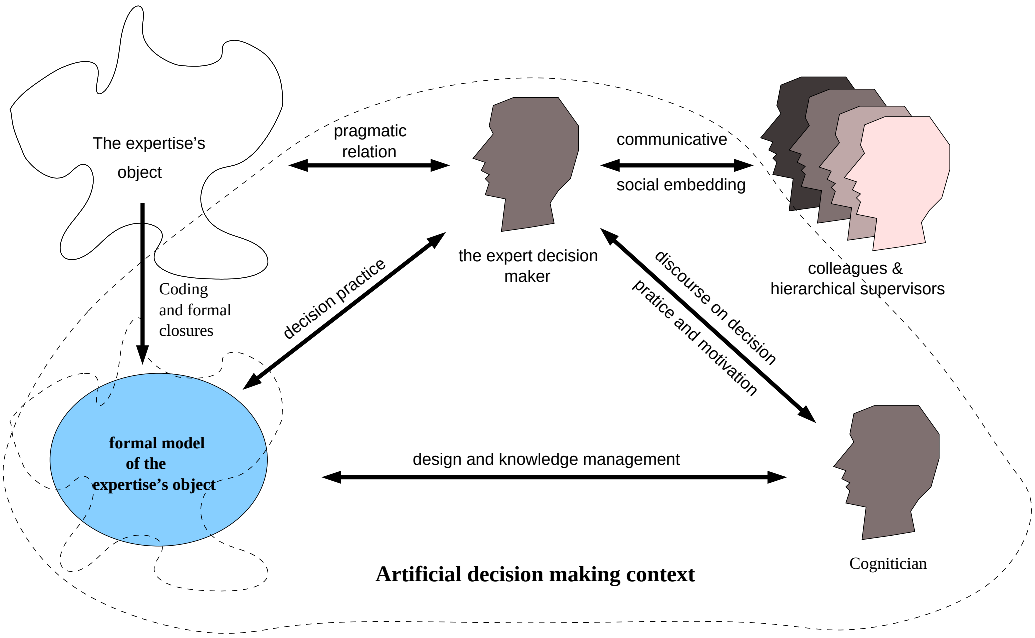

Figure 3.7: Installing a cognitive validation
source: *Pichon* (1996)

solving strategies which is in the centre of our attention. But this model, in fact the cognitive artifact produced, must be validated.

For this the cognitician will use a formal agent in order to calculate and compare artificial decision making extensions with those observed in the real decision practice. Therefore, we will use a constraint programming approach.

3.4.2 Using constraint logic programming

If we put aside for one moment the global optimization constraints, the decision problems we consider may easily be viewed as a special kind of finite constraint satisfaction problems (CSPs) (Mackorth, 1992), extensively discussed in the AI community (Freuder and Mackworth, 1992). These problems are very often NP-hard, and most solving strategies and heuristics must face the main difficulty of backtracking, i.e. serious time and space limits.

Now, a lot of research in Artificial Intelligence since 1970 has been focused on backtrack reduction for CSPs solving (Kumar, 1992). One of the essential ideas is to maintain constraint graph consistency by propagating constraints over the associated graph. Freuder established sufficient conditions (Freuder, 1982, 1988) to completely suppress backtracking by consistency techniques and, among others, it appeared that for CSPs where the underlying constraint graph is in tree-form, local node- and arc-consistency is sufficient to achieve such a backtrack-free solution. Unfortunately, almost all real FDPs we consider do not present such a simple underlying constraints tree and the necessary backtracking remains mostly rohibitive.

Other research concentrated on global consistency checking techniques (Hower, 1993, 1998), but, in general, higher-order consistency necessary for complete backtrack-free solving is only available through an algorithmic complexity that is comparable to the backtracking we want to avoid (Kumar, 1992). Some recent studies deal with the possibility of developing CSP efficient parallel implementation of these techniques (Hower, 1992; Hower and Jacobi, 1994). But these results are still uncertain for our practical purpose.

On the other hand, noticing that a constraint tree may exhibit a backtrack-free solution, Dechter proposes to extract some covering-tree from the constraints graph in order to obtain, with a deterministic algorithm, a first possible ordered instantiation without any backtrack (Dechter, 1990). Unfortunately, at present no commercially available solving system for CSPs in industrial application areas provides this solving technique. But some of these consistency techniques were integrated into constraint logic programming systems under the form of finite domains solver, thus allowing us to solve FDPs efficiently with the help of constraint logic programs.

Indeed, the finite domains (FD) computation facilities in the commercial software CHIP (Aggoun and Beldiceanu, 1991; Dincbas et al., 1990, 1988b) or more recently GNU-Prolog (Diaz, 1999) for instance allow us to easily formulate and solve FDPs thanks to consistency techniques such as node-consistency (achieved through forward checking) and arc-consistency (achieved through looking-ahead techniques). All these local consistency techniques deal with finite domains decision variables with their associated admissible domain values which are managed concurrently by daemon techniques. Solving complete FDPs including a set of global optimization constraints is thus achieved through a kind of branch and bound technique using explicit enumeration of the potential decison actions set (primitive predicate `min_max` in CHIP for instance). A variety of FDPs including symbolic, numerical and user-defined constraints may be solved with this tool. And lots of examples like warehouse location (Dincbas et al., 1989), car sequencing (Dincbas et al., 1988a), industrial disposing problems (Bisdorff and Laurent, 1995), even NP-complete problems like graph colouring (Dincbas et al., 1990), illustrate the efficiency of these implementations.

However, real size cases, such as those encountered in industrial production contexts, often lead to heavy combinatorial problems (Bisdorff and Laurent, 1995; Chamard and Fischler, 1993). These cannot be solved in a reasonable amount of time, even by using all the facilities of the finite domains tools, because of space and time consuming properties of the still necessary backtracking. Therefore, the FD solvers offer several strategies to order the selected variables. Possible heuristics are proposed to select either the variable having the smallest number of elements in its domain, or the most constrained variable or the variable having the smallest/largest value in its domain. The solver also proposes to order the possible domain values of the FD variables and to start the instantiation either by the minimum, maximum, middle or a specific value in the variable domains.

But all these solving facilities require particular decision expertise of the specific application domain in order to be able to efficiently prune the enormous search space and intelligently first-instantiate the decision variables. It is, therefore, necessary to take into account existing human decision expertise.

This constitutes the basic idea of what we propose to be a Cognitive Decision Support System (CDSS).

3.4.3 A human centred system design

The aim of such a CDSS is to take into account the repetitive aspect of a given FDPs sequence, not simply by translating the terms of the global problem into a Prolog program, but especially by considering and integrating human decision expertise into the overall solving process. Thus, the cognitician installs a cognitive link between the concrete application context and the formal description of the problem.

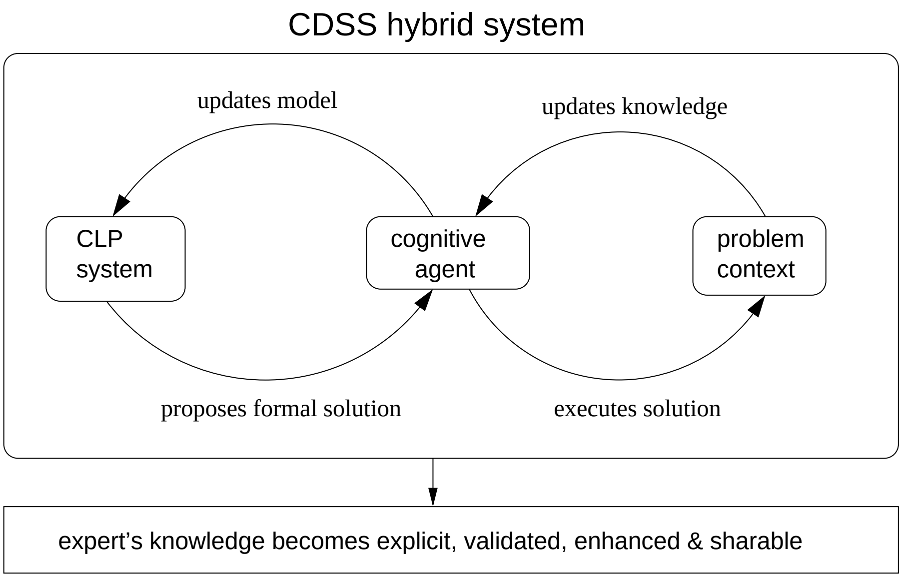

Figure 3.8: A cognitive decision support system (CDSS)

Such a hybrid system, as illustrated in Figure 3.8, necessitates the context description of the FDPs sequence with which a cognitive agent is related, and a constraint logic programming system (CLP), which is able to efficiently model and solve the entire problem.

After executing the CLP solution for the previous FDP in the sequence, the cognitive agent confronts his prolem description with reality and notices all the differences with the preceding case. Then he updates his knowledge about the problem according to the changes found and integrates them formally into the CLP model. Solving the corresponding CLP program then returns a formal solution which can be used either for the effective decision task or to perform a simulation of future results.

Behind the cognitive agent represented in Figure 3.8 on the preceding page stand three individual persons exchanging their results and knowledge. These are respectively the human decision maker, the cognitician and the programmer (see Figure 3.9). As expected the human decision maker is the expert who knows the problem context

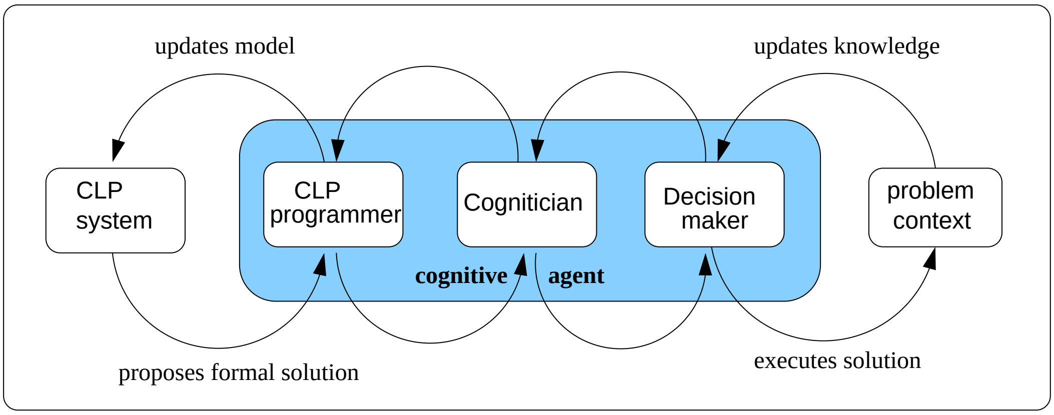

Figure 3.9: CDSS: the cognitive agent

and solves the FDPs sequence manually. The cognitician is the mediator who extracts the expert's knowledge. Finally, the programmer translates the rules obtained by the cognitician into a CLP source code which can be executed by the CLP system.

3.4.4 Solving by resolving

The general CDSS framework, detailed in Figure 3.8 on the preceding page, formalizes the CDSS principles presented above.

Let $B = \langle B_0, B_1, ..., B_t \rangle$ represent the sequence of decision expertise constructs, E_0 denote the initial context of the sequence of FDPs and $\Delta = \langle \delta_1, \delta_2, ..., \delta_t, ... \rangle$ symbolizes a sequence of observed changes in the successive contexts of the FDPs. $d = \langle d_0, d_1, ..., d_t \rangle$ expresses the sequence of formal solutions elaborated by the CLP solver.

Figure 3.10 on the following page shows the outline of a general decision expertise updating procedure in Prolog style. Two phases may be distinguished:

$(t = \mathbf{0})$ During the initial step, the cognitive agent builds, via the `expertise_init` function, a formal representation of the initial decision expertise B_0, i.e. FDP and corresponding cognitive solving strategies, taking into accunt an initial problem context E_0. Thanks to this formal construction, (s)he is now able to create, via

```
cdss (E0, B0, P0, d0) :-
        expertise_init(E0, B0),
        model_init(E0, B0, P0),
        solve(P0, d0).

cdss (δt, Bt−1, Pt−1, dt−1, Bt, Pt, dt) :-
        expertise_update(δt, Bt−1, Pt−1, dt−1, Bt),
        model_update(δt, Bt, Pt),
        solve(Pt, dt).
```

Figure 3.10: **CDSS Algorithm**: expertise updating

the `model_init` function, a CLP model P_0 of the problem. In return, the CLP solver proposes, via the `solve` function, the corresponding formal solution d_0.

(t) At current time t, the expert updates his decision expertise construct (`expertise_update`) according to the results of the previous step. After comparison of the old construct with the new one, the eventual creation of a new model P_t is decided upon (`model_update`). If nothing has changed, the old solution d_{t-1} is used again. Otherwise a new model P_t is built, implementing B_t and giving the formal solution d_t.

The `expertise_init` and `expertise_update` functions concern directly the decision maker. Indeed, he is the expert who solves each problem of the FDPs sequence, and thus he elaborates and improve his knowledge through the corresponding B_0, B_1, ...

These cognitive constructs may be interpreted as symbolic components of mental models (Cavazza, 1993) which the decision maker uses to formulate and solve the FDP. Therefore, they respect the following characteristics:

1. First, they are only *homomorphic* and not isomorphic with reality in order to retrace the world operations. Indeed, they constitute a reduced or simplified view, as all the parameters and reactions of the real world are obviously not reflected by them.

2. Secondly, they are essentially *changeable* as they generally remain only valid in the narrow scope of the current specific solving step.

3. Thirdly, they appear as being essentially *constructive*, i.e. the `expertise_update` function is profoundly recursive. This is why we need to repeat a large number of times the solving task in order to make these cognitive solving aids emerge as semantic fixed points.

A human decision maker is able to show a certain rationality but bounded to his field (Simon, 1979). Our CDSS is based on this idea and necessitates to consider the three principles of the Moving Basis Heuristic (Barthélemy and Mullet, 1992)[11].

A *parsimony* principle: due to the human expert's inability to process the whole data set, the decision maker extracts some data subset whose size is small enough to be compatible both with human short-range storage abilities (there is no intermediate storage in a long term memory) and with human computational abilities.

A *reliability/warrantability* principle: this principle works, in some sense, as the opposite of the preceding one. Concerned by reliability (socially as well as personally), the expert extracts from the data set a subset large enough and composed in such a way as to appear meaningful (comparisons on several attributes, conjunctive rules). For instance in case of binary choices a decision is made if and only if the gap between the two alternatives is large enough (threshold rules).

A *decidability/flexibility* principle concerned with the necessity to achieve choice in almost all cases, the expert extracts subsets of data in a manner flexible enough to achieve, almost all the time, a decision, on relatively short notice. Minimal conflict corresponds to such a decision.

The knowledge about the evolution of the cognitive constructs over time is not generally mentally present to the expert. Indeed, a person with decision expertise in a given field is generally not an expert of his own decision expertise and a direct query about his knowledge update rules does not give any valuable results. In consequence, we need special methods to extract this particular knowledge.

Actually, the difficulty in making the `model-update` function explicit, that is to find formal updating rules for cognitive parameters, is generally due to the fact that these cognitive constructs appear as a result of multicriteria choices (Barthélemy and Mullet, 1986; Barthélemy and Mullet, 1989). This is verified in the wire-drawing case as the typical production sequence choice depends on the quality criteria, the typical order-book and so on.

In order to discover these multi-criteria choice rules for cognitive decision aid constructs, we apply the cognitive model of the moving basis heuristics (MBH)[12] (Barthélemy and Mullet, 1987, 1992) relying on a bounded rationality and the three principles described above. This model can be expressed as follows:

- The cognitive effort involved in a judgmental process may be considered as to be minimized under constraints like social justifiability, flexibility of the process, etc;

- The notion of minimization itself may be weakened into parsimony principles and

[11] See Setion 2.3 on page 39.
[12] See Section 2.3 on page 39

- And finally, a «local» utilitarian-like point of view may be introduced as the search for a dominance structure (Montgomery, 1983).

The resulting model of our CDSS consists in a cognitive decision aid laboratory in which the three actors represented by the cognitive agent interact as illustrated in Figure 3.11.

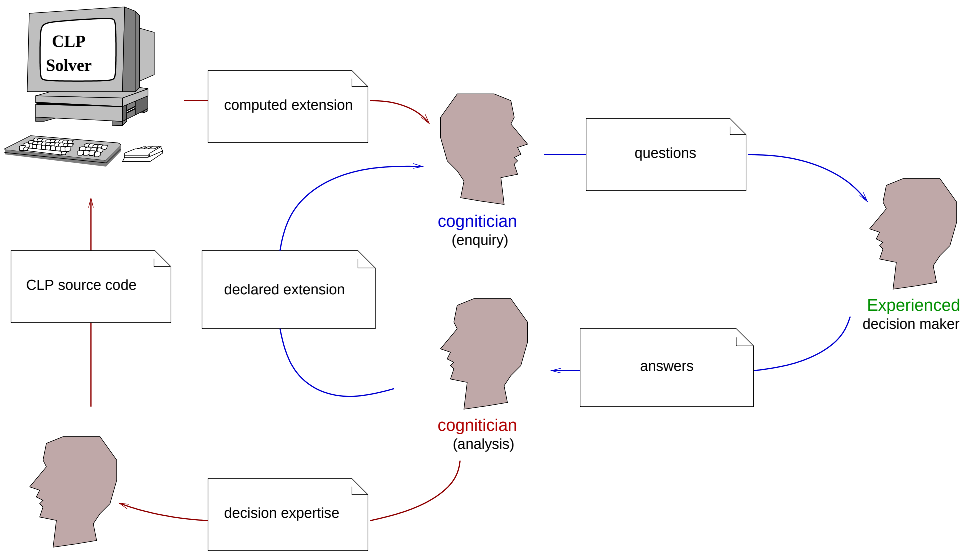

Figure 3.11: Cognitive assistance for expertise formulation

source: *Pichon* (1996)

In such a laboratory, the cognitician helps the decision maker in expressing and modeling his own knowledge. First, in order to get a basic model P_0 elaborated from E_0 and B_0, a classical analyzing step is performed through numerous dialogues. Then the programmer translates the rules emerging from the preceding interaction in a CLP code. For all P_i in the FDPs sequence, the trio will process in a particular way. Because the solution given by the formal agent does not often correspond exactly to the expert solution, the cognitician has to elaborate some precise questions. The aim of this questionnaire is to make apparent the missing rules that the decision maker has failed to disclose, and which differentiate the formal and expert solutions. Once again, the programmer will add or modify the CLP model according to the answers of the expert and will return a new solution. As long as the two results do not correspond, this same loop will be performed. Thanks to this cycle, the expert may clarify, validate and improve his knowledge about the decision problem and its solutions. Moreover, this laboratory succeeds in avoiding the deviations encountered in classical expertise extraction, i.e. listing of typical examples and excessive generalization of the rules by the expert.

The CLP solver associates the declarative aspects of logic programming with the efficiency of constraint solving techniques. Therefore, this system is well adapted to write clearly and in a short code the constraints and rules of the expert. Indeed, the CLP language allows the expression of all physical, technical, organizational or cognitive parameters of the repeated problems. All parameters, except the cognitive ones, are static symbols isomorphic with some specific reality taken into account. For example in the SysCog case, such parameters would be the technical specification of all types of wires.

Moreover, the CLP solving facilities allow, especially in the finite domains, to achieve good results thanks to their consistency techniques. The cognitive parameters introduced into the CLP program through the `model_update` function are exclusively concerned with the solving process of the underlying FDP. They are not related to the problem specification but to the current state of the decision expertise emerging through repetitive solving trials. Such cognitive parameters may be illustrated by the typical production sequence in the wire-drawing example. In general they may take three different aspects: static domain restrictions for decision variables, emerging noticeable inconsistencies, or even stable satisfactory static instantiation of the decision variables.

In the next section we shall describe the practical results we obtained with our CDSS.

3.5 Uncovering the scheduling expertise

First, we will present the decision aid process that generated the delimitation of potential production campaigns. Secondly, we will show a similar application to the problem of defining admissible campaign transitions. Lastly, we will show the strategy to instantiate a typical production campain cycle and the refined final solving strategies of the expert.[13]

3.5.1 Delimiting potential production campaigns

As initial information, the expert scheduler provided a *declared extension* Y_d of 49 production campaigns together with some general rules expressed on the semantics S_Y for delimiting precisely these campaigns. These rules were translated into CLP source code and the CLP solver generated as *calculated extension* Y_c over 3000 campaigns (see Figure 3.12 on the following page). We thus obtain three subsets of potential production campaigns:

1. $Y_1 = Y_d - Y_c$ represents those production campaigns initially cited by the expert, but apparently not verifying the corresponding communicated selection rules;

[13] This part represents the most interesting part of Pichon's PhD dissertation (Pichon, 1996). We presented these results at the Third International Conference on Practical Application of Prolog in Paris (see Bisdorff et al. (1995a)).

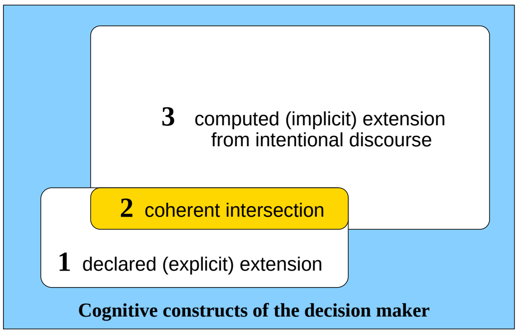

Figure 3.12: Declared versus computed extension
source: *Pichon* (1996)

2. $Y_2 = Y_d \cap Y_c$ represents the common part between declared and computed extension. Campaigns initially present in this subset are considered to be *typical* campaigns in accordance with the provided delimitation rules. Most of the declared extension belongs, in fact, to this subset;

3. $Y_3 = Y_c - Y_d$ represents those campaigns that formally verify the delimitation rules, but were not mentioned by the expert scheduler. They represent the lage majority of the computed extension and they apparently result from *typically* over-generalized delimitation rules.

Careful comparisons of production campaigns belonging to either of these three parts gives the expert scheduler the possibility to notice the very *contradictions* between his *typically* declared extension and intention, i.e. admissible production campaign and applicable delimitation rules.

We achieve this confrontation through a written questionnaire addressed to the expert scheduler (see Figure 3.11 on page 84) with a list of questions that should point to such apparent contradictions. In order to minimize the cognitive effort put on the human expert, each question compares two production campaigns in the terms of S_Y from different sub-parts. Discussion and confrontation are thus treated on a local *extensional* level, where in fact the expertise of the human scheduler is best supported from his weekly scheduling practice.

The first campaign of each question always belongs to the common part Y_2 and it serves as reference campaign for each question. The pairwise comparison between proposed production campaigns is not focused on preference situations but on declaration modes: extension versus intention. The questions have a double aim, on the one hand, enlarge the declared extension and, on the other hand, modify locally the delimitation strategy in order to restrict the computed extension.

A sample question is shown in Figure 3.13 on the facing page.

Two types of question may be asked:

Are you considering *only the first* of these two production campaigns as a potential candidate for a production plan?

wire types (Y)	type 1 (Y_1)	...	type n (Y_n)
1rst campaign	$y_{1,1}$	...	$y_{1,n}$
2nd campaign	$y_{2,1}$	...	$y_{2,n}$

☐ yes,
☐ no, I consider that both campaigns are possible

if *yes*, for what reasons ?
first hypothesis:

...

other hypothesis:

Figure 3.13: Sample question for delimiting potential production campaigns

- Y_2 versus Y_1: comparing two campaigns that were in fact cited by the scheduler, but the second does not not verify the apparent delimitation rules;
- Y_2 versus Y_3: comparing two campaigns both verifying the delimitation rules, but the second is not cited by the scheduler.

In the first case, the expert may either confirm the rejection of the second campaign, i.e. reduce his/her declared extension, or accept both campaigns and provide a formal justification. Two different cases may appear:

- A local modification of the delimitations rules is provided, i.e. the common extension Y_2 is enlarged;
- And a new delimitation rule is provided, i.e. the computed extension Y_c and thereby the common extension Y_2 are enlarged in order to include the both campaigns.

The second type of question has two objectives, on the one hand, extend the declared extension Y_d and, on the other hand, adjust the delimitation rules. If both campaigns are accepted as potential candidates, the declared extension Y_d is simply enlarged. In case the second campaign is rejected, again two cases may be distinguished:

- The apparent delimitation rules don't distinguish the proposed campaigns. In this case the expert scheduler must provide a new delimitation rule in order to justify this rejection;

- The delimitation rules are discriminating both campaigns and the expert may locally adjust the rejection thresholds.

A detailed presentation of the interaction with the expert scheduler through such questions is provided in Pichon 1996. To summarize let us mention that: New delimitation rules could be made apparent and; A lot of potential campaigns could be added to the declared extension. The final agreement was reached with a set of about 360 potential production campaigns associating at most three different types of wire. The corresponding delimitation strategy was based on a set of 13 delimitation rules separated in two different domains:

- *Technical production constraints* given by the physical and chemical specifications of the plater installation and;
- – *Organizational constraints* related to the type of the wire and corresponding organizational strategies.

The first subset represents completely independent constraints from the effective scheduling problem. The second subset is, in fact, based on a stable preference structure arising from the repetitive resolving of the weekly scheduling problem.

The GNU-Prolog program, shown in Figure 3.14 on the next page, may easily visualize the CLP model we have built from the delimitation strategies that the expert is apparently using. GNU-Prolog, similar to IndexCHIP, is a constraint logic programming (CLP) language designed with the aim to solve constraint enumeration problem with dynamic generation and propagation of finite domains constraints. The attractivness of the CLP languages result from the combination of two important features: they join the *efficiency of constraint resolution* with the *declarative aspect of the logical formulation.* Constraints may thus be expressed under a logical formulation very near to the actual formulation of the decision expertise and such CLP systems allow to model in an elegant way our delimitation problem.

A CLP program manipulating finite domain variables is generaly divided into three parts:

- First, finite domain variables with their associated possible range of finite values are declared (`fd_domain` predicate in Line 5 in Figure 3.14 on the facing page).
- In a second step, all necessary constraints are declared, that act on the first declared finite domain variables (see for instance Lines 11 and 13);
- Finally, a *labelling* process generates the admissible solutions (see Line 29).

The number of possible wire types offered by TREFILARBED , is around 33: 17 types of steel cord wires and 16 of hose wire (see Tables 3.3 on page 62 and 3.4 on page 63). In this way, each of the three decision variables, `Wire1`, `Wire2` and `Wire3` may be given one of the index numbers of the wire type (see Line 5).

```
campaign(NbWires, NbClasses, [Wire1, Wire2, Wire3]) :-
        % NbWires = 33 wire types
        % NbClasses = 10 patenting classes
        % a maximum of 3 wires
        % Wire1 and Wire2 on LineI and Wire3 on LineII
    fd_domain([Wire1, Wire2, Wire3], 1, NbWires)
        % finite domain initalization:
    fd_element(Wire1, [97, 108, 117, 117, ...  , 218], Diameter1),
    fd_element(Wire2, [97, 108, 117, 117, ...  , 218], Diameter2),
    fd_element(Wire3, [97, 108, 117, 117, ...  , 218], Diameter3),
        % each Wirex may contain one of the 29 wire types
    Diameter1 #<= Diameter2,
        % increasing diameters for wires 1 and 2 (Line I)
    Diameter3 #>= 155,
        % minimal diameter required for wire 3 (Line II)
    fd_element(Wire1, [1, 1, 1, ...  , 2, ..., 2], Type1),
    fd_element(Wire1, [1, 1, 1, ...  , 2, ..., 2], Type2),
    Type1 #= Type2,
        % same global type reqired on LineI: steel cord (1) or hose wire (2)
    fd_domain([Class1, Class2], 1, NbClasses),
    equivalent(Diameter1, Class1),
    equivalent(Diameter2, Class2),
        % fd association of diameters and patenting equivalence classes
    associate(NbWires, Wire1, Wire2, Wire3,
            Diameter1, Diameter2, Diameter3,
            Dens1, Dens2, Dens3),
    min-dist(Dens1, Dens2, Dens3, MinE),
    MinE #<= 1.45,
        % dynamic generation of physical and chemical constraints
    labelling(Wire1, Wire2, Wire3).
        % constraint enumeration of all possible association of wire types
        % with dynamic fd constraints propagation.
```

Figure 3.14: GNU-Prolog program for potential campaign generation

In order to apply the selection rules for potential prouction campaigns, we have to define also the variables representing the possible diameters, the global type (steel cord or hose wire) as well as the patenting equivalence class etc of the wires identified by `Wire1`, `Wire2` and `Wire3`. These relations are initiated via the `fd_element` primitive. The following line illustrate the case of wire diameters:

```
fd_element(Wire, [94, 108, 117, ...  ], Diameter)
```

The list `[94, 108, 117, ... ]` gives for each of the 28 wire types its diameter in micrometer. The predicate `fd_element` associates to each value of `Wire` from 1 to 28 a corresponding diameter, for instance for `Wire` = 3, we obtain a corresponding `Diameter` of 117.

In fact, the `fd_element` predicate installs a dynamical link between both the `Wire` and the `Diameter` variable. As soon as the first gets changed, the second is adjusted in consequence and vice versa. Take for instance that the diameters of the wires on LineI have to be lower or equal to 1.7mm and those on LineII greater or equal to 1.28mm. In GNU-Polog this may be immediately translated as:

```
Diameter1 #<= 170,
Diameter2 #<= 170,
Diameter3 #>= 128.
```

The relation '#<=' installs an inequation constraint on variables `Diameter1`, `Diameter2` and `Diameter3`. Thanks to the preceeding `fd_element` constraint, the three variables `Wire1`, `Wire2` and `Wire3` are automatically reduced accordingly to their respective ranges of values, i.e. variables `Wire1` and `Wire2` may no more admit any wire type of diameter greater than 170 for instance.

After installing all patenting and plating constraints (see Lines 14–28 in Figure 3.14 on the page before), the admissible ranges for the three wire type variables are strongly reduced. It is worth noticing that not all constraints act as straightforwardly on the admissible ranges as the preceeding ones. For instance, in order to check constraint '`MinE #<= 1.45`', all threee wire types variables must be previously instantiated, so that the constraint is simply delayed until the execution of the `labelling` primitive (see Line 29 in Figure 3.14 on the preceding page), where all currently remaining possible values in the ranges of the variables are subsequently tested for admissibility. With this mechanism, all potential production campaigns may be generated via the standard `findall` primitive.

Let us now turn our attention to a second application of our CDSS.

3.5.2 Delimiting potential campaign transitions

In this application, the expert scheduler didn't provide any declared extension of potential campaign transitions, but only a set of initial delimitation rules. A first questionnaire with 31 questions was therefore designed in order to approximately delimit such a first declared extension. The corresponding questions involved transitions

wire 1	wire 2	wire 3
type A	type B	nothing

is the actual production campaign.

Select the next possible campaigns ?

wire 1	wire 2	wire 3	yes	no
type B	not(type C)	type G	✓	
type C	type D	type G		×
type D	type E	type G		×
type F	type G	nothing	✓	
type G	not(type H)	type K		×
type H	type I	type K		×

Figure 3.15: Sample question for delimiting potential campaign transitions

appearing near to each side of the delimitation rules. The set of possible wire types appears in a special ordering (A, B, C, D, E, F, G, H, I, J, K) normally used by the expert scheduler[14].

A sample question is shown in Figure 3.15. The expert scheduler selects (✓) or rejects (×) the proposed sequence. In this example above, with the given selections, the expert confirms two possible campaign transitions: the passage to a wire type B is accepted, whereas a transition to a mixture of types C and D and higher ranked types is rejected. A second possible transition is confirmed towards wire types F and G. Higher ranked wire types are again rejected.

In fact, three questionnaires were necessary before arriving at a stable formulation of a total of 50 confirmed transitions. In the last questionnaire, a different type of questions was considered. Indeed, the outlay showed a list of potential production campaigns that were followed by the same unique campaign. The expert scheduler was this time asked to select those campaigns that may well preceed the given one.

Again the application of our CDSS allowed to make apparent some interesting cognitive artifacts used by the expert scheduler for constructing the potential set of campaign transitions. In fact an important technical delimitation rule only became apparent after the second questionnaire. But more important, a clustering of the wire types into four main classes concerning the technical difficulty to produce these types was uncovered. This clustering, based on the diameter of the principal wire type, allowed to strategically group all equivalent production campaigns into four partly

[14]This ordering relies in fact on the typical production cycle we shall discuss in next Subsection.

overlapping clusters and transitions selection reduces itself to the potential passing from one equivalence class to another one.

Similar to the delimitation of the potential production campaigns, again the final delimitation strategy for satisfactory transitions make apparent two separated set of rules: on the one hand, technical constraints depending on physical and chemical characteristics of the plater installation independent of the scheduling problem and, on the other hand, organizational constraints integrating in fact preferential considerations from the selection of a satisfactory or optimal production plan.

3.5.3 Analyzing the final scheduling strategy

A same divide and conquer strategy, as observed in the two precedent delimitations is observed in the final scheduling of the actual production plan. The four principal equivalence classes of wire types are placed globally into four different pre-defined zones (I, II, III, and IV) of the actual production plan as shown in Figure 3.16.

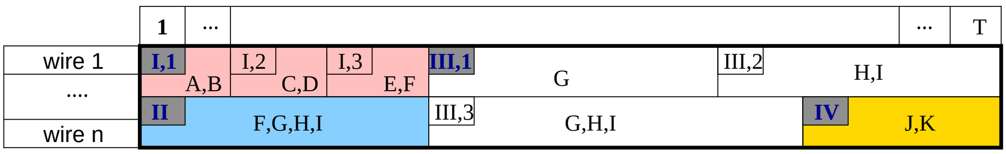

Figure 3.16: Independent zoning of the global production plan

Each production zone, allocated to one of the four equivalence classes of production campaigns is scheduled independently one from the other. Zone I represents the smallest, rather rare diameters and therefore the most difficult wire types to produce. They are always scheduled at the beginning of a new production plan, when the installation has been freshly checked and cleaned and in association with the most common, i.e. the most frequently produced wire types. Zone IV regroups rare wire types of very large diameters, always produced at the end of a production cycle.

Cumulative constraints concerning minimal security stocks for each wire type, in order to avoid shortage in the production of the fine-drawing section, are applied globally zone by zone. Inside a zone, only production quality constraints influence the transitions of the scheduled production campaigns. Therefore a quasi-diagonal production vector as mentioned in Section 3.2.6 on page 68 appears.

To avoid out of stock situations for wire types in zone II, i.e F, G, H, I, this zone is started in parallel to the zone I. Here we notice that the scheduling strategies are cognitively integrated into the delimitation strategies selecting the set of potential production campaigns and the set of admissible campaigns transitions.

Again we may notice the importance of the stable cognitive artifacts for solving efficiently and in reasonable time limits (the expert needs about two hours each week to elaborate a given two week plan) the given production scheduling problem.

3.6 Concluding the SysCog case study

This chapter, the first of our three chapters concerned wih practical illustration of human expertise centred decision aid (HECDA), illustrates some methods and tools for critically uncovering the actual decison expertise a confirmed, experienced decision maker may have developed in the context of a complex poduction scheduling context. A thorough discussion focusing on the practical validation of the human expertise centred decision aid, as revealed through this case, is given furthermore in Chapter **6**.

The cognitive decision aid laboratory presented before, enables the cognitician to "solidify" such expert scheduling knowledge through a critical confrontation of artificial versus natural scheduling expertise. The artificial scheduling, using constraint logic programming tools, indeed mimicks the human scheduler's approach and allows us to check the intentional versus the extensional discourse concerning expert scheduling strategies.

The decision aid is, in the SysCog case, more or less confined to the linguistic dimension of the uttered decision expertise (see Figure 2.2 on page 35, showing the cognitive modelling of the decision problem).

In the next case study (see Chapter 4), the HECDA developed in the context of the Comaps project is discussed. There the main focus will be put on the semiotical link between a strategic discourse on decision pratice and the historical observation of the corresponding effective decision practice.

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Chapter 4

The COMAPS case: Designing a guarded production control

> «*L'histoire est de bout en bout écriture. À cet égard, les archives constituent la première écriture à laquelle l'histoire est confrontée, avant de s'achever elle-même en écriture sur le mode littéraire de la scripturalité. L'explication/compréhension se trouve ainsi encadrée par deux écritures, une écriture d'amont et une écriture d'aval. Elle recueille l'énergie de la première et anticipe l'énergie de la seconde.*»
> P. Ricœur, La mémoire, l'histoire, l'oubli (2000, p.171).

Contents

4.1 Summary of the COMAPS case

The second case study we want to present in this work concerns a historical approach to decision aid. From a careful reconstruction of the past decision practice of an experienced decision maker we are able to implement specific decision aid tools which do not aim at replacing the experienced decision maker but, on the contrary, try to enhance both the historical knowledge concerning the past decision practice and also the maintenance of the apparent decision expertise. The main innovative feature in this case is the design of a Check as You Decide device, which helps the experienced decision maker in his daily decision practice and in the management of the explicit knowledge about his/her decision expertise.

This case is extracted from the work around the BRITE Euram Comaps project (see COMAPS, 2000) executed by the Statistics and Decision Department of the Centre de Recherche Public–Gabriel Lippmann (Luxembourg), in collaboration with a

Fraunhofer Institute laboratory specialized in industrial process optimization (EPO) in Berlin and the Department «Intelligence artificielle et Systèmes Cognitifs» (IASC) at the Ecole Supérieure des Télécommunications de Bretagne in Brest, which lasted from January 1997 to January 2000. The European project involved furthermore three industrial production sites: THOMSON Brest (F), TEXTAR Leverkusen (D) and CIRCUIT FOIL Wiltz in Luxembourg[1]. In this introductory section we present the general features of the case before illustrating more specifically our own contributions to the COMAPS project, and specifically to the CIRCUIT FOIL problem in the sequel of this chapter. First, we present the general description of the CIRCUIT FOIL production

Figure 4.1: At a COMAPS team meeting in Luxembourg, early 1999

problem, followed by the descriptions of the experienced decision maker and the institutional context of the decision making process. Finally, a last subsection concerns the practical results actually achieved through the COMAPS project.

4.1.1 Description of the production control problem

The case study is conducted at the CIRCUIT FOIL Luxembourg plant. CIRCUIT FOIL practices the technique of copper electro-refining to produce foils in wide strips with thickness between 9 and 160 micrometers. These foils are pressed onto various dielectric supports. The resulting laminate is used in the manufacture of printed circuit boards for the electronic industry. Various conditions of mechanical resistance and

[1] In Figure 4.1 are represented from left to right, in the front row: M. Streel (CIRCUIT FOIL), E. Pollmann (TEXTAR), N. Lépy (IASC), M. Leroux (THOMSON), G. Coppin (IASC, THOMSON), E. Le Saux (IASC); in the back row: R. Schneider (CAMTEC), J.-P. Barthélemy (IASC), P. Saunier (CRP-GL), E. Wiederhold (IITB-EPO), K. (TEAMWORK), P. Picouet (IASC), W. Müller (IITB-EPO), R. Bisdorff (CRP-GL).

surface topography must be satisfied by the foil in order to meet the numerous operating constraints imposed on the printed circuits in different situations (electronics, automobile, business automation, telecommunications, ...).

The electrolysis baths are, at present, controlled and adjusted by various on-line monitors, namely copper concentration, acid concentration and temperature. Copper foil surface topography is monitored on-line using a gloss meter. All these sensors are currently managed by Siemens PLCs (Programmable Logic Control).

In principle, on a daily basis, expert productions controllers have to determine the ideal rate of addition of the refining agents generally used for copper electro-refining, based on the above-mentioned on-line parameters, coupled with discrete measurements, and depending on the type of end-products required. In case the production outcome is not confined to predefined admissible values, differential control settings are decided in order to possibly correct the quality of the future outcome.

4.1.2 The decision-maker

In the COMAPS case, the experienced decision-maker is in fact a board of normally three persons: the plant production manager, a production engineer and an R&D engineer. They meet every day around noon in order to check the settings of the production machines. Each meeting takes generally no more than 10 minutes. The production engineer, i.e. the person responsible for the plant's production, is steering the meeting. The R&D engineer is responsible for the quality of the production outcome and, therefore, he manages the official rules for the production control settings. All three persons are recognized experts concerning the control problem in question.

The fact that, in this case, the decision-maker is a board, allows us to access, with the help of audio-visual recordings, to verbal protocols of the arguments the three experts exchange before making a control decision. Fortunately, we could hereby gather interesting insight in the cognitive work being done by the three experts before some difficult control decision.

4.1.3 Institutional context

The daily production control meeting was in fact instituted shortly before theCOMAPS project started. It was observed before that the overall control of the production machines followed a confusing scheme, so that the R&D department, in fact in charge of supervising the quality of the production outcome, had no clear overview of the effectively decided control settings.

The daily meeting now concentrates the recurrent control decision process on a precise time instant, and in presence of a stable board of responsible persons including necessarily an R&D engineer, responsible for the quality supervision of the production outcome.

4.1.4 Practical objectives of the COMAPS project

The COMAPS project took, as practical goal, to assist the daily meeting board in its control decisions from a cognitive point of view, i.e. without, in fact, changing the cognitive involvement of the assisting experts.

A first objective was to make all relevant production information, that tends to be used by the board, available o-line during the daily meeting. This information concerns, on the one hand, reports such as the properties and shift reports specially prepared for the meeting, and, on the other hand, chart diagrams showing the recent evolution of all on-line, continuously recorded (every three minute) process state parameters on individual machine level.

A second and more ambitious objective was to provide the experts with what we call a CHECK AS YOU DECIDE device: A device which should implement a guarded decision making process without altering essentially the cognitive work of the experts board.

4.1.5 The results of the COMAPS project

The COMAPS project has produced positive results on following topics:

- Exhaustive specification of the parameters/constraints presently taken into consideration by the expert controllers for an optimal management of refining additives in the electrolyte. A precise knowledge of the information processed during the control decision meeting has been established and a complete production information system has been developed around these control decisions that enables a complete, automatic archiving of all daily control decisions. An exhaustive history of the past control decision practice is now available for technical, as well as cognitive studies;
- The new insight into the complex production parameter space revealed some unsuspected physical and technical dependencies unknown beforehand;
- A CHECK AS YOU DECIDE device is, at the moment of this writing, in its final implementation and testing phase. Preliminary tests with a prototype device had already shown some convincing results. The aim of this decision aid device is to improve the control strategy acquisition by the expert decision-makers in enhancing the online access to all relevant production parameters, i.e. by better using all available information at the moment of the control decision and, especially, the simultaneous consideration of continuous on-line measurements of the production process with the final product characteristics available from the quality control measures at the end of the production phase.

In the next sections we present, in detail, the formal description of the considered decision practice and our approach for cognitive decision aid.

4.2 Archiving the control practice

In this second section we first present our case-based approach for describing, in great detail, the daily decision practice. A second part is devoted to the formal description of the control decision situations and, a last one, presents the official CIRCUIT FOIL production control rules.

4.2.1 Empirical observation

We start by specifying the necessary knowledge we should gather in order to be able to precisely formulate the given decision problem and design adequate decision aid concepts and tools[2] . The items involved were the following:

- Detailed description of the part of the production process relevant for the COMAPS decision aid purpose;
- Detailed description of the effective decision making process;
- Expected outcome of the decision aid for the decision maker;
- Real context of insertion of the COMAPS decision aid tool: Where to place it and how to use it?

Three different information sources were used: (1) Existing written documents concerning the production process; (2) An experienced decision maker in the person of a R&D engineer; (3) and finally, audio-visual recordings of a continuous set of daily decision making sessions (from October 15 to 24). Each recording was immediately followed by a semi-directive interview with the R&D engineer in order to get "hot" comments upon the just recorded decision making session and to explain the specific daily production context in which this decision making session had taken place. These extensive recordings were preceded by two test recordings (22 and 22 September 1997) in order to calibrate the audio-visual recording technique.

Detailed transcription and analysis of these audio-visual recordings helped in defining the actual control decision making process with the complete informational support used be the decision maker (Lépy, 1997b) . Cross-validating all information sources allowed in a second step to construct a precise formal description of the CIRCUIT FOIL production control decision problem (Lépy, 1998b).

In the next subsections we briefly present and discuss the outcome of our observations[3].

[2]Actual field observation was mainly done by Nathalie Lépy, a PhD student from the IASC Department at Telecom Bretagne. Several technical notes were produced under the form of confidential internal COMAPS deliveries (Lépy, 1997a,b, 1998a,b).

[3]Obliged to confidentiality about the precise production strategies of the CIRCUIT FOIL plant, we restrain our discussion to those aspects that are relevant from a general methodological point of view.

4.2.2 The decision making context

Let us recall that, in this cae, the experienced decision maker is a board of several experts: The plant production manager (chair of the board), one of the production engineers and the R&D engineer responsible for the quality supervision of the production process.

This meeting takes place every working day around noon and lasts for about 5 to 10 minutes, depending on the number of individual control decision situations to discuss. The aim of the meeting is to analyze the resulting properties of recent outcome on all production machines and if necessary readjust the settings of those machines where a non satisfactory outcome had been observed. During the period under review, the number of concerned machines varied between 10 and 20, so that we may record in average around 15 control decision situations per working day.

Several printed documents support the decision making process. The principal document used is the so called *properties report*, containing the mechanical properties of the production outcome of the day of the meeting either recorded off-line after finishing a product or on-line with the help of continuous observation stations. On this document are noted, as they happen, the actual control decisions taking during the meeting. The second document used in the meeting is a daily so called *shift report*, indicating the actual settings of the control parameters. On this document are eventually reported the final control decisions, i.e. the decided variations of the levels of these parameters. After the meeting, the completed shift report is returned to the person responsible for the shop floor, where the new control decisions are then put into practice.

Generally, the chair of the meeting announces for all machines the decision he thinks is appropriate: either do nothing (everything is OK) or increase or decrease the level of one or more control parameters. A short discussion is sometimes started. Finally, a decision is taken and the person reporting the final decision on the shift report announces the resulting new levels of the control parameters.

4.2.3 Individual control decision situations

A first and most important point was to discover all relevant decision attributes that the board in charge of the daily production control settings would use during the elaboration of its control decisions. The following parameters have appeared to be relevant in the observed decision making process.

- Environment parameters:
  - electrolysis bath,
  - row of the machine,
  - age of the machine,

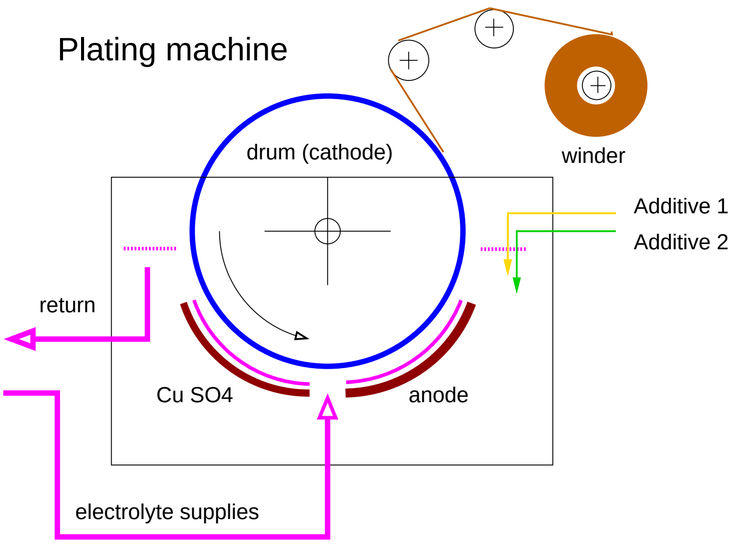

Figure 4.2: Circuit Foil plating machine

- nature of additives,
- age of the filters of the electrolyte,
- product type,
- product thickness;

- Continuous process state parameters:
  - temperature, copper – as well as acid concentration of the electrolyte,
  - pressure of the electrolyte flow measured on the filters,
  - electrical current in the system,
  - rotating speed of the drum (cathode),
  - voltage applied to the machine,
  - anode – cathode distance,
  - transversal weight distribution of the electrolytic copper deposit on the drum;
  - on-line quality measures of the product outcome:
    - longitudinal tensile strength measured on the trims at room temperature and at 180°,
    - gloss of the sheet through an automatic optical supervising device,
    - smoothness of the surface noted down periodically by visual inspection;
- Final product outcome parameters:

  - longitudinal and transversal elongation measured at room temperature and at 180°,
  - tensile strength measured at room temperature and at 180°,
  - roughness of the surface of the copper sheet;

- Production control parameters:
  - levels of two additives and of electrolyte flow in the machine;

- Control decisions actions:
  - variations of the levels of the control parameters;

Not all of these decision attributes are actively used at present during the control decision making process, but it was decided to include, at least for descriptive purposes, all available parameters. In fact, 32 different parameters out of the preceding categories, those for which there exists a reliable measure and recording practice, were finally retained as so called *decision attributes*, i.e. attributes representing the information that apparently underly or should somehow underly the practical control decision making.

The three final so-called *control decision actions* generally take integer values in a common range $[-5, +5]$.

The alignment of a vector of values for all the decision attributes with a corresponding control decision, a triple of decided variations, is called a *control decision situation* or shortly a *control situation*.

4.2.4 The COMAPS database: a factual control history

Starting from July 1996, the R&D responsible at CIRCUIT FOIL has recorded all daily control situations handled by the control decision board in a database called COMAPS database. For illustration, Table 4.1 on the following page presents a small extract from the COMAPS database showing control situations concerning the production of a specific product of given thickness (35μ) and type (6) on a given machine (D3) observed in March 97 (see appendix Table 4.2 for a long term observation of machine D3 from September 96 to April 97). All parameters are anonymous and numeric figures are coded for confidentiality reason. Process state description and product outcome properties are coded as X_i for $i = 1 \dots 8$. Two production control parameters are coded as X_1^c respectively X_2^c. The corresponding control decision actions, taken for each role number at each given date, is coded as a pair of integer values representing the changing of the levels of X_1^c and X_2^c from time t to $t+1$. For instance, on March 13 1997, production control parameter X_2^c was lowered by one unit from level 8 to level 7 whereas on March 19 1997, production control parameter X_1^c was increased by one unit from level 6 to level 7 (see Table 4.1 on the next page). Table 4.2 on page 107 shows

# Rol	Date	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_1^c	X_2^c	Action
D3-3750	08/03/97	58.75	39.52	2	5.35	55	26.6	8.5	11	6	8	<0,0>
D3-3751	10/03/97	59.73	38.02	2	6.05	51	25.8	7.6	13	6	8	<0,0>
D3-3752	13/03/97	62.45	37.77	3	6.83	55	25.4	11.0	17	6	8	<0,-1>
D3-3753	15/03/97	63.33	37.52	2	4.60	54	26.0	9.0	15	6	7	<0,0>
D3-3754	17/03/97	58.18	40.52	2	5.84	54	29.0	10.7	12	6	7	<0,-1>
D3-3755	19/03/97	44.95	39.02	2	5.03	52	26.8	10.1	14	6	6	<+1,0>
D3-3756	21/03/97	59.98	35.27	2	4.68	53	24.8	8.5	15	7	6	<0,0>
D3-3757	23/03/97	59.13	41.52	2	6.59	52	24.4	7.8	13	7	6	<0,0>
D3-3758	25/03/97	58.63	36.77	2	6.95	50	21.6	7.7	14	7	6	<0,0>
D3-3760	30/03/97	58.23	41.02	2	6.35	52	25.8	9.8	11	7	6	<0,0>
D3-3761	01/04/97	59.33	41.02	2	5.57	51	27.2	8.5	11	7	6	<0,0>

Table 4.1: Observed control situations during March 97 for product 35–6 on machine D3

a complete set of control situations that appeared during that period of observation concerning machine D3[4]. The actual COMAPS database contains around a 100 control situations per year for each of the CIRCUIT FOIL machines (32 during the COMAPS study). Each record of a given control situation, identified by a date and a role number, contains 32 fields describing all decision parameters including three production control parameters and three supplementary fields containing the corresponding three control decision actions. At CIRCUIT FOIL effective recording of all daily control situations started from July 96 and is on going right now, so that at present a large history of several thousands of real control situations is available for consultation and analysis[5].

Beside the description of these control situations, we could also gather from the R&D responsible, explicit information about the official CIRCUIT FOIL production control rules that gouvern, or say "should gouvern", the control decision making.

4.2.5 Official control instructions

Following ISO 9000[6] standards for quality management of the production process, all control decision actions at CIRCUIT FOIL plant are supported by noted down production control rules or instructions. These rules directly derive from the final product quality requirements as negotiated with the CIRCUIT FOIL customers. Furthermore, they generally concern some important final product outcome properties such as transversal elongation, tensile strength, and roughness properties.

It is, therefore, not astonishing to observe that, in practice, not all 32 parameters are effectively used in the decision making. From the exploitation of our audio-visual

[4] The name of the machine, in fact, identifies the third machine connected to the electrolyte system D.

[5] A purely statistical study with an emphasis on time series analysis could certainly give interesting complementary results. Such a study is actually envisaged at CIRCUIT FOIL .

[6] CIRCUIT FOIL is an ISO 9000 certified company since the middle of the nineties.

# Rol	Date	P1	P2	P3	P4	P5	Q1	Q2	Q3	Q4	Q5	Q6	V1	V2	Decision
D3-3618	04/07/96	8	41	57.8	40.52	2	3.33	60	17.8	6.2	30	10	3	16	<0,+4>
D3-3619	06/07/96	6	41	58.18	43.52	2	5.88	57	18.4	7	30	10	3	20	<0,+2>
D3-3620	09/07/96	6	28	59.28	44.52	3	5.47	58	20.6	7.9	32	11	3	22	<0,0>
D3-3621	11/07/96	6	28	57.65	44.02	2	5.23	59	25.2	10.1	31	11	3	22	<0,-2>
D3-3622	13/07/96	6	28	55.33	41.27	2	4.31	58	26.2	11	31	11	3	20	<0,0>
D3-3623	15/07/96	6	28	57.15	41.77	2	5.08	56	25.4	11	30	11	3	20	<0,-5>
D3-3624	18/07/96	6	40	56.33	40.77	3	5.12	56	25.4	9.9	30	10	3	15	<0,0>
D3-3625	20/07/96	6	41	59.05	38.52	2	4.51	55	22	10	29	12	4	15	<+1,0>
D3-3626	22/07/96	6	41	57.1	38.77	2	4.32	54	24.4	10.5	29	12	4	15	<0,-1>
D3-3627	24/07/96	6	41	56.15	41.77	2	4.28	53	25.4	9.4	30	13	4	14	<0,0>
D3-3628	26/07/96	6	41	56.88	40.02	2	4.24	58	25	11	30	7	4	14	<0,-2>
D3-3629	28/07/96	7	41	53.55	45.02	2	4.06	55	23	9.7	30	8	4	12	<0,0>
D3-3630	31/07/96	7	40	57.03	42.77	3	4.46	57	25.2	9.3	31	9	4	12	<0,0>
D3-3631	02/08/96	7	40	58.23	40.52	2	5.36	56	21.8	7.6	30	9	4	12	<0,0>
D3-3632	04/08/96	7	42	55.93	46.77	2	4.87	56	19	8.5	31	12	4	12	<0,0>
D3-3633	07/08/96	7	42	55.45	44.52	3	4.5	54	19.2	8.5	30	12	4	12	<0,0>
D3-3634	09/08/96	7	40	56.85	38.27	2	4.71	54	21.6	8.5	29	13	4	12	<0,0>
D3-3635	11/08/96	7	40	57.78	42.27	2	5.13	53	24.6	9.2	29	15	4	12	<0,0>
D3-3636	13/08/96	7	40	58.3	40.27	2	4.16	56	20.2	11	31	9	4	12	<+1,-2>
D3-3637	16/08/96	7	41	58.65	39.52	3	3.88	56	21	9.3	31	11	5	10	<0,0>
D3-3638	18/08/96	7	41	56.78	40.52	2	5.33	56	23.6	10.2	30	11	5	10	<0,0>
D3-3639	20/08/96	8	31	59.85	42.27	2	4.78	54	23.4	8.5	29	11	5	10	<0,0>
D3-3640	22/08/96	8	42	60.15	40.02	2	4.6	54	21.6	8.5	29	13	5	10	<0,0>
D3-3641	24/08/96	8	41	56.78	41.02	2	4.2	58	23	11	31	9	5	10	<0,0>
D3-3642	26/08/96	8	42	57.7	43.27	2	4.3	56	26.6	11	30	8	5	10	<0,-2>
D3-3643	28/08/96	8	42	60.9	40.52	2	4.47	55	24.6	9.1	30	10	5	8	<+1,0>
D3-3648	06/09/96	7	42	57.05	40.77	3	4.9	54	26.8	6.9	29	7	6	8	<0,+2>
D3-3649	08/09/96	7	42	55.83	43.02	2	5.5	55	24	9.5	31	9	6	10	<-1,0>
D3-3655	20/09/96	8	43	55.75	43.27	2	5.92	58	25.6	11	31	12	5	10	<0,-2>
D3-3656	22/09/96	9	43	55.15	41.02	2	4.45	56	26.2	10.3	31	13	5	8	<0,0>
D3-3657	23/09/96	9	43	54.55	40.27	1	4.97	53	23.6	6.9	31	14	5	8	<0,0>
D3-3658	25/09/96	9	42	59.15	34.02	2	4.5	56	25.4	9.6	30	11	5	8	<0,0>
D3-3665	08/10/96	8	45	57.68	39.02	1	4.8	56	21.4	9.5	31	6	5	15	<0,0>
D3-3666	10/10/96	8	44	58.43	40.52	2	5.03	57	15	7.3	29	6	5	15	<0,0>
D3-3667	12/10/96	8	45	55.28	38.02	2	4.87	56	23	11	31	9	5	15	<0,-2>
D3-3668	14/10/96	7	44	56.93	37.52	2	5.06	55	22.2	10.5	30	8	5	13	<0,-2>
D3-3669	16/10/96	7	44	55.83	36.77	2	4.98	56	25	11	30	10	5	11	<0,0>
D3-3737	08/02/97	14	44	60.73	39.52	3	5.54	53	27.4	8.5	30	14	6	13	<0,0>
D3-3739	12/02/97	16	44	59.1	43.52	2	5.16	53	26.4	9.7	30	12	6	13	<0,0>
D3-3740	15/02/97	16	44	61.25	32.77	3	5.55	53	26.2	9.5	30	12	6	13	<0,0>
D3-3741	17/02/97	16	44	60.13	35.27	2	5.42	54	18.4	11	31	11	6	13	<0,-2>
D3-3742	19/02/97	16	44	57.6	46.27	2	5.76	54	27	8.5	32	9	6	11	<0,0>
D3-3743	21/02/97	16	44	55.88	37.27	2	5.04	56	17.6	11	31	11	6	11	<0,0>
D3-3744	24/02/97	16	44	56.35	35.02	3	4.88	55	25	11	32	12	6	11	<0,-1>
D3-3745	25/02/97	16	44	24.99	33.52	1	5.58	55	26.2	9.9	32	13	6	10	<0,0>
D3-3746	28/02/97	15	46	25.65	38.52	3	5.18	58	28.4	11	34	11	6	10	<0,-2>
D3-3747	02/03/97	15	46	24.99	36.27	2	5.79	54	17	9.6	31	12	6	8	<0,0>
D3-3748	04/03/97	15	46	24.99	34.52	2	5.74	54	28	9.9	31	14	6	8	<0,0>
D3-3749	06/03/97	18	46	24.99	40.02	2	5.6	52	20	8.5	30	13	6	8	<0,0>
D3-3750	08/03/97	18	46	58.75	39.52	2	5.35	55	26.6	8.5	32	11	6	8	<0,0>
D3-3751	10/03/97	18	46	59.73	38.02	2	6.05	51	25.8	7.6	30	13	6	8	<0,0>
D3-3752	13/03/97	20	46	62.45	37.77	3	6.83	55	25.4	11	32	17	6	8	<0,-1>
D3-3753	15/03/97	18	45	63.33	37.52	2	4.6	54	26	9	31	15	6	7	<0,0>
D3-3754	17/03/97	13	45	58.18	40.52	2	5.84	54	29	10.7	32	12	6	7	<0,-1>
D3-3755	19/03/97	18	45	44.95	39.02	2	5.03	52	26.8	10.1	30	14	6	6	<+1,0>
D3-3756	21/03/97	20	46	59.98	35.27	2	4.68	53	24.8	8.5	30	15	7	6	<0,0>
D3-3757	23/03/97	20	46	59.13	41.52	2	6.59	52	24.4	7.8	30	13	7	6	<0,0>
D3-3758	25/03/97	20	46	58.63	36.77	2	6.95	50	21.6	7.7	28	14	7	6	<0,0>
D3-3760	30/03/97	23	48	58.23	41.02	2	6.35	52	25.8	9.8	31	11	7	6	<0,0>
D3-3761	01/04/97	23	48	59.33	41.02	2	5.57	51	27.2	8.5	30	11	7	6	<0,0>

Table 4.2: Observed control situations from July 96 to March 97 for product 35-6 on machine D3

recordings[7], we could establish frequency statistics with the most often used parameters apparently involved in the decision making process[8].

Indeed, Table 4.3 shows the frequency of apparent use of the most often used parameters in the control decision making process during our period of observation.

Parameter	frequency in %
machine identification	100
product thickness	100
product type	99
tensile strength (20°)	99
transversal elongation (180°)	82
roughness	12
control parameters	3
previous product	2
...	...

Table 4.3: Relative frequency of the use of the main decision attributes

It clearly appears here (see Table 4.3) that major attention is put on the main qualitative aspects of the outcome product, i.e. the elongation and tensile strength of the finished product, as required by the customer specifications.

In fact, the R&D manager at CIRCUIT FOIL has in charge the technical design of the production process, and in this context, he has noted detailed instructions for adjusting the level of additives necessary in order to achieve a correct quality of the production outcome. We will call in the sequel such official control instructions by the name "*intentional control theory*". They are expressed under simple rule form, such as "*if tensile strength is slightly too low then raise the level of the relevant additive by one unit*". Most important appears also the implicit 'instruction' where a *doing nothing* control decision action is considered to be adequate. This is generally the case if the final product outcome quality indeed meets the customer requirements with respect to elongation, tensile strength and roughness properties.

In Table 4.1 on page 106 these most relevant decision attributes appear under the labels X_1 respectively X_7. The values taken for a production outcome on these specific attributes indeed have to be checked against compliant customer's specifications. Here

[7]Nathalie Lépy has produced extensive reports (Lépy, 1997b) of all recorded meetings and designed an observational protocol in order to describe all information exchange between the experts during the daily meetings

[8]The fact that the decision maker in the CIRCUIT FOIL case is a board of several experts greatly serves the effective observation of the information effectively used during the decision making process (Lépy, 1998a). We shall come back to this point in Chapter 6 where we discuss the practical validation of our various approaches with respect to cognitive decision aid paradigm.

for instance, their measures have to be maintained in the following ranges:

$$\begin{aligned} X_1 &\in [50.0, 65.0] \\ X_7 &\in [7.5, 10.0] \end{aligned} \tag{4.1}$$

Clearly, two types of decisions thus appear in Table 4.1 on page 106:

do nothing the default decision ($< 0, 0 >$), i.e. do not change the control settings in case the production shows compliant outcome, is by far the most frequently appearing decision action in practice;

adjustment depending on the case of divergence from the required qualitative characters of the outcome product, a specific variation (more or less supported by an official control rule) of the levels of the control parameters is proposed.

It is interesting to notice that the CIRCUIT FOIL R&D Department precisely installed the daily meeting in order to be able to convince in practice the production control responsible persons to follow the given official control strategies. Checking the actual control practice against these official control rules is precisely the mission of the R&D responsible in the daily decision board.

4.2.6 Qualifying the historical control practice

In the same vein, but on higher level, we may finally qualify the result of a given control decision, by checking the outcome of the following product on a given machine against the necessary quality requirements (see Relations 4.1 for instance). In Table 4.1 on page 106 we may notice for instance that '*to do nothing*' on March 10 was apparently not the right decision, whereas decreasing X_2^c by one unit on the following date was successful, but doing nothing then was again unsatisfactory.

This allows us to assess the overall quality of the production control strategies, as implemented in practice first with respect to the actual decision making process. We will use a bi-polar annotation of all observed control situations noted as *OK* respectively as *KO*. Exploitation of this quality annotation allows first, to distinguish satisfactory control decisions from unsatisfactory ones, and secondly, to assess the overall quality of the official production control strategies. This appears as a meta-goal of the cognitive decision aid in the context of the CIRCUIT FOIL production control problem

This concludes the historical description of the control decision making at CIRCUIT FOIL . If the empirical observation of the decision making process allowed us to verify the pertinence of the apparent information gathered in the COMAPS database, we still have to verify that from a model theoretic point of view, the information, gathered in the COMAPS database, indeed allows to relate an extensional description of a decision expertise with given intentional decision strategies. In other terms, is it possible to reflect, in the COMAPS database, the underlying official production control rules? This is the formal problem we tackle in the following section.

4.3 Towards a comprehension of the control expertise

> "... *In any field of study not yet reduced (or elevated) to the status of a genuine science, thought remains the captive of the linguistic mode in which it seeks to grasp the outline of objects inhabiting its field of perception.*" Metahistory (White, 1973) .

In this section we first present an abstract model of an extensional control expertise[9]. In a second step, we show how to construct an intentional description of this control expertise. A third subsection will show how to make consistent in practice such an intentional control representation. Finally, a last one introduces the most important distinction we discover between context switching and effectively discriminating decision attributes.

4.3.1 From a control history to a control reference

In order to properly formulate a given control decision practice, we must first introduce some abstract terminology.

Definition 4.3.1 (control history).
The process is described by a finite set $\mathbf{X} = \{X_1, X_2, \ldots, X_i, \ldots, X_n\}$ of *decision attributes* (*environment parameters*, *process state parameters* as well as *production control parameters*), to which correspond possibles value ranges $V^X = \Pi_i V_{X_i}$. We call the couple $(\mathbf{X}, V^X)$ the attribute spectrum of the decision problem. On the basis of the values taken by these parameters, the decision maker proposes *control decision actions* which consist in differential settings of the previously introduced production control parameters. These decision actions are represented by a finite set $\mathbf{Y} = \{Y_1, Y_2, \ldots, Y_j, \ldots, Y_m\}$, with corresponding possible value ranges $V^Y = \Pi_j V_{Y_j}$. The set $V^X \times V^Y$ represents all potential control decisions we may formulate with the given attribute spectrum V^X and the given potential decision actions V^Y. A *historic control situation* h is then defined by the relation $(id\#, date, x, y)$ where *id#* represents the identifier of the product concerned, *date* indicates the date of observation and x, respectively y, represents the values observed on the attribute spectrum, respectively the corresponding decision action. A *control history* $\mathcal{H}$ denotes a historic set of observed factual control situations. Each control situation $h \in \mathcal{H}$ is uniquely identified by its date and the identification number of the product concerned.

The COMAPS database presented in the previous section is our natural instance of a control history. Such a database covers the factual decision practice over a given period determined by the date of the individual control situations contained in the

[9]This section as well as the next one represent two original contributions of ours to the COMAPS project (Bisdorff, 1997b,c).

history. We have seen in the previous Section, that not all recorded factual control situations represent actually a satisfactory control practice from a control quality point of view. Control errors may be observed in the decision making as well as in the measures of the decision attributes X for instance. Very rare and special control situations may appear that have no degree of generality. Weak or even bad control practice might be observed during weekends, for instance, when the usual control expertise is not available. Furthermore, not all recorded control situations may be of the same decision making type. Indeed, in the COMAPS database we have to distinguish those control situations starting a new product type on a given machine from those where a same product type as the previous is being produced. In the COMAPS project we were only interested in the second type of control decision. Finally, the control history may cover a long period, several years as it is actually the case in the COMAPS database for instance, and thus spawn some essential technical revisions of the production process. Early control situations might thus have become obsolete with respect to the present official control instructions. A first step towards a comprehension of the control expertise, existing a certain moment in time, therefore, consists in extracting from a factual control history a qualified subset of control situations we shall call the *control reference* in the sequel.

Definition 4.3.2 (control reference).
The quality judgment made by the decision maker upon a given control situation is represented by a parameter Q taking values in a range $V_Q = \{ok, ko\}$. The set Ω of *expressible qualified control decisions* is now given by the Cartesian product $V^X \times V^Y \times V_Q$.

We call $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V_Y, Q, V^Q)$ our *abstract universe of control discourse.* A *reference control decision* is given by a triplet $p = (\mathbf{x}, \mathbf{y}, q) \in \Omega$ where $\mathbf{x} = (x_1, x_2, ..., x_n)$ represents a given vector of decision attributes, $\mathbf{y} = (y_1, y_2, ..., y_m)$ represents a vector of control decision actions and q represents the quality judgment associated with this control decision. A set $\mathcal{R}$ of reference control decisions formulated in $\mathcal{M}$ is called a *control reference.*

As mentioned before, a control reference formally differs from the control history in the sense that it is ideally a *timeless* concept. In the control history each control situation h is a unique precisely dated event, showing a certain control decision. The recorded history thus archives the control practice over a given period of time. On the contrary, in a control reference, each reference control decision stands for an always topical instance of an *exemplary* control situation, a *good or bad practice case* in some sense. The reference control decision is supposed to *represent*, i.e. *make always present* in the mind of the decision maker, certain factual control situations implementing the given control decision. In this sense, the reference control decision exemplifies into present time a certain class of factual control situations as a recognized extensional instance of the official control theory. As each reference control decision is pointing to generally multiple, real factual (dated), control situations, it might be weighted with respect to its relevance for the presently applicable control theory in proportion to its distance from the actual present of the control practice. Reference control decisions supported by recent factual control situations tend to be more relevant for illustrating the present control expertise than those supported by much earlier factual control situations.

As exposed in the former section, the formal description of a control history and reference is based on a behavioural observation of the real control decision practice. To this description naturally belongs, as mentioned in the CIRCUIT FOIL process description above (see section 4.2.3 on page 103), the actual control decision actions (for instance changing or not some control settings). The a posteriori *quality assessment* of a given control situation allows to assess the quality (Q) of the subset control decision actions (Y) w.r.t. the given process description as described by the set of decision attributes (X) of the shown control decision. In the case of the CIRCUIT FOIL control problem, these quality assessments are in principle easy to deduce from the empirically observed dynamic behaviour of the system following a given real setting of the control variables. It thus appears that the COMAPS approach to cognitive decision aid is in fact anchored on two different levels: (1) A first (normal) level concerning the empiric observation of a complete given control practice with all satisfactory but also unsatisfactory control situations; (2) And a second, more specialized level, where a qualified control practice (for instance all satisfactory control situations) is contextually isolated and analyzed w.r.t. to the apparent control strategies the decision practice is showing[10].

To illustrate the concept of control reference, let us consider in Table 4.4 on the facing page a small didactic example. In this short control history $\mathcal{H}$, the attribute spectrum is given:

- First, by two observable process state parameters denoted as X_1 and X_2 associated with their first differences from date $t-1$ to t, denoted $\Delta_t^{t-1}(X_1)$ and $\Delta_t^{t-1}(X_2)$ respectively;

- And secondly, a tunable process control parameter, denoted X_c.

The control decision parameter $Y = X^c_{t+1} - X^c_t$ is given as the first difference between dates $t+1$ and t of this tunable process parameter X^c. A two-fold quality judgment ($\{ok, ko\}$) is shown in the last column. This indicator is depending on the values taken by the process state parameters X_1 and X_2 at time $t+1$. Following some hypothetical

[10]This double level approach was heavily debated by the research partners in the COMAPS project. The more mathematical psychology oriented approach promoted by Jean-Pierre Barthélemy considered the qualified control situation approach too much machine learning and artificial intelligence oriented. We shall come back extensively in the third part of our work on the different epistemological arguments underlying both Barthélemy's and our approach to the COMAPS decision aid paradigm.

#	X_1	$\Delta_t^{t-1}(X_1)$	X_2	$\Delta_t^{t-1}(X_2)$	X_c	Y	Q
01	65	0	64	0	23	-3	*ok*
02	61	-4	61	-3	20	0	*ok*
03	61	0	60	-1	20	0	*ok*
04	60	-1	60	0	20	0	*ok*
05	*60*	*0*	*60*	*0*	*10*	*0*	*ignore*
06	61	+1	61	+1	20	+1	*ko*
07	60	-1	62	+1	21	+3	*ko*
08	64	+3	64	+2	24	-4	*ko*
09	60	-4	59	-5	20	+1	*ko*
10	62	+2	64	+5	21	-1	*ko*

Table 4.4: Example of hypothetical control history $\mathcal{H}$

quality requirements, we suppose that X_1 and X_2 must both together be confined to the same range $[60, 61]$.

Furthermore, we may notice the presence of an *ignored* qualified control situation (see record #05 in Table 4.4). This decision is supposed to be ignored in our attempt to comprehend/explain the underlying apparent control theory.

It is also important to notice here that from such a given control history, not only exemplary *ok* qualified control situations, but also exemplary *ko*-qualified control situations may be considered for the control reference. The concept of control reference is thus not restricted to represent solely optimal or at least satisfactory control practices but also, and perhaps more necessarily, from the quality manager's point of view, problematic control practices as shown in Table 4.4 above.

Finally, the constructive step from a control history towards a control reference represents the first step in our effort to construct a formal model of an apparent control theory underlying the decision making illustrated by a given control history. In fact, the control reference represents the *extensional* representation of a given control expertise. We shall now try to uncover the associated *comprehensional* or *intentional* representation of it.

4.3.2 Intentional models of the decision expertise

In the previous section, concerned with the archive of past control situations, we have introduced official control rules or instructions that guide the CIRCUIT FOIL control practice. We shall now define, on the basis of a given universe of control discourse, a constructive formalism for generating such formal expressions called *control rule sentences* denoting a possible expert knowledge apparently underlying the decision maker's control expertise.

$$
\begin{array}{lcl}
S & \rightarrow & (\text{if } E \text{ then } C) \text{ is } Q \\
E & \rightarrow & (E) \mid E \wedge E \mid E \vee E \mid A \\
A & \rightarrow & X_i = x_i \mid X_i \in [x_i^m, x_i^M] \\
C & \rightarrow & Y = \mathbf{y} \\
Q & \rightarrow & q
\end{array}
$$

Table 4.5: Grammar for generating well-formulated control rule sentences

Definition 4.3.3 (control rules).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our abstract universe of control discourse. We formally define a *control rule sentence* S on $\mathcal{M}$ with the help of the grammar shown in Table 4.5. The set $\{S, E, A, C, Q\}$ represents the non-terminal symbols of the grammar.

To each non-terminal symbol corresponds a specific production rule (see Table 4.5). The first rule defines the axiom of the grammar, i.e the overall syntactic structure and components of a sentence S. The non-terminal E stands for a possibly bracketed *expression*, a conjunction or a disjunction of expressions concerning the attribute spectrum of the control decision. The non-terminal A for his part stands for what we call an *aspect* of the control. Such an aspect is either defined by a single value ($X_i = x_i$) or by an interval range ($[x_i^m, x_i^M]$), delimited by a minimum value x_i^m and a maximum value x_i^M. If a control rule sentence S does not contain any disjunctive expression, we call it an *elementary* control rule.

The E part of a sentence S is also called the *premise* of the expressed control rule. The set of aspects contained in the premise is denoted A_S. The C part of the sentence S is called the *conclusion* of the rule. For short we denote generally an elementary rule sentence as $S = (A_S, \mathbf{y}_S, q_S)$. We denote $\mathcal{S}$ the set of all well formed finite control rule sentences we may construct in a given universe of discourse $\mathcal{M}$.

We may illustrate this definition with the help of the following example. The sentence "(*if* $(X_1 = 60) \wedge (X_2 = 60)$ *then* $Y = 0$) *is ok*" expresses an elementary *ok*-qualified control rule in the universe of discourse underlying the control reference shown in Table 4.4 on the page before above. The premise of this rule combines two aspects, $(X_1 = 60 \wedge X_2 = 60)$ with the conclusion $(Y = 0)$. We may gather all such *ok*-qualified control rules concerning the $(Y = 0)$ decision action to form a large disjunctive control rule sentence. In the case of ordinal or continuous attributes, we may also express premises with aspects showing interval ranges. A natural example of such control rule sentences is given by the official CIRCUIT FOIL control rules we have introduced in the previous Section (see Expression 4.1 on page 109). The corresponding rule sentence would be:

$$\big(\text{ if } \quad (X_1 \in [50.0, 65.0]) \wedge (X_7 \in [7.5, 10.0]) \quad \text{then} \quad \mathbf{Y} =< 0, 0 > \big) \quad \text{is} \quad ok.$$

If we gather a set of such control sentences we obtain what we call a *control theory*.

Definition 4.3.4 (control theory).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse. A set $\mathcal{T}$ of *ok*-qualified control rule sentences, well-formulated in $\mathcal{M}$ with the help of Grammar 4.5 on the preceding page is called a *control theory* on $\mathcal{R}$.

A control theory $\mathcal{T}$ represents, from the cognitive point of view, an intentional description of the decision maker's satisfactory control practice.

Example 4.3.5 (The canonical control theory $\mathcal{T}_\mathcal{R}$).
A special and important example of such a control theory is given by a set $\mathcal{T}_\mathcal{R}$ of elementary control rule sentences, canonically rewriting the *ok*-qualified reference control decisions observed in a given $\mathcal{R}$. Indeed, every reference control decision $p = (\mathbf{x}, \mathbf{y}, ok) \in \Omega$ with $\mathbf{x} = (x_1, \ldots, x_n)$ may be rewritten as "(*if* $(X_1 = x_1) \wedge \ldots \wedge (X_n = x_n)$ *then* $Y = \mathbf{y}$) *is ok*".

Let us now investigate the formal link we may install between a control theory $\mathcal{T}$ and a given control reference $\mathcal{R}$ (see Figure 4.3).

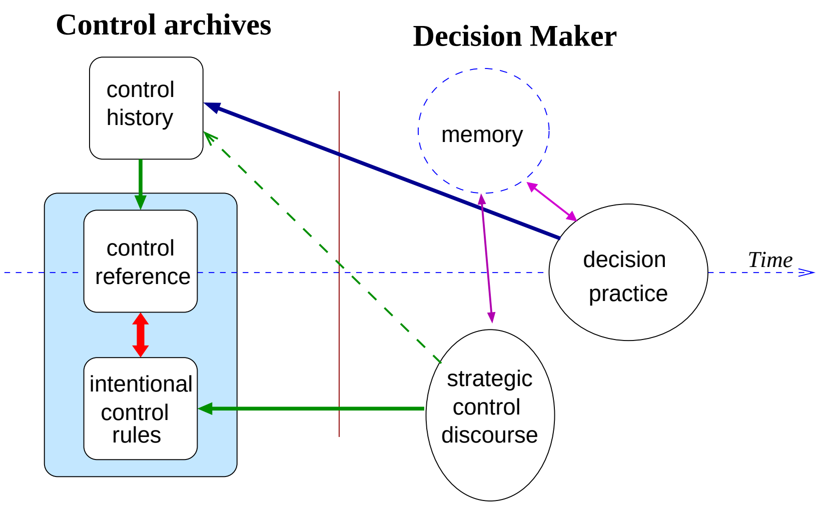

Figure 4.3: Apparent models of a same control expertise
(see Figure 2.3 on Page 37)

It follows from Definition 4.5 on the preceding page that both the observed control reference, as well as the uttered intentional control rules, represent apparent formal models of the same control expertise[11]. Naturally, there exists a strong double bind between both models. The control reference represents the extensional representation, i.e. the qualified cased based representation, of the control expertise, whereas the rules represent the strategic discourse the experienced controller addresses to his working colleagues and supervisors. From a cognitive point of view both expressions will show a natural divergence in the sense that the first will be systematically *parsimonious* and the second systematically *over-generalized*. It is one of the major goals of our cognitive decision aid to try to match, as tight as possible, both models.

In order to do so, we have to investigate to what extent, the control reference we observe on the CIRCUIT FOIL control history, reflects effectively these official CIRCUIT FOIL control rules. The following formal constructions will help clarify how the official control rules model the control decision practice.

Definition 4.3.6 (model relation).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse. Let $\mathcal{R} \subseteq \Omega = V^X \times V^Y \times V^Q$ be a control reference defined in $\mathcal{M}$ and let $S = (A_S, y_S, q_s) \in \mathcal{S}$ be a well-formed, elementary control rule sentence expressed in $\mathcal{M}$.

The fact that S *models* a certain reference control decision $p = (\mathbf{x}, \mathbf{y}, q) \in \mathcal{R}$ with $\mathbf{x} = (x_1, \ldots, x_i, \ldots, x_n)$ is denoted as $S \vdash p$ and means that $\forall i = 1 \ldots n$ either $(X_i^s = x_i^s) \in A_S : x_i^s = x_i$ or $(X_i^s = [x_i^m, x_i^M]) \in A_S : x_i \in [x_i^m, x_i^M]$. If, furthermore, $(\mathbf{y}_S = \mathbf{y}) \wedge (q_S = q)$, we say that S *correctly models* p, a fact we denote as $S \models p$. Let $\mathcal{T}$ be a control theory formulated in $\mathcal{M}$ modelling the given control reference $\mathcal{R}$. We call the inverse correctly modelling relation from $\mathcal{R}$ to $\mathcal{T}$ the *rule supporting* relation.

We may illustrate this definition with the help of the previous example concerning the control reference shown in Table 4.6.

#	X_1	$\Delta_t^{t-1}(X_1)$	X_2	$\Delta_t^{t-1}(X_2)$	X_c	Y	Q
01	65	0	64	0	23	-3	*ok*
02	61	-4	61	-3	20	0	*ok*
03	61	0	60	-1	20	0	*ok*
04	60	-1	60	0	20	0	*ok*
05	61	+1	61	+1	20	+1	*ko*
06	60	-1	62	+1	21	+3	*ko*
07	64	+4	64	+2	24	-3	*ko*
08	60	-4	59	-5	20	+1	*ko*
09	62	+2	64	+5	21	-1	*ko*

Table 4.6: Example of hypothetical control reference $\mathcal{R}$

[11]Both models, the control reference as well as the intentional control rules represent a mimic implementation of the apparent control expertise, as discussed in Part **A** (see 2.2.2 on page 37).

The elementary control rule:

$$\big(\ \textit{if}\quad (X_1 \in [60,62]) \wedge (X_2 \in [60,62]) \quad \textit{then}\quad Y = 0\ \big)\quad \textit{is}\quad \textit{ok} \tag{4.2}$$

models the reference control decisions #02, #03, #04, #05 and #06, but only the first three control decisions are correctly modelled. Conversely, only the first three control situations support control rule 4.2.

Consider now for instance the following control rule:

$$\big(\ \textit{if}\quad (X_1 \in [64,65]) \wedge (X_2 = 64) \quad \textit{then}\quad Y = -3\ \big)\quad \textit{is}\quad \textit{ok} \tag{4.3}$$

that models both situations #01 and #07. Rule 4.3 correctly models situation #01, but at the same time appears '*contradictory*' with respect to reference situation #07, where the same decision action $Y = -3$ is in fact qualified as being *ko*. To be able now to evaluate the control rule sentences, in this sense, and with respect to a given control reference, we introduce the following *soundness* property.

Definition 4.3.7 (sound control theory).
An elementary control rule sentence $S = (A_S, y_S, q_S)$ is called *sound* w.r.t. a given control reference $\mathcal{R}$ iff there do not exist $p, p' \in \mathcal{R}$ with $p = (x, y, q)$, $p' = (x', y', q')$ and $(S \models p) \wedge (S \vdash p')$ such that $\big((y = y') \wedge (q \neq q')\big)$. A control theory $\mathcal{T}$ is called *sound* w.r.t. $\mathcal{R}$ iff all elementary sentences $S \in \mathcal{T}$ are sound w.r.t $\mathcal{R}$.

A rule sentence is sound if it qualifies in the same way all its models of reference control decisions recommending the same decision action. Definitely *unsound*, however, appears a rule sentence, which models different reference control decisions recommending a same decision action, but differently qualified in the control reference.

As an illustration of a sound rule sentence, let us reconsider the control reference shown in Table 4.6 on the facing page. Consider now the control rule:

$$\big(\ \textit{if}\quad (X_1 = 65) \wedge (X_2 = 64) \quad \textit{then}\quad Y = -3\ \big)\quad \textit{is}\quad \textit{ok}.$$

This time the contradictory case #07 (see Table 4.6 on the preceding page) is excluded and the sentence is, therefore, sound w.r.t. the given control reference.

The soundness condition allows to formulate a first requirement concerning the elaboration of a control reference from a recorded control history.

Working Hypothesis 4.3.8 (Sound control reference).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse. Let $\mathcal{R} \subseteq \Omega = V^X \times V^Y \times V^Q$ be a control reference defined in $\mathcal{M}$. The canonical control theory $\mathcal{T}_\mathcal{R}$ (see Example 4.3.5 on page 115) associated with the *ok*-qualified part of $\mathcal{R}$ is assumed to be sound. For short, we will say in this case that *the control reference is sound.*

We impose on the construction of the control reference that the resulting subset of exemplary *ok*-qualified control reference decisions delivers a canonical control theory $\mathcal{T}_{\mathcal{R}}$ that is sound. In other words, the same control decision in terms of considered decision aspects with its associated decision actions must not be multiply qualified.

In the case of the control reference shown in Table 4.6 on page 116, we have seen, besides a set of *ok*-qualified control situations, also a set of ko-qualified sentences that we could consider as the expression of a *negative* control theory, some kind of *anti*-control theory pointing to an exemplarily bad control practice. It is worthwhile noticing that this *anti*-theory is not formally symmetric to the concept we established under the term control theory. Indeed, what becomes evident, if one tries to associate a control theory with its mirrored anti-theory, is that on the one side, a *positive* control theory, has to satisfy some kind of *sobriety* condition in order to be operationally performing. In each control situation to be mastered, there should ideally exist a unique optimal or at least satisfactory control decision action to be recommended to the decision maker. On the other side, however, in a given control situation, there might well exist several known control decision actions that will result without any doubt in a bad control of the process. From a general descriptive point of view, such *uniqueness* of the good control action has no necessity. But from a *prescriptive* point of view, this *sobriety* condition makes operationally sense[12].

Definition 4.3.9 (sober control theory).
An elementary control rule sentence $S = (A_S, y_S, ok)$ is called *sober* w.r.t. a given control reference $\mathcal{R}$ iff there do not exist $p, p' \in \mathcal{R}$ with $p = (x, y, ok)$, $p' = (x', y', ok)$ and $(S \models p) \wedge (S \vdash p')$ such that $(y \neq y')$. A control theory $\mathcal{T}$ is called *sober* w.r.t. $\mathcal{R}$ iff all elementary sentences $S \in \mathcal{T}$ are sober w.r.t $\mathcal{R}$.

The sobriety property does not admit, for a same *ok* qualifying control rule sentence, models of control decisions which recommend different decision actions. We may illustrate the soberness property with the control reference shown in Table 4.7 on the facing page. The following control rule for instance:

$$\big(\ \textit{if} \quad (X_1 = 60) \wedge (X_2 = 60) \quad \textit{then} \quad Y = 0\ \big) \quad \textit{is} \quad \textit{ok} \tag{4.4}$$

is not sober w.r.t. to this control reference in the sense that the rule sentence in fact

[12]The importance of this discussion on the operational design of the decision aid may not be underestimated. In the COMAPS project, a prescriptive point of view was implicitly taken and strongly defended by the Brestian team. Indeed, as will become evident later on, all artificial control theory constructions envisaged require at least some sobriety axiom to give adequate methodology and results. It is interesting to notice afterwards, that the COMAPS team did not recognize this implicit methodological requirement the time being, a situation probably resulting from the Brestian objection to properly investigate the cognitive relationship between an observed control history and a necessarily qualified control reference underlying the construction of any control theory, will it be a *natural* or an *artificial* one. We shall come back on this point in the last part of our work when discussing practical validation issues of the COMAPS project's results.

#	X_1	$\Delta_t^{t-1}(X_1)$	X_2	$\Delta_t^{t-1}(X_2)$	X_c	Y	Q
01	60	-1	60	0	20	0	*ok*
02	60	-4	60	-5	20	+1	*ok*
...							
03	61	+1	61	+1	20	+1	*ko*
04	60	-1	62	+1	21	+3	*ko*
...							

Table 4.7: Example of hypothetical control reference $\mathcal{R}$

models two reference control situations, namely #01 and #02, that recommend two different decision actions, respectively $Y = 0$ and $Y = +1$.

It is worth noticing that, contrary to the soundness property which concerns all rule sentences however qualified, the sobriety property is supposed to hold only for *ok*-qualified rule sentences. It is indeed considered normal that multiple decision actions might well be known in similar control situations that lead certainly to a *ko* qualification. Considering that we aim normally at realizing, if possible, *ok* qualified control situations, the sobriety condition guarantees, that there exist in the control reference for similar or even identical control situations, only one unique decision action that will lead to such an *ok* qualification.

The soberness condition allows us, thereby, to introduce a second working hypothesis concerning the ideal control reference.

Working Hypothesis 4.3.10 (Sober control reference).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse. Let $\mathcal{R} \subseteq \Omega = V^X \times V^Y \times V^Q$ be a control reference defined in $\mathcal{M}$. The canonical control theory $\mathcal{T}_{\mathcal{R}}$ (see Example 4.3.5 on page 115) associated with $\mathcal{R}$ is assumed to be sober. For short, we shall say, in this case, that the *the control reference is sober*.

In practice, the soberness condition imposes on the construction of a control reference some kind of a *minimal principle*. To each premise E appearing in the control reference is associated a unique *ok*-qualified decision action $\mathbf{y}$.

Let us now introduce a further property that may characterize a control theory with respect to a given control reference.

Definition 4.3.11 (complete and consistent control theories).
Let $\mathcal{R}$ be a control reference and $\mathcal{T}$ a control theory.

1. $\mathcal{T}$ is called *complete on* $\mathcal{R}$ iff $\forall p \in \mathcal{R}, \exists$ at least one $S \in \mathcal{T}$ such that $S \vdash p$,

2. $\mathcal{T}$ is called *consistent w.r.t* $\mathcal{R}$ iff $\mathcal{T}$ is *sound* and *complete w.r.t* $\mathcal{R}$.

Following this definition, a control theory that is consistent with a given control reference, provides a set of elementary control rules that *completely* model this control reference in a *sound* (i.e. no conjointly *ok* and *ok* qualified reference situations) way.

It follows immediately from our definitions and working hypotheses that the canonical control theory $\mathcal{T}_{\mathcal{R}}$, simply rewriting the ideal control reference, renders a consistent and sober control theory with this reference. Here each control rule is supported by a single reference decision.

Following the principles of the Moving Basis Heuristic (see Section 2.3 on page 39) we are particularly interested in short and concise control rules involving the less possible aspects without resulting in potentially contradictory modelled reference control decisions. In logical terms, the shorter the control rule in terms of involved aspects, the greater the abductive power of the rule, but also, the more we risk that the rule models contradictory qualified reference control situations. We, therefore, want to maximize the abductive power of a control rule without introducing *unsound* control decisions. To formulate this abductive power of a control theory, we extend the model relation (see Definition 4.3.6 on page 116) to all potential control situations that might be formulated in a given universe $\mathcal{M}$.

Definition 4.3.12 ($\mathcal{T}$-labelling of potential control situations).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse. Let $\mathcal{T}$ be a control theory and $\mathcal{R}$ a given consistent and sober control reference. We denote $\Omega_{/\mathcal{R}}$ the set of all potential control situations we may formulate besides the given control reference on the basis of our universe of discourse M, i.e. $\Omega_{/\mathcal{R}} = \Omega - \mathcal{R}$. We naturally extend the model relation of Definition 4.3.6 on page 116 to all possible situations, i.e. $\vdash \subseteq \mathcal{T} \times \Omega$.

We call *$\mathcal{T}$-labelling* the procedure which associates with each potential control situation $p = (x, y_p, Q) \in \Omega_{/\mathcal{R}}$ the set $Q = \{y_i / i = 1 \ldots n\}$ of *ok*-qualified rule conclusions, i.e. decision actions that are recommended by each $S_i = (A_i, y_i, ok) \in \mathcal{T}$ such that $S_i \vdash p$.

For a given control theory $\mathcal{T}$, the corresponding $\mathcal{T}$-labelling gives only a partial labelling of $\Omega_{/\mathcal{R}}$. The more potential control situations are thus labelled the more general the control theory will be.

On the one side, a most general and trivial theory would consist for instance in labelling all potential control situations with "<*do nothing*> is *ok*", but this '*lazy*' theory with maximum abductive power, cannot be consistent w.r.t. any non-trivial consistent and sober control reference that contains not only *do nothing* and *ok* qualified control decisions.

On the other side, the canonical control theory $\mathcal{T}_{\mathcal{R}}$, directly rewriting the given control reference (see Example 4.3.5 on page 115), gives an empty $\mathcal{T}$-labelling as it does not allow any labelling of potential control situation outside the exemplary control reference. This '*initial*' theory, with zero abductive power, is therefore essentially anecdotal and allows no generalization of the control practice outside the given control reference.

To discuss more thoroughly the abductive power of a given control theory we need following cover relation.

Definition 4.3.13 (cover relation).
Let Ω be the set of all control decisions we may possibly formulate on the basis of our universe of discourse M. Let $\mathcal{T}$ be a given control theory. We denote $\Omega_{/S} = \{p \in \Omega : S \vdash p\}$, the set of all control decisions potentially modelled by a given elementary rule sentence $S \in \mathcal{T}$. Let $S, S' \in \mathcal{T}$ be two elementary rule sentences. We say that S *covers* S', denoted as $S \sqsubseteq S'$ iff $\Omega_{/S} \supseteq \Omega_{/S'}$. Let $\mathcal{T}$ and $\mathcal{T}'$ be two control theories. By simple extension, we say that theory $\mathcal{T}$ *covers* theory $\mathcal{T}'$, denoted as $\mathcal{T} \sqsubseteq \mathcal{T}'$ iff $\forall$ elementary $S' \in \mathcal{T}'$, $\exists S \in \mathcal{T}$ such that $S \sqsubseteq S'$.

Proposition 4.3.1. *Let $\mathcal{R}$ be a given consistent and sober control reference and let $\mathbb{T}^{\mathcal{R}}$ be the set of all possible consistent and sober control theories we may formulate w.r.t. $\mathcal{R}$. The '$\sqsubseteq$' relation gives a partial order on $\mathbb{T}_{\mathcal{R}}$ with the canonical $\mathcal{T}_{\mathcal{R}}$ theory as bottom element.*

Proof. Indeed, reflexivity, antisymmetry and transitivity properties of the '$\sqsubseteq$' relation easily follow from the definition of the covering relation. Furthermore, $\mathcal{T}_{\mathcal{R}}$, the canonical rewriting of the control reference, consistently and soberly covers by definition exactly the *ok*-qualified part of the control reference $\mathcal{R}$, a part that is anyway covered by every possible consistent and sober control theory w.r.t $\mathcal{R}$. □

It is important to notice that the soberness of the control theory with respect to a given control reference does not in general imply that the theory be sober on the set of potential control decisions Ω. To formally express this condition let us introduce '*determinism*', a further property of control theories.

Definition 4.3.14 (Deterministic control theories).
Let $\mathcal{T}$ be a control theory defined on a given universe of control discourse $\mathcal{M}$. Let Ω define all expressible control situations in $\mathcal{M}$.

1. $\mathcal{T}$ is called *deterministic* iff $\forall p \in \Omega, \exists$ at most one elementary rule sentence $S \in \mathcal{T}$ such that $S \vdash p$.

2. $\mathcal{T}$ is called *prescriptive* iff $\mathcal{T}$ is *consistent and sober on* the control reference as well as *complete* and *deterministic* on Ω .

A control theory is *deterministic* if each potential control situation may be handled by at most one elementary rule sentence. If the control theory is furthermore complete on Ω, as well as consistent and sober w.r.t. such a control reference $\mathcal{R}$, we obtain a *prescriptive* theory $\mathcal{T}$ that gives a consistent $\mathcal{T}$-labelling function. To each potential control situation is associated a unique decision recommendation that is consistent with the underlying control reference.

Before going on now in our theoretical exploration of control theories, let us briefly come back to the COMAPS project and the CIRCUIT FOIL production control problem.

4.3.3 Intentional versus observed control reference

We have seen in the previous case study (see Chapter 3) an application of Operations Hermeneutics in order to uncover a given scheduling expertise. Some similar approach (see Figure 4.4) is used here in the COMAPS project in order to check the consistency of the official control rules with respect to the objectively recorded and qualified control history[13].

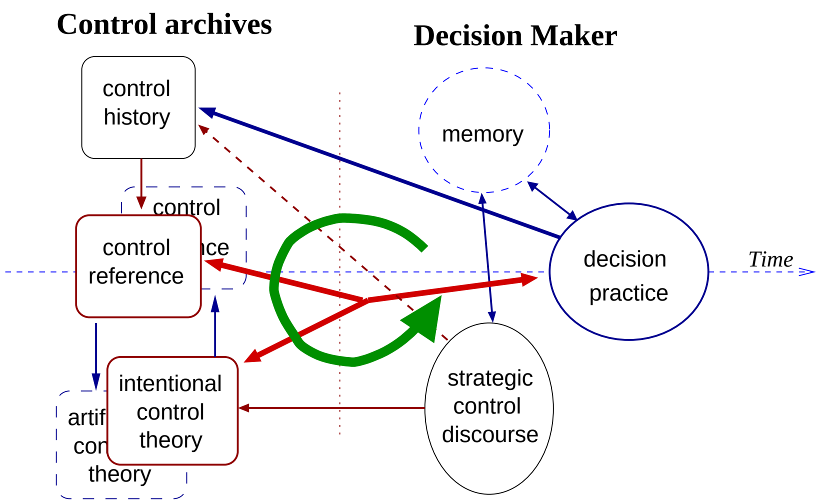

Figure 4.4: Validating hermeneutical circle

(see Figure 2.3 on Page 37)

In a previous Section 4.2.5 on page 106, we have seen that at CIRCUIT FOIL the control practice officially follows production control instructions which precisely represent control rule sentences formulated in the CIRCUIT FOIL universe of control discourse. On the basis of the CIRCUIT FOIL control history available in the COMAPS database, the R&D engineer may now construct a specific CIRCUIT FOIL control reference $\mathcal{R}_{CF}$. Following our methodological approach explained in the SYSCOG project, we install two opposed formal checks:

[13] At CIRCUIT FOIL and at the German TEXTAR site, this confrontation reserved some surprises both to the production managers and the quality control responsible. The control practice really observed was by far not completely compliant with the official production control rules, a fact initially either contested or ignored.

- A first check, working on the level of the control reference concept, i.e on a case-based level, tries to match the official control theory with the observed control practice via the qualified control reference emerging from the COMAPS database. This procedure allows to qualify the official control theory with respect to our formal properties announced above. We compare the apparent control reference, objectively constructed from the recorded control history, with a hypothetical control reference, as it should result in the case we would observe a strict compliance with the official control rules (see Figure 4.4 on the facing page);

- A second check, working this time on a theoretical level, tries to match an artificial control theory computed from the observed control reference with the given official control theory. In this case, the discussion is control rule sentence oriented (see Figure 4.4 on the preceding page).

Turning our attention to the first of both formal tests presented above, interesting practical questions may now be asked, such as:

- Is it possible to construct a sound, and possibly sober, control reference $\mathcal{R}_{\mathrm{CF}}$ from the daily recorded control practice?

- Do the official control instructions give a control theory $\mathcal{T}_{\mathrm{CF}}$ that is consistent and complete with respect to the observed control reference $\mathcal{R}_{\mathrm{CF}}$, i.e. do they consistently cover all reference control decisions as required by the ISO 9000 standard?

- Finally, is there a possibility that in practice the official CIRCUIT FOIL control rules might constitute a *prescriptive* control theory?

Similar questions appeared at TEXTAR, the German industrial participating in the COMAPS project. Unfortunately, the industrial reality showed in both cases, that none of these questions could be positively answered and the reasons for this were the following:

- In the ongoing control practice there naturally appear, at the limit of the ranges of the quality measuring parameters, some identical control situations that show alternatively *ok* and *ko* qualified *do nothing* decisions. Identically *ok* qualified control situations with alternative decisions may be systematically observed in the same context. These observations, rather rare but well understood and not at all based on irrational behaviour in the eyes of the control experts, directly violate, at least marginally, the soundness, as well as the soberness, property of the control reference[14].

[14] In the global COMAPS approach, this problem of the control theory is mastered by introducing priority relations between concurrent applicable control rules.

- Given the large spectrum of possibly appearing control situations in reality, it is not astonishing that the official control instructions cannot be a 100% complete. There will always exist some hopefully rare and exceptional control situations, on which it is unreasonable to spend an extensive amount of time in order to discover general control instructions. But there also appears a problem with the continuous detailed adaptation of the official control instructions to the ever changing technological environment in which the production control takes place. If the control reference would tend to a stable limit state, then naturally, the corresponding control theory would tend to be complete.

- Finally, due to the complexity of the industrial production processes to be controlled at CIRCUIT FOIL , it seems difficult, if not impossible or industrially irrelevant, to work on designing a general prescriptive control theory required by the implementation of a control automata. The physical and chemical properties of the electrolysis process are not well known enough from a technical engineering point of view to give access to a complete deterministic control theory[15]. Human control expertise is, therefore, essentially required in order to tackle all those critical control situations that are not easily covered by the general official control theory.

Considering the preceding points, it is clear that the intentional control theories we observe in the industrial practice cannot verify all formal properties required for a prescriptive control theory. Some parts of the rules obviously verify them, but it is unreasonable to expect to see these properties being satisfied in the whole. Despite this negative statement, we claim that, with an appropriate cognitive decision aid, it will be possible to move a given official control theory, such as the one we observed at CIRCUIT FOIL in the beginning of the COMAPS project, towards more and more formal prescriptiveness, or at least consistency. This may be achieved by a guarded decision making approach as promoted in the COMAPS project and which we will present in the last Section, i.e. Section 4.6 on page 143 of this Chapter.

Let us now turn our attention to the second kind of formal checks. We will now compare the official control rules with control rule sentences we may compute artificially from a the given control reference.

[15]It may seem interesting, and this depends on the necessary resources, to further investigate if nevertheless a deeper technological and engineering study of the electrolysis process could not result in such an automatic controller. But this issue was not at all in the scope of the COMAPS project. On the contrary, the COMAPS team wanted to develop generic human centred decision aid tools that can be implemented for various industrial control problems in which experienced human decision-maker have to operate.

4.4 Critical control expertise

In this Section we present in detail the critical part of our reconstruction of the CIRCUIT FOIL historical control practice[16]. We will introduce, in a restricted formalism, computational approaches for generating prescriptive and/or consistent control theories from a given ok-qualified control reference, as presented in the previous section. We close this section by discussing possible differences we may observe between such artificial control theories and the natural control theories we may observe on site.

4.4.1 Artificial control theories

Similar to the natural control theory we observe at CIRCUIT FOIL , artificial or automatically generated control theories may be computed on the basis of a given control reference[17]. Working here in a context of linguistic communication[18], we naturally favoured, for this purpose, machine learning algorithms which give results under rule form, interpretable by human experts. We mean machine learning algorithms in the close sense (Michie et al., 1994), decision tree algorithms like CAL5 (Müller, 1994), CART (Buntine and Caruana, 1991), C4.5 (Quinlan, 1993), ripple down methods like CUT95 (Scheffer, 1995) or rule extraction methods like CN2 (Clark and Niblett, 1989)). In the models of control expertise introduced above (see section 4.3.2 on page 113), all control strategies are defined by rule sentences. The control rules obtained by rule extraction methods correspond canonically to such rule sentences. Decision trees delivered by decision tree algorithms or ripple down methods, however, have to be transformed into such rule sentences. Each leaf of a decision tree delivers one elementary rule sentence and the disjunction of all rule sentences represents a prescriptive control theory. Prescriptiveness (see Definition 4.3.14 on page 121) refers here to the fact that all possible control decisions are uniquely classified by the decision tree.

Checking the formal properties of elementary rule sentences, requires that a given control reference $\mathcal{R}$ be available during the entire life cycle of the corresponding control theory. This means that the supporting relation between an elementary rule

[16]This Section is based again on original contributions of ours to the COMAPS project (Bisdorff, 1997b,c).

[17]This part is reusing material from a common article with W. Müller (Bisdorff and Müller, 1997). In the context of the COMAPS project, not all three industrial sites presented such official control rules as observed at the CIRCUIT FOIL plant. Therefore, it was provided an initialization phase consisting in computing automatically an intensional representation of the control expertise on the basis of a given control reference. The German research partner participating in the COMAPS project is a specialist of machine learning by using decision trees. W. Müller, the main researcher involved in our project, is the author of the decision tree algorithm CAL5 working with a continuous attribute spectrum (see Müller, 1994).

[18]Explicitly required by the ISO 9000 standard for quality control of the production process among other.

sentence and all its supporting reference control decisions has to be one of the outlets of the learning algorithm. Furthermore, using machine learning algorithms for the generation of artificial control theories raises the problem that the parameters of real production processes are mostly continuously valued, whereas our description language requires discretely valued parameters. In principle, all the machine learning algorithms mentioned above, when dealing with continuously valued parameters, automatically discretize them into intervals during the learning phase. The derived rules thus satisfy the restrictions according to the types of the process parameters. On the other hand, there are effective preprocessing techniques to split continuous parameter values into optimal sub intervals (see also Weiss et al., 1990) before the classification step starts. This allows optimal discretization of the range of continuous values adapted to the given learning data set.

In order to study the formal properties of the maximum entropy segmentation techniques compared to "natural" or cognitive control theories, as observed at Circuit Foil , we shall develop in the next subsection some formal algorithmic constructions. As our personal operational style is very logic-programming oriented, we will, therefore, restrict our attention to a class of control problems involving only discrete, not necessarily ordinal, attribute spaces. This restriction allows to, first, introduce a method for generating a most general prescriptive control theory and, secondly, to generalize this approach to the case of most general consistent theories, dropping the determinism of the control rules.

4.4.2 Computing prescriptive control theories

In the Comaps project, two decision tree extraction tools were implemented: (1) A classic maximum entropy segmentation method and (2) the CAL5 algorithm. As we will show here, both these methods construct prescriptive control theories,

Let $\mathcal{M} = (\mathbf{X}, \mathsf{V}^{\mathsf{X}}, \mathbf{Y}, \mathsf{V}^{\mathsf{Y}}, \mathsf{Q}, \mathsf{V}^{\mathsf{Q}})$ be a model for our universe of discourse. Let $\mathcal{R}_{\text{ok}} \subset \mathsf{V}^{\mathsf{X}} \times \mathsf{V}^{\mathsf{Y}} \times \{\text{ok}\}$ be an ok-qualified control reference defined in $\mathcal{M}$. We shall decompose $\mathcal{R}_{\text{ok}}$ with respect to the concerned decision actions $\mathbf{Y}$ in a tree form by the algorithm shown in Figure 4.5 on the next page.

To each leaf corresponds naturally an elementary ok-qualified control rule sentence, and the set of equally labelled leaves w.r.t. $\mathbf{Y}$ gives us a general disjunctive rule sentence. Thus, the leaves of out-coming Segtree($\mathcal{R}_{\text{ok}}$) provide us with a control theory which we shall denote $\mathcal{T}_{\text{Seg}}$ in the sequel.

The practical interest of the segmentation technique for generating control theories is pointed out by the following proposition.

Proposition 4.4.1. *The control theory $\mathcal{T}_{\text{Seg}}$, generated from a given control reference $\mathcal{R}_{\text{ok}}$ by the algorithm shown in Figure 4.5 on the facing page, gives a most general prescriptive control theory, i.e. a most general theory that is consistent*

Segtree($\mathcal{R}_{ok}$) $\leftarrow$ **segmentation**($\mathcal{R}_{ok}$)
  if | Image($\mathcal{R}_{ok}$) | < 2
    then output t($\mathcal{R}_{ok}$), [])
  else
    $X_i \leftarrow$ maximal discriminating attribute on $\mathcal{R}_{ok}$ w.r.t. $\mathbf{Y}$
    $\mathcal{R}(X_i)^{-1} \leftarrow$ inverse image subsets on $\mathcal{R}_{ok}$ through X_i
    for each $\mathcal{R}^i_j \in \mathcal{R}(A_i)^{-1}$
      Segtree($\mathcal{R}^i_j$) $\leftarrow$ **segmentation**($\mathcal{R}^i_j$)
    endfor
    output t($\mathcal{R}_{ok}$, [Segtree($\mathcal{R}^i_1$, Segtree($\mathcal{R}^i_2, \ldots,$)])
  endif
  endsegmentation

Figure 4.5: Classic segmentation algorithm

and sober w.r.t. $\mathcal{R}_{ok}$, as well as complete and deterministic on the set Ω of all potential control situations.

Proof. From the attribute segmentation algorithm described above it follows that each reference control decision $p \in \Omega$ may appear at most once in a leave of the segmentation tree, so that the computed theory is deterministic. Furthermore, for each leaf, the corresponding generated elementary rule S correctly models all reference control decisions equivalently labelled, so that the corresponding elementary rule is indeed sound and complete w.r.t to the control reference $\mathcal{R}_{ok}$ by construction. Finally, all ok-qualified reference control decisions are distributed among the leaves, so that every control decision is at least correctly modeled by a given rule, so that the theory is also sober w.r.t. $\mathcal{R}_{ok}$ and complete on Ω, again by construction.

In order to check that $\mathcal{T}_{Seg}$ is also most general, we must show that it is maximal w.r.t to the '$\sqsubseteq$' relation on the set of all possible complete prescriptive theories based on $\mathcal{R}_{ok}$. Consider that there exists a different prescriptive control theory $\mathcal{T}'$ on $\mathcal{R}_{ok}$, with $\mathcal{T}' \sqsubseteq \mathcal{T}$. It follows that there must exist at least one control decision $p \in \mathcal{R}_{ok}$ supporting an elementary sentence $S \in \mathcal{T}_{Seg}$ and another elementary sentence $S' \in \mathcal{T}'$ with $S' \sqsubset S$. This contradicts the stopping mechanism of the segmentation algorithm shown in Figure 4.5, in the sense that the given rule sentence S must be a leaf of the segmentation tree and therefore will be the first node on the tree that covers p and is uniquely labelled. □

A main drawback in the above segmentation approach consists in the necessity to fix once for all an importance ordering on the given attribute spectrum, in order to guarantee the determinism of the supporting relation. In our case, we introduced the maximum entropy principle for doing so. But this choice is difficult to justify from both cognitive and practical points of view and does not correspond clearly to the cognitive model of the decision maker the MBH approach[19] is promoting.

Moreover, the robustness of this importance ordering in a naturally continuously learning situation under changing environment is generally not given. The real control expertise underlying the control practice is certainly not tending asymptotically to a fixed ideal segmentation tree[20]. Therefore, we develop a generalization of this approach, relaxing the need for a deterministic control theory.

4.4.3 Generating a consistent control theory

Our approach is the following: First we may notice that it is possible to link the above defined covering relation between elementary rule sentences to a corresponding meet construction[21].

Proposition 4.4.2. *Let* $S \rightarrow$ *"if* E *then* $Y = \mathbf{y})$ *is* ok*" and* $S' \rightarrow$ *"(if* E' *then* $Y' = \mathbf{y}')$ *is* ok*" be two elementary rule sentences from a given control theory* $\mathcal{T}$*.*

$$S \sqsubseteq S' \Leftrightarrow E \wedge E' = E.$$

Proof. Let X stand for $(X_1 = \nu_1) \wedge \ldots \wedge (X_m = \nu_m)$ and X' for $(X'_1 = \nu'_1) \wedge \ldots \wedge (X'_m = \nu'_m)$. From S covering S' it follows that all situations modelled by S must also be modelled by S', so that S' must contain all aspects $(X_i = \nu_i)$ for $i = 1, \ldots, m$. Conversely, if $E \wedge E' = X$, S' must contain at least all aspects from S and therefore models at least all situation modelled by S. □

If we gather all observed situations identically labelled in terms of $\langle Y, \text{ok} \rangle$, in a disjunctive rule sentence, we may construct for each such label a large basic disjunctive rule sentence canonically rewriting the control reference.

In order to construct a most general theory upon these basic rule sentences, we shall try to find the smallest combinations of aspects we may extract from the given ok-qualified control reference that gives a sound and sober covering meet for one or more decisions w.r.t. the otherwise labelled reference control decisions.

Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for our universe of discourse and let $\mathcal{R}_{\text{ok}}$ be a given control history formulated in M. We shall denote $\wp(X)$ the power set construction on the given attribute spectrum X of dimension n and $X^i \in \wp(X)$ a given subset of dimension $i = 1, \ldots, n$. The combination of aspects involving the subset X^i of decision attributes are denoted A^i. Finally, A^i_p denotes the subset of aspects involving the subset X^i of attributes describing a given control decision $p \in \mathcal{R}$. The algorithm **mgtheory** proposed is shown in Figure 4.6 on the facing page.

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[19] See Section 2.3 on page 39.

[20] This issue we denote as the "*Galoisian*" property of the control expertise is discussed in some detail in Section 6.3 on page 192 in Chapter 6.

[21] See Definition 4.3.13 on page 121.

```
T_mg ← mgtheory(V^Y × V^Q, H, ℘(X)) :
        T_mg = ∅
        for y ∈ V^Y
            R_/y ← {p(_, Y, ok) ∈ R_ok | Y = y}
            R_/−y ← {p(_, Y, ok) ∈ R_ok | Y ≠ y}
            i ← 1
            A_y ← ∅
            while (i ≤ n) ∧ (R_/y ≠ ∅)
                for X^i ∈ ℘(X)
                    A^i_y ← ⋁_{p∈R_/y} A^i_p
                    A^i_−y ← ⋁_{p∈R_/−y} A^i_p
                    E^i_y ← A^i_y − A^i_−y
                    S^i_y ≡ "(if E^i_y then y) is ok "
                    R_/y ← R_/y − {p ∈ R_/y | S^i_y ⊢ p}
                    T_y ← T_y ∪ S^i_y
                endfor
                i ← i + 1
            endwhile
            T_mg ← T_mg ∪ T_y
        endfor
        return T_mg
        endmgtheory
```

Figure 4.6: Most general consistent theory algorithm

In order to illustrate the result of this algorithm, let us reconsider the example in Table 4.4 on page 113. In our ok-qualified control reference we find two control decisions: one *do nothing* $(Y = 0)$ and one for lowering the control variable by three units $(Y = -3)$. The most general consistent rule sentence concerning the last decision would be:

$$(\textit{ if } \big((X_1 = 65) \lor (X_3 = 64) \lor (X_5 = 23) \lor (X_5 = 2)\big) \quad \textit{then} \quad (Y = -3) \textit{ is } \mathrm{ok}.$$

Recall that the production rules (see 4.1 on page 109) require that the values observed for variables X_1 and X_3 must be confined both to the interval $[60, 61]$. Furthermore, it appears from the given control reference that high values observed for the control parameter X_5 coincide with too high values observed on variables X_1 and X_3, hence the necessity to introduce the above disjunctive control rule. Let us now show that this construction indeed renders a most general consistent control theory.

Proposition 4.4.3. *Let* $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ *be a model for an abstract universe of discourse and let* $\mathcal{R}_{ok}$ *be a given set of* ok*-qualified reference control* *decisions formulated in $\mathcal{M}$. The control theory $\mathcal{T}_{\mathrm{mg}}$, generated from $\mathcal{R}_{\mathrm{ok}}$ by the algorithm shown in Figure 4.6 on the page before, is consistent and most general. Furthermore, $\mathcal{T}_{\mathrm{mg}}$ is the only possible most general consistent theory computable on $\mathcal{R}_{\mathrm{ok}}$.*

Proof. First, it follows from the construction that no elementary rule sentence is selected that may model, on the given control reference, more than one decision action y. Thus all elementary rule sentences are necessarily sound and sober and the computed theory is consistent. For each observed decision action y, *all* ok-qualified reference decisions are considered and correctly modeled by at least one elementary rule sentence generated. At worst, the complete set of attributes is used to model canonically the reference control decision. This makes the proposed control theory necessarily complete w.r.t. $\mathcal{R}_{\mathrm{ok}}$.

That the computed theory is also most general is implied by the fact that we consider the possible covering combinations of control settings in increasing dimension, starting with singleton settings and finishing, eventually, with possible complete attribute specifications. Suppose that another most general consistent theory $\mathcal{T}'$ w.r.t $\mathcal{R}_{\mathrm{ok}}$ would exist with $\mathcal{T}' \sqsubset \mathcal{T}_{\mathrm{mg}}$. This would imply that $\exists$ at least an elementary rule sentence S' in $\mathcal{T}'$, such that $\exists S \in \mathcal{T}_{\mathrm{mg}} : S' \sqsubset S$. Now, this may only be the case, if S' is based on a less dimensioned combinations of attributes than S. But, in this case, the elementary rule sentence S' would have been included in theory $\mathcal{T}_{\mathrm{mg}}$ at some earlier step and the corresponding supporting reference decision(s) would have been eliminated from the current control reference to be considered, so that S would not appear in $\mathcal{T}_{\mathrm{mg}}$. The argument also implies that there exists a unique most general prescriptive theory on a given ok-qualified control reference. □

As we pointed out above, the most general consistent control theory necessarily covers all possible prescriptive theories.

Proposition 4.4.4. *Let $\mathcal{M} = (\mathbf{X}, V^{X}, \mathbf{Y}, V^{Y}, Q, V^{Q})$ be a model for an abstract universe of discourse and let $\mathcal{R}_{\mathrm{ok}}$ be a given set of ok-qualified reference control decisions formulated in $\mathcal{M}$. Let $\mathcal{T}_{\mathrm{mg}}$ be the most general consistent theory computed on $\mathcal{R}_{\mathrm{ok}}$. Any most general prescriptive theory $\mathcal{T}_{\mathrm{Seg}}$ generated with the help of the segmentation algorithm shown in Figure 4.5 on page 127 is covered by $\mathcal{T}_{\mathrm{mg}}$.*

Proof. Indeed, supposing that there exists a most general prescriptive theory $\mathcal{T}'$ not covered by $\mathcal{T}_{\mathrm{mg}}$, implies the same sort of contradiction as we have pointed out in the proof above. □

Following Proposition 4.4.4, the most general consistent control theory appears as the unique join of all possible sound and sober coverings one may define on a given control reference. In this sense our construction gives the maximum anti-chain in the

'$\sqsubseteq$' relation on the set of possible consistent theory constructions based on a given control reference. It covers, therefore, any possible outcome of a segmentation approach for generating prescriptive control control theories. Knowing this most general consistent control theory allows foro the exploration of the complete realm of potential of consistent and prescriptive control theories one may compute on a given control reference.

Analyzing the complexity of the most general consistent theory computation, one may notice that, apart from the severe restriction to only nominal attribute dimensions, the main difficulty remains in the fact that we have to, for a spectrum of dimension n, eventually inspect all combinations of attributes, that is the whole spectrum power set of dimension 2^n. For each set of equally dimensioned combinations of attributes, we have to consider several times the control reference $\mathcal{R}_{ok}$. And all this must be repeated for all possible decision action y. In practice, the dimension of the attribute spectrum will be very small compared to the generally given number m of reference control decisions, so that the algorithm may approach a polynomial complexity $\mathcal{O}(cm^k)$ with $c = 2^n$ and $k \pm 3$. Nonetheless, the space requirements outgrow rapidly and inevitably with a substantial control reference. The computational effort for constructing control theories is confronted here with the same complexity as the natural cognitive approach. In accordance with our cognitive approach to decision aid, it was, therefore, decided in the COMAPS project to restrict the outcome of our computations to control rule sentences containing at most four aspects[22].

Let us now present the methodological approach taken in the COMAPS project with respect to the practical computation of artificial control theories from a given control reference.

4.4.4 Reflecting the control reference on an artificial control theory

We may notice beforehand that, from an epistemological point of view, our most general consistent control theory cannot acquire any real certainty concerning the actual representation of the operator's control expertise, as would be expected by a "classic", objective scientific model. But in the narrow scope of a given observed history of control situations, "most general consistency" provides us with the necessary argument to pretend that our computed control theory gives a representation of apparent (or empirically observable) expert control strategies. Without the condition that this representation must be the true one, used by the expert in his actual control practice. Apart from empiric observation of effective qualified control situations, we have no direct formal access to the cognitive expertise of the human operator. The generated intentional formal discourse on this practice by our most general consistent control theory is naturally limited to an a posteriori linguistic formulation, taking its sense only in the more or less narrow scope of the observed control practice. In

[22] We shall come back to the motivations underlying this methodological requirements in Chapter 7.

this sense, the actual control practice always precedes apparent intentional control representations, with the all important consequence that it is only in the factual qualified control practice that there resides the real control expertise, not in the ad hoc formulated intentional control theories. But, nevertheless, an explicitly formulated most general consistent control theory on a given historic control practice allows one to speak and, therefore, to *cognitively reflect* upon this practice. In general, the genuine task of learning algorithms, such as our segmentation algorithm, is to generalize the set of pre-classified control situations (control reference $\mathcal{R}_{\mathrm{ok}}$) in such a way that every new incoming control situation can be classified with minimum error or cost.[23] However, the task corresponding to the generation of a cognitively satisfactory control theory is to find a set of possibly consistent elementary control rule sentences S which eventually delivers a complete theory.

Due to the methodological restriction of taking into account only short control rules with up to a maximum of four aspects, every classifier (e. g. one decision tree) provides a complete but not necessarily prescriptive or even consistent control theory in most cases. Therefore, a first approach to a construction of a prescriptive control theory proposes to generate a set of *contrasted* classifiers selecting a as large as possible set of sound and sober elementary rule sentence, even largely redundant ones. On the basis of this set we construct, finally, by using the covering mechanism defined in section 4.3 on page 110, a complete consistent control theory limited to control rule sentence containing at most four different aspects.

If it is impossible to generate a consistent control theory in this way, one may try to revise the control reference $\mathcal{R}_{\mathrm{ok}}$ by using conflict solving methods. There are two contradictory aims in formulating the most general consistent control theory, as proposed above. The theory must be both consistent and as general as possible. A possible measure of soundness with respect to a given generalization of a control strategy could be the misclassification rate of the classifier. In most real world cases one cannot directly compute a consistent control theory from a classifier produced by a machine learning algorithm. The main reasons for misclassification concerns generalization errors (e. g. axis parallel splitting of the state space), which means methodological lacks, or badly conditioned training data sets (control reference). The methodological deficiencies can be, on the one hand, more or less eliminated by using conjointly different machine learning algorithms. A badly conditioned control reference, on the other hand, will lead to unsound control strategies (overlapping of the class regions in the state space). Such a case may happen for the following reasons:

- A control situation is falsely qualified;
- The quality measure evolves during the collecting time of the control reference (training data set);

[23] This corresponds to a prediction task. We try to predict the class (a given decision action) in case a new control situation arises.

- There are outliers within the control reference due to measurement failures of a process parameter for instance; And/or

- there are hidden process parameters either not considered or not detectable (can not be measured or observed) leading to an implicit transformation of control situations, arranged in disjunct class regions, from a higher to a lower dimensioned state space. Thus the image of the control reference can apparently contain overlapping class regions.

The occurrence of such badly conditioned control situations within a given control reference cannot be automatically detected nor repaired. This operation demands the conscious intervention of a human expert controller.

In general, the more simplistic a control theory, the more effective it is (Parsimony Principle). Simplicity can be reached only by generalization, but often at the cost of a certain correctness (consistency). The acceptance of only partly correct or sound control strategies exclusively depends on the process itself and the expertise of its operators. Generally a sound control strategy of real world processes is required. This means that after computing the control strategy (generalization) the reasons for each misclassified reference control situation have to be detected and the misclassification has to be eventually repaired. Some misclassifications caused by methodological deficiencies can be automatically assessed. We reclassify incorrectly modeled control situations once more by using other machine learning algorithms. If the reclassification of the current misclassified control situations now delivers the correct result, the cause of the fault was a methodological deficiency, and an automatic updating of the control theory can be performed. The remaining incorrectly modeled reference control situations have to be tackled by conflict solving methods in explicit interaction with the human expert operators. This topic will be discussed in the last section of this chapter, but before, let us conclude the critical discussion of control theories with a contextual approach to the decision attribute spectrum.

4.5 On the importance of switching over context

We have noticed from the observation of the control practice that there appears a strong cognitive predominance of certain "*main*" decision parameters in the decision making process[24]. We try to investigate this issue more formally in the following pages[25]. In a first part, we will introduce a case study on switching over context taken from the color vision area. In a second section, we will study the formal aspects of switching over context and its effect on the computational difficulty of generating and maintaining a most general consistent control theory.

[24]See Table 4.3 on page 108.

[25]This part is based on a corresponding official COMAPS report (see Bisdorff, 1997a).

4.5.1 The colour vision example

In 1955, Edwin Land, a research worker at the Polaroid laboratory on color photography, discovered during his experiments on color pictures, that the human cognitive capacity allowed the reconstruction of a weakly, but completely colored image from a red filtered and black and white recorded slide and a normal black and white recorded slide of the same picture (Land, 1964).

This astonishing result hints towards the fact that the luminosity indication, recorded by the human eye at the same time as the classic three color attributes, is in some sense redundant to the latter. This redundancy would allow to reconstruct by complementarity, the missing complete color informations. We will identify this possible redundancy between attributes in our model with context information. This approach allows us to simplify, the case given, the computation of apparently underlying control theories. To illustrate this idea, we introduce a small example of a simple control reference[26] inspired by the human color vision system. Let us consider the following data:

Example 4.5.1 (The colour vision example). The attribute spectrum $\mathbf{X}$ is given by the following four attributes: $\{X_r, X_g, X_b, X_l\}$ of type: $V_i = \{0, 1, 2\}$ with $i \in \{r, g, b\}$ and $V_l = \{0, 1, 2, 3\}$. The decision parameter Y is of type $V_y = \{$black, red, yellow, green, blue, purple, turquoise, grey, white$\}$. The three first attribute dimensions may be seen as the classic RGB color channels (X_r = red, X_g = green and X_b = blue). The fourth attribute dimension (X_l) may be considered as a global luminosity or brightness indication. The color superposition is supposed to be *subtractive*, in the sense that all three color channel on minimum value give the color black and all three color channel on their maximum give white as outcome, red and green give yellow, red and blue give purple, and blue and green give turquoise, as is normal for a RGB 256 color device. The fourth attribute is in a nearly functional correspondence to the three color channels.

Supposed observed reference control decisions are listed in Table 4.8.

In this control reference we may notice, first, that all possible control settings for the three color defining attributes are exhaustively observed. If we limit our abstract universe of discourse to the three color attributes X_r, X_g and X_b, the resulting most general consistent control theory, shown in Table 4.9 on page 136, is canonically identical to the control reference (see Table 4.8 on the next page). No generalization is possible without introducing some unsoundness. In other words, the number of distinguished outcome qualities is so high, as compared to the possible control settings, that the complete set of possible aspects is necessary for a globally consistent colour classification.

[26] In order to simplify the notation, we shall assume here that the control reference is exclusively constituted of ok-qualified control decisions and drop the corresponding index.

#	X_r	X_g	X_b	X_l	Y
1	0	0	0	0	*black*
2	0	0	1	0	*blue*
3	0	0	2	1	*blue*
4	0	1	0	1	*green*
5	0	1	1	1	*turquoise*
6	0	1	2	1	*blue*
7	0	2	0	1	*green*
8	0	2	1	2	*green*
9	0	2	2	2	*turquoise*
10	1	0	0	1	*red*
11	1	0	1	1	*purple*
12	1	0	2	1	*blue*
13	1	1	0	2	*yellow*
14	1	1	1	2	*grey*
15	1	1	2	2	*blue*
16	1	2	0	2	*green*
17	1	2	1	2	*green*
18	1	2	2	2	*turquoise*
19	2	0	0	2	*red*
20	2	0	1	2	*red*
21	2	0	2	2	*purple*
22	2	1	0	2	*red*
23	2	1	1	3	*red*
24	2	1	2	3	*purple*
25	2	2	0	3	*yellow*
26	2	2	1	3	*yellow*
27	2	2	2	3	*white*

Table 4.8: Example of ok-qualified reference control decisions

If we enrich now the underlying universe of discourse, by considering in addition the global luminosity indicator, we observe a phenomena similar to that observed by Land (1964)[27], i.e. the most general consistent control theory will stay no longer canonically identical to the control reference. Some new short rule sentences actively involving the luminosity aspect appear, as may be seen in Table 4.10 on page 137.

Not all three colour aspects are necessary for successfully classifying the complete colour spectrum. The suddenly appearing cognitive simplification of certain rule sentences is a direct consequence of the redundancy between the additive values of the color attributes and the global subtractive luminosity indicator. As a matter of fact, the luminosity indication synthesizes some global information about the three individual color settings, so that, for a certain color quality, the luminosity and only one of the three color setting is sufficient to decide what must be the corresponding outcome

[27]If we define a functional relation, such as $X_l = 3X_g + 2X_g + X_b$, between the luminosity and the three color attributes, we obtain in fact a most general consistent and even prescriptive theory only containing pairs of aspects, such as the luminosity combined with one of the three colour attributes. The (luminosity, red colour attribute) combination renders in this case a sound classification of the nearly complete colour spectrum, especially for higher luminosity levels as observed by Land in his experiment.

$$
\begin{array}{ll}
\text{if } \big((X_r = 0) \wedge (X_g = 0) \wedge (X_b = 0)\big) & \text{then } (Y = \textit{black}). \\
\text{if } \big((X_r = 1) \wedge (X_g = 1) \wedge (X_b = 1)\big) & \text{then } (Y = \textit{grey}). \\
\text{if } \big((X_r = 2) \wedge (X_g = 2) \wedge (X_b = 2)\big) & \text{then } (Y = \textit{white}). \\
\text{if } \big((X_r = 1) \wedge (X_g = 0) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 0) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 1) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 0) \wedge (X_b = 1)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 1) \wedge (X_b = 1)\big) & \text{then } (Y = \textit{red}). \\
\text{if } \big((X_r = 1) \wedge (X_g = 1) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 2) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 2) \wedge (X_b = 1)\big) & \text{then } (Y = \textit{yellow}). \\
\text{if } \big((X_r = 0) \wedge (X_g = 1) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 0) \wedge (X_g = 2) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 0) \wedge (X_g = 2) \wedge (X_b = 1)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 2) \wedge (X_b = 0)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 2) \wedge (X_b = 1)\big) & \text{then } (Y = \textit{green}). \\
\text{if } \big((X_r = 0) \wedge (X_g = 1) \wedge (X_b = 1)\big) \vee & \\
\quad \big((X_r = 0) \wedge (X_g = 2) \wedge (X_b = 2)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 2) \wedge (X_b = 2)\big) & \text{then } (Y = \textit{turquoise}). \\
\text{if } \big((X_r = 0) \wedge (X_g = 0) \wedge (X_b = 1)\big) \vee & \\
\quad \big((X_r = 0) \wedge (X_g = 0) \wedge (X_b = 2)\big) \vee & \\
\quad \big((X_r = 0) \wedge (X_g = 1) \wedge (X_b = 2)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 0) \wedge (X_b = 2)\big) \vee & \\
\quad \big((X_r = 1) \wedge (X_g = 1) \wedge (X_b = 2)\big) & \text{then } (Y = \textit{blue}). \\
\text{if } \big((X_r = 1) \wedge (X_g = 0) \wedge (X_b = 1)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 0) \wedge (X_b = 2)\big) \vee & \\
\quad \big((X_r = 2) \wedge (X_g = 1) \wedge (X_b = 2)\big) & \text{then } (Y = \textit{purple}).
\end{array}
$$

Table 4.9: Example of consistent control theory canonically rewriting its control reference

color name. The luminosity may be considered as a context information with respect to the possible outcome of the color settings and, in our case, such context knowledge may have dramatic simplifying effects on the most general consistent theory, as may be seen with the following rule sentence for instance:

$$\textit{if} \quad \big((X_l = 0) \wedge (X_b = 1)\big) \vee \big((X_l = 1) \wedge (X_b = 2)\big) \quad \textit{then} \quad Y = \textit{blue} \tag{4.5}$$

Two aspects are sufficient for discriminating four out of the five reference decisions concerning the blue colour for instance. It is, furthermore, remarkable that in this example, besides the newly appearing rules, such as the one shown in Equation 4.5, the original most general consistent theory remains partly present in the underlying augmented most general consistent theory consistent. Solely new aspect combinations, involving the luminosity attribute, appear now. Some of these new sound classifying rule sentences are very attractive in the sense of the maximum entropy segmentation. The luminosity attribute thus acts as a context switching attribute which allows for the construction of shorter control rule sentences without changing the original underlying most general consistent control theory.

Attribute combination	Attribute Values	Supporting situations	Decision Action (Y)
$X_l X_b$	(0, 0)	1	black
$X_l, \mathbf{X_b}, \mathbf{X_g}$	(3, 1, 1), **(2, 1, 0)**, **(2, 0, 0)**, ,(1, 0, 0)	23, 20, 19, 10	red
$X_l, \mathbf{X_b}, \mathbf{X_r}$	**(2, 0, 2)**, **(2, 1, 2)**, (1, 0, 1)	22, 20, 19, 10	red
$X_l, \mathbf{X_g}, \mathbf{X_r}$	**(2, 1, 2)**	22	red
X_l, X_b	(3, 0)	25	yellow
X_l, X_b, X_g	(3, 1, 2)	26	yellow
X_l, X_g	(1, 2)	7	green
$X_l, \mathbf{X_b}, \mathbf{X_g}$	**(2, 1, 2)**, **(2, 0, 2)**,(1, 0, 1)	17, 16, 8, 4	green
$X_l, \mathbf{X_b}, \mathbf{X_r}$	**(2, 1, 0)**, (1, 0, 0)	8, 4	green
$X_l, \mathbf{X_b}, \mathbf{X_g}$	**(2, 2, 2)**, (1, 1, 1)	18, 9, 5	turquoise
$X_l, \mathbf{X_b}, \mathbf{X_r}$	**(2, 2, 0)**, (1, 1, 0)	9, 5	blue
X_l, X_b	(1, 2), (0, 1)	12, 6, 3, 2	blue
$X_l, \mathbf{X_b}, \mathbf{X_g}$	**(2, 2, 1)**	15	blue
$X_l, \mathbf{X_b}, \mathbf{X_g}$	(3, 2, 1), **(2, 2, 0)**, (1, 1, 0)	24, 21, 11	purple
$X_l, \mathbf{X_b}, \mathbf{X_r}$	**(2, 2, 2)**, (1, 1, 1)	21, 11	purple
$X_l, \mathbf{X_b}, \mathbf{X_g}$	**(2, 1, 1)**	14	grey
X_l, X_b, X_g	(3, 2, 2)	27	white

Table 4.10: Most general consistent sub-theory based on the luminosity attribute

Finally, let us mention that the same properties are not naturally given for a most general *prescriptive* theory as resulting from a maximum entropy segmentation for instance. Before introducing the luminosity aspect, all possible prescriptive control theories are identically confined to the trivial and unique canonical control reference. By taking into account the luminosity aspect, the decision tree approach will show a balanced result. Some colours, such as black and blue for instance, are indeed discriminated via shorter control rules. But others, such as yellow and white, will now need four aspects to be correctly categorized; A price we have to pay in order to get a deterministic control theory. It is indeed the flexibility[28] in the selection of possible combinations of aspects that eventually shortens the rules in the case of the most general consistent theory construction.

Considering now the global luminosity as a context discrimination, we may try to calculate most general consistent sub-theories for each context dependent control sub-reference, in this case for a given level of luminosity.

4.5.2 Decomposing a control reference by switching over context

To illustrate this idea, let us select from Table 4.8 on page 135, the subset of all reference colour decisions showing a luminosity of $X_l = 2$, namely decisions #8, #9 and #13 − 22. If we compute the most general consistent sub-theory on this subset,

[28]We see in this example how the flexibility principle, as promoted by the Moving Basis Heuristic (see Barthélemy and Mullet, 1986), may indeed enhance the operational performance of a control theory.

we obtain the theory shown in Table 4.11.

Attributes	Values	Situations	Decision action
X_b, X_g	(1, 0), (0, 0)	20, 19	red
X_b, X_r	(0, 2), (1, 2)	22, 20, 19	red
X_g, X_r	(1, 2)	22	red
X_b, X_g	(1, 2), (0, 2)	17, 16, 8	green
X_b, X_r	(1, 0)	8	green
X_b, X_g	(2, 2)	18, 9	turquoise
X_b, X_r	(2, 0)	9	blue
X_b, X_g	(2, 1)	15	blue
X_b, X_g	(2, 0)	21	purple
X_b, X_r	(2, 2)	21	purple
X_b, X_g	(1, 1)	14	grey

Table 4.11: Most general sub-theory based on a constant luminosity of value 2

As the luminosity aspect is maintained at a constant level in this sub-reference, it may be ignored in the control rule sentences. Comparing now this context restricted sub-theory (see Table 4.11) with the original most general consistent theory (see Table 4.10 on the preceding page), we may notice that the sub-theory corresponds exactly to the corresponding restriction we emphasized in this latter table.

The context restriction, based on the luminosity aspect, is thus a stable restriction operator for the most general consistent theory construction, in the sense that restricting the reference and computing the corresponding most general consistent theory, or restricting the global, most general consistent theory, gives the same result.

This most important result, from an operational point of view, will be more thoroughly analyzed in the following part[29].

4.5.3 Context switching attributes

Let us start with defining the formal properties of what we call a *stable context switching attribute*.

Definition 4.5.2 (Stable Context Switching Attribute).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for an abstract universe of discourse. Let $\mathcal{R}$ be a control reference described in M and $\mathcal{T}(\mathcal{R})$ be the corresponding most general consistent control theory. For a given attribute $X_i \in \mathbf{X}$ of nominal type $V_i = \{0, 1, \ldots\}$, we note $\mathcal{R}/X_i$ the partition of $\mathcal{R}$ given by the equivalence classes modelled by X_i on $\mathcal{R}$. Similar, we note $\mathcal{T}_{/X_i}$ the subset of elementary most general consistent rule sentences modelling possible values of attribute X_i which we call the most general consistent *sub-theories* corresponding to X_i. We say that X_i is a *stable context switching* attribute iff

$$\mathcal{T}(\mathcal{R}_{/X_i}) = \mathcal{T}_{/Xi}(\mathcal{R}), , \tag{4.6}$$

[29]The text is based upon an internal COMAPS delivery (Bisdorff, 1997c).

i.e. iff the context restriction is *natural* for the most general consistent theory construction.

Computing sub-theories on context restricted control reference gives the same result as dividing a global control theory with respect to a stable context switching attribute. Conversely, joining all context restricted sub-theories recovers, in fact, the original global control theory.

Proposition 4.5.1. *If $X_i \in X$ is a context switching attribute, the join of the most general consistent sub-theories computed from respective restricted control references by switching over X_i, will re-compose the most general consistent control theory with respect to $\mathcal{R}$.*

Proof. If the context restriction is indeed *natural* for the most general consistent control theory, i.e. satisfies Equation 4.6 on the preceding page, each partial context restricted most general consistent sub-theory will correspond exactly to the corresponding restriction of the most general consistent theory, and the join over all possible sub-theories will, therefore, re-compose this complete original most general consistent control theory. □

An open problem remains for the moment the question of what are the formal properties an attribute must satisfy w.r.t. a given control reference, in order to imply the requested naturality of respective context restrictions for most general consistent theory computations.

A trivial example of natural context switching is given by the case where the control reference is identical in all possible context restrictions. In this case, for each selected context, we observe the same (sub)-theory and the global theory will thus be trivially stable.

More generally, we may assume that a certain "similarity" of the control theory is observed for each context restriction. In the color vision example, for instance, we observe approximately the same cycle of appearing colors for each level of luminosity. In the Circuit Foil control problem, one may suspect that the different production machines gathered on a same electrolyte, when producing a same product, show a very similar control practice. Another didactic illustration would be given by the example[30] shown in Table 4.12 on the next page.

The second set of four control decisions is in bijection to the first ones. Only the name of the concerned product is changed and the values observed on variables X_1 and X_3 are lowered by 20. For product *a*, control variables X_1 and X_3 must be confined to the interval $[60, 61]$ and for product *b* the same variables must be confined to the interval $[40, 41]$. The corresponding most general consistent global theory is disjointly split into two most general consistent sub-theories, such that the join of the two gives back the global most general consistent theory.

[30] We use a modified version of the example shown in Table 4.4 on page 113.

#	X_p	X_1	$\Delta_t^{t-1}(X_1)$	X_2	$\Delta_t^{t-1}(X_2)$	X_c	Y	Q
01	a	65	0	64	0	23	-3	*ok*
02	a	61	-4	61	-3	20	0	*ok*
03	a	61	0	60	-1	20	0	*ok*
04	a	60	-1	60	0	20	0	*ok*
05	b	45	0	44	0	23	-3	*ok*
06	b	41	-4	41	-3	20	0	*ok*
07	b	41	0	40	-1	20	0	*ok*
08	b	40	-1	40	0	20	0	*ok*

Table 4.12: Example of control reference with natural context switching

Recognizing such context switching attributes allows us, therefore, to greatly simplify the computational task of generating a most general consistent theory. The case given, we are allowed to split the global control reference into different disjoint parts that we may consider independently.

These formal results might explain why context switching appears to be an essential feature of an apparent decision expertise. Recalling our discussion from Chapter 2, we know that it is precisely the use of context switching strategies which distinguishes a novice decision maker from an experienced one. The better at context switching a decision maker is, the more likely he will be an expert.

To elaborate a formal criterion for recognizing such stable context switching attribute, we introduce the concept of *independent* control sub-theories.

Definition 4.5.3 (Independent control sub-theories).
Let Ω be the set of all possible control situations we may potentially observe on the basis of our model M. Let $\mathcal{T}$ be a given control theory and $S, S' \in \mathcal{T}$ two of its control rule sentences. Let $\Omega_{\mathcal{T}}$ denote the subset of potential control decision modelled by all rule sentences in $\mathcal{T}$.

We say that S is *independent* of S', denoted as $S \parallel S'$ iff $\Omega_{/S} \cap \Omega_{/S'} = \emptyset$.

By simple extension, we say that two given control theories $\mathcal{T}$ and $\mathcal{T}'$ are *independent* one of another, denoted as $\mathcal{T} \parallel \mathcal{T}'$ iff $\Omega_{/T} \cap \Omega_{/T'} = \emptyset$.

This situation corresponds to our example of natural context switching (see Table 4.12 above). If $S \rightarrow$ "if E then Y is ok" and $S' \rightarrow$ "if E' then Y' is ok" are two *independent* elementary control rule sentences then E and E' share the same attribute combination, but differently evaluated.

Proposition 4.5.2. *Let $S, S' \in \mathcal{T}$ two elementary control rule sentences.*

$$S \parallel S' \Leftrightarrow \big(\forall i : (X_i = x) \in E \Rightarrow (X_i = x') \in E'\big) \wedge \big(\exists i : (x \neq x')\big).$$

Proof. Suppose first that $\Omega_{/S} \cap \Omega_{/S'} \neq \emptyset$. In this case $\exists p \in \Omega_{/S} \cap \Omega_{/S'}$ such that $S \vdash p$ and $S' \vdash p$ which contradicts the right hand side of proposition 4.5.2 on the preceding page. Vice versa, suppose $(X_i = x) \in E$ and $(X_i = x') \notin E'$. In that case, it is easy to construct a p such that $p \in \Omega_{/S} \cap \Omega_{/S'}$. □

Trivial examples of parallel elementary rule sentences are given by the canonically rewritten reference control decisions. Indeed, as the control reference is sound, necessarily all ok-qualified reference decisions give *independent* elementary rule sentences. In our color vision example, for instance (see Table 4.8 on page 135), the restriction to the three color attributes gives us a trivial most general consistent control theory, where all elementary rule sentences are independent one of another.

Proposition 4.5.3 (Stable context switching attribute).
Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y, Q, V^Q)$ be a model for an abstract universe of discourse. Let $\mathcal{R}$ be a given control reference formulated in $\mathcal{M}$. If $X_c \in \mathbf{X}$ is an attribute, such that all corresponding restricted most general consistent sub-theories $\mathcal{T}_{/X_c}$ build on $\mathcal{R}_{/X_c}$ are mutually independent, *then X_c is a stable context switching attribute.*

Proof. The context switching w.r.t. X_c gives a partition of $\mathcal{R}$ we note $\mathcal{R}_{/X_c}$. Let $\mathcal{T}_{/i}$ and $\mathcal{T}_{/j}$ be the most general consistent sub-theories corresponding to such disjoint parts $\mathcal{R}_{/i}$ and $\mathcal{R}_{/j}$ of $\mathcal{R}_{/X_c}$ and let $\mathcal{T}_{/ij}$ being their join. By assumption, $\mathcal{T}_{/i}$ and $\mathcal{T}_{/j}$ are independent, so that $\mathcal{T}_{/ij}$ is indeed a consistent theory. We must show that it is also a most general one w.r.t. the union of both reference restrictions. Suppose that there exists a most general consistent theory $\mathcal{T}'(\mathcal{R}_{/ij})$ which is different from $\mathcal{T}_{/ij}$. By uniqueness of the most general consistent theory it follows that either $\mathcal{T}_{/i}$ or $\mathcal{T}_{/j}$ cannot be a most general consistent sub-theory. □

Providing independent sub-theories appears as a strong formal requirement for stable context switching attribute dimensions. In fact, it is possible to relax the independence condition and consider simply *compatible* sub-theories.

Definition 4.5.4 (Compatible control sub-theories).
Let $\mathcal{R}$ be a given control reference formulated in $\mathcal{M}$ and $\mathcal{R}_\omega$ the set of all expressible control decisions in $\mathcal{M}$. Let $S \rightarrow$ 'if X then Y is ok' and $S' \rightarrow$ 'if X′ then Y′ is ok' be two elementary rule sentences formulated in $\mathcal{M}$ and let $\mathcal{R}_{/S} = \{p(x, y, ok) \in \mathcal{R}_\omega \mid S \vdash p\}$ denote again the set of control situations modeled by a given rule sentence S. We say that S is *compatible* with S', denoted as $S \bowtie S'$ iff $(Y = Y') \vee ((\mathcal{R}_{/S} \cap \mathcal{R}_{/S'}) \subseteq \mathcal{R}_\omega - \mathcal{R})$. By simple extension, we say that two given control theories $\mathcal{T}$ and $\mathcal{T}'$ are *compatible* one with another, denoted as $\mathcal{T} \bowtie \mathcal{T}'$ iff $\forall$ elementary $(S, S') \in T \times T'$: $S \bowtie S'$.

Two ok-qualified elementary control rule sentences are compatible, one with another, if either they conclude on the same decision action, or their generalization concern disjoint sets of potential decisions. This last condition is naturally given by independent control rules.

Proposition 4.5.4. *Let* $\mathrm{S}, \mathrm{S}' \in \mathcal{R}$ *be two rule sentences.* $\mathrm{S} \parallel \mathrm{S}' \Rightarrow \mathrm{S} \bowtie \mathrm{S}'$.

Proof. The proposition follows immediately from the definitions. □

Compatibility and soundness conditions are in fact closely linked, as evidenced by the following proposition.

Proposition 4.5.5. *Let* $\mathcal{R}$ *be a reference control and let* $\mathcal{T}$ *be the corresponding most general consistent control theory. All elementary rule sentences in* $\mathcal{T}$ *are mutually compatible.* $\forall \mathrm{S}, \mathrm{S}' \in \mathcal{T} : \mathrm{S} \bowtie \mathrm{S}'$.

Proof. By construction the most general consistent theory is sound so that $\forall \mathrm{S}, \mathrm{S}' \in \mathcal{T}$: $\mathrm{Y} \neq \mathrm{Y}'$, we have that $(\mathcal{R}_{/\mathrm{S}} \cap \mathcal{R}_{/\mathrm{S}'}) = \emptyset$, so that they are incidentally compatible. □

It appears now that the compatibility condition for control sub-theories is a sufficient condition for defining stable context switching attributes.

Proposition 4.5.6. *Let* $\mathcal{M} = (\mathbf{X}, \mathrm{V}^{\mathrm{X}}, \mathbf{Y}, \mathrm{V}^{\mathrm{Y}}, \mathrm{Q}, \mathrm{V}^{\mathrm{Q}})$ *be a model for an abstract universe of discourse. Let* $\mathcal{R}$ *be a given control reference formulated in* $\mathcal{M}$. *If* $\mathrm{X_c} \in \mathbf{X}$ *is an attribute, such that all corresponding restricted most general consistent sub-theories* $\mathcal{T}_{/\mathrm{X_c}}$ *build on* $\mathcal{R}_{/\mathrm{X_c}}$ *are* mutually compatible, *then* $\mathrm{X_c}$ *is a stable context switching attribute.*

Proof. It is sufficient to complete the proof for independent sub-theories by the case where we observe compatible pairs of rule sentences. The compatibility property assures us that, in this case, the computed sub-theories conclude either on identical decision actions or that their respective joined theories do not produce unsound rule sentences w.r.t. the given control reference. □

It is worthwhile noticing, that in the trivial case, where the most general consistent theory is identical to the canonically rewritten control reference, all attribute dimensions give, in fact, context switching attributes. This may be easily confirmed on the color vision example above (see Table 4.8 on page 135). The more general a given theory is, the more unlikely a given attribute may give a context switching attribute. Indeed, to each attribute we may associate a conditional most general theory, such that this attribute remains a natural context switching attribute. This observation may give us some hint for constructing general control theories approaching the most general consistent one. This issue has still to be investigated[31].

[31] Unfortunately, the resources available in the COMAPS project did not allow to design and implement an algorithm for detecting potential context switching attributes. N. Lépy is however concentrating her forthcoming PhD dissertation on precisely this issue (Lépy, 1999).

Summarizing the results of our investigation, we may recall the cognitive usefulness of contextual attributes which allow us to switch over context for the elaboration of a most general consistent theory. If a given attribute allows a control reference partition resulting in compatible most general consistent sub-theories, i.e. mutually compatible rule sentences, then we may use this attribute safely as a context switch, at least w.r.t. the actually given control reference. Furthermore, assuring that a given contextual attribute may safely allow a switch over context in our intentional description of the expert control practice, may give us a 'cognitive' criteria for judging the level of generalization we want to give our theoretical discourse w.r.t. the observed expert control practice.

After this long discussion concerned with critical control theory, let us now turn our attention, in a last section, to the decision aid tools we are able to design on the basis of our critical control theory.

4.6 Operations Hermeneutics

The last part of our historical description of the CIRCUIT FOIL control expertise concerns a practical application of *Operations Hermeneutics*[32]. After a short general introduction, we present, in some detail, the complete COMAPS algorithm for on-line maintenance of a control expertise. A last part will concern the discussion of the CHECK AS YOU DECIDE device.

4.6.1 Hermeneutic validation of the control expertise

The core concern of Operations Hermeneutics is turned towards the development of artificial scientific models of human decision expertise that implement a mimic human decision making. In the COMAPS project, the research partners used mainly a classic maximum entropy segmentation approach for computing artificial control theories from a given control reference in order to initialize and calibrate the COMAPS application at a given industrial site. In the general case, no pre-existing official control rules need to exist, but at the CIRCUIT FOIL , where we have seen that such "natural" control rules have been written down, it was most interesting to compare such artificial control rules with those known from this official control theory. This comparison must necessarily rely on an efficient dialogue between the artificial control

[32] Under this scientific discipline, we subsume the science of understanding human operational decision strategies from the empiric observation of their decision practice via structural communicative tools, allowing the human decision maker to formalize, and thereby enhance the symbolic expression of his/her decision practice and intention. *Operational Hermeneutics* as a scientific programme appeared first publicly in autumn 1999 under the form of a European Thematic Network proposition submitted for the IST Programme of the European Union initiated by Michel Grabisch. Ironically, the European Commission rejected the proposition with the mention that is is too innovative and research oriented for EU funding.

system implementing an artificial control theory, and the CIRCUIT FOIL control board using its "natural" control expertise.

These comparisons led to cognitively interesting discussions In the context of the COMAPS project: First, giving insight in the pertinence of the universe of control discourse (see Definition 4.3.3 on page 113) and the regularity of the observed control history as recorded in the COMAPS database, but also, and this is the main purpose in the CIRCUIT FOIL problem, confirming or contesting the scope and pertinence of the official control rules with respect to the underlying control reference. We shall come back in more detail to the results of this part of the COMAPS project in Chapter 6, but we may quickly say here that the decision tree algorithms appeared very reliable during practical experiences for generating artificial control theories from all kinds of given control references. We shall, in this section, first present a general methodology for installing a hermeneutic validation circle of the practical control expertise. This will lead eventually to the design of an on-line control decision aid tool, a CHECK AS YOU DECIDE device.

The interface design follows the general idea of "check spelling and grammar as you type" devices which are implemented in the context of proofing tasks for office suites. As the operator is providing the control decision to the COMAPS system, the new input will be annotated in case it is detected as being inconsistent with the current apparent control theory. The severeness of the actual inconsistency is shown to the operator by a coherent decoration of the decision values. Starting a conflict solving phase is generally under continuous control of the operator who has the possibility to ignore the critical annotation of the COMAPS system.

The CHECK AS YOU DECIDE tool design is entirely rooted in the COMAPS methodology, therefore, we shall, in the next part, briefly sketch the general COMAPS algorithm design[33].

4.6.2 The general COMAPS algorithm

We may recall first that the COMAPS project had two main goals:

1. To extract and capitalize the decision strategies of production control operators;
2. And to allow these operators to maintain their efficiency and to adapt their control expertise to the process evolution, by comparing new judgments with the recorded control reference.

It is well known that in such multi-attribute settings, the operator will perform a judgment on the basis of a relatively small amount of information (*parsimony principle*). But from one control situation to an other the information processed could vary (*flexibility principle*).

[33]We use material produced by the Brestian COMAPS team (Faure, 1997; Le Saux, 2000).

More precisely, in a multi-attribute settings, the information processed by the operator involves a limited number of *aspects* of a control situation. It was assumed that each aspect considered by the operator may be matched with a set of attribute values and that a given value for an attribute never corresponds to several aspects. Because of the limitations of his/her working memory, the decision maker will be able to process only two, three or possibly four aspects simultaneously. That is to say that, eventually, his judgment is performed on the basis of one, two, three, or at most, four aspects. Formally, the various aspects related to one attribute correspond to a partition of the values V_i of an attribute X_i.

Moreover, the COMAPS team assumed that the operator will apply *priority order* for choosing a proper combination of aspects in his/her decision making (*priority principle*). According to the flexibility principle, the operator will use various favorite combinations of attributes. But, for a given sample, if he/she could apply several of those combinations, there will be an order of priority between them for selecting the judgment. This order of priority is limited to a partial order between the different combinations. Furthermore, these combinations of aspects are actually a couple "*combination of aspects/associated judgment*". Thus the priority order may be applied to the judgments or to the combinations of aspects themselves. This means that in the first case, his/her decision lies on the judgments associated with different combinations of aspects in competition and, in the second case only, to the combinations themselves, regardless the associated judgments. A priority order between judgments will be called a *dominance order*. The combinations of attribute values corresponding to a combination of aspects involving a given judgment is called a *judgment basis*. It is most important to notice that the COMAPS algorithm is not intended to account directly for the control strategies of the operator but to compute the various judgment bases corresponding to the various control issues[34].

Classical machine learning or data mining approaches allow to infer and update from an evolving control reference a partition of the attribute space $\mathbf{X}$, whose individual parts or clusters are labeled with the various judgment modalities. These practices usually lead to NP-complete problems and need intensive use of heuristics. In the COMAPS approach, the notion of judgment basis restricts the search to low dimensional attribute sub-spaces (dimension one, two, three or, eventually, four). Thus, in addition to the cognitive relevancy of the association basis/judgment to account for the expert behavior, this strategy has the computational advantage of producing time-efficient algorithms, a strict requirement for the intended on-line processing.

Definition 4.6.1 (cylinders).

[34]The chosen methodological position with respect to the cognitive modelling of the control strategies, was another heavily debated topic within the COMAPS project. Indeed, against the black-box approach of the Brestian team, I always defended a cognitive responsibility principle for all cognitive artifacts produced. We shall come back to this issue in some more detail when discussion the practical validation of the COMAPS results at CIRCUIT FOIL (see Chapter 6).

Let $\mathcal{M} = (\mathbf{X}, V^X, \mathbf{Y}, V^Y)$ be a model for an abstract universe of discourse and let $\mathcal{R}_\omega$ the set of all expressible control decisions in $\mathcal{M}$. Let us consider a subset $X' \subseteq \mathbf{X}$ and $\forall X_i \in X'$, the subset $V_i^{'} \subseteq V_i$ and let V' be the Cartesian product of the $V_i^{'}$. We define the *cylinder* $\mathcal{C}(X', V')$ with base $(X', V)'$ as the subset of $\mathcal{R}_\omega$ such that $(x_1, \ldots, x_n) \in \mathcal{C}$ iff $X_i \in X' \Rightarrow x_i \in V_i^{'}$. When the dimension X' and V' is not explicitly needed, a cylinder will be denoted by $\mathcal{C}$. The *dimension* of the $\mathcal{C}(X', V')$ cylinder is just the cardinality of X'.

Let $\mathcal{R}$ be a control reference[35] and let $y \in \nu^Y$. The cylinder $\mathcal{C}$ is said to be $\mathcal{R}$-compatible with $\mathbf{y}$ whenever $\forall h = (\mathbf{x}, \mathbf{y}') \in \mathcal{R} \cap \mathcal{C}$, $(\mathbf{y} = \mathbf{y}')$. Such a cylinder will be denoted $\mathcal{C}_y$. The $\mathcal{R}$-volume of the cylinder $\mathcal{C}$ is the cardinality of the set $\mathcal{C} \cap \mathcal{R}$. This notion extends to stochastic reference where the volume of $\mathcal{C}$ is defined by $P(\mathcal{C} \cap R \times \{\mathbf{y}\})$, with P the distribution of probabilities associated with $\mathcal{R}$. A set $\mathcal{T}$ of $\mathcal{R}$-compatible cylinders $\mathcal{C}_y$ is covering the complete control reference is called a *cylindrical paving* of the attribute space, or a control theory.

Following Definition 4.6.1 on the page before, the Brestian COMAPS team took a geometrical approach to the definition of what we called a control theory in the last section. In fact, our *elementary* control rule sentences models a *convex* cylinder in $\mathcal{R}_\omega$, a concept, they defined as *cylindrical block*. The principle of the general COMAPS algorithm may be viewed as an adaptation of the search for a most general consistent control theory as presented in the preceding Section, in the sense that the COMAPS algorithm searches for maximal cylindrical blocks of a "certain type" $\mathcal{R}$-compatible with $\mathbf{y}$. Most general consistency or maximality of the cylindrical block account for the parsimony principle and multiplicity of available maximal cylinders account for the flexibility principle. The COMAPS cylinders are computed under three constraints: (1) at each time, to be compatible with the control reference, (2) to have a minimal dimension and, (3) to have a maximal volume (relatively to the reference at time t). All these requirements are obviously contradictory and even ill posed. The proposed COMAPS algorithm tries to realize a pragmatic compromise between them.

In the most general case, $\mathbf{x}' \in V'$ corresponds to the E part of an elementary control sentence sentence. When the variables are numerical, the *base* of $\mathcal{C}$, denoted B_C, constitutes a convex subset of V'. In order to tackle possible non-sobriety and non-determinism of the computed cylindrical paving, a partial order of priority between the different cylinders in competition for a given decision making is introduced[36].

The COMAPS algorithm design had to face two main difficulties :

[35] In fact, following the methodological decision to drop the quality indication of control situations, control history and control reference got confused in the design of the COMAPS algorithm.

[36] Unfortunately, this ordering of the compatible cylinder for a given control reference was not deeply explored and mastered in the COMAPS implementation. The confusion between what we identified as control history respectively control reference coupled with the lack of a precise distinction between ok-qualified control decisions and all others led the priority feature of the COMAPS algorithm in a certain unclear operational status.

1. The search for a maximal cylinder and for a minimal partition or covering into cylinders are NP-hard problems in general. It is also a NP-complete problem to check if a family of cylinders intersects (reduction for 3-SAT);

2. The expert may use a priority order between rules or a dominance order between judgments.

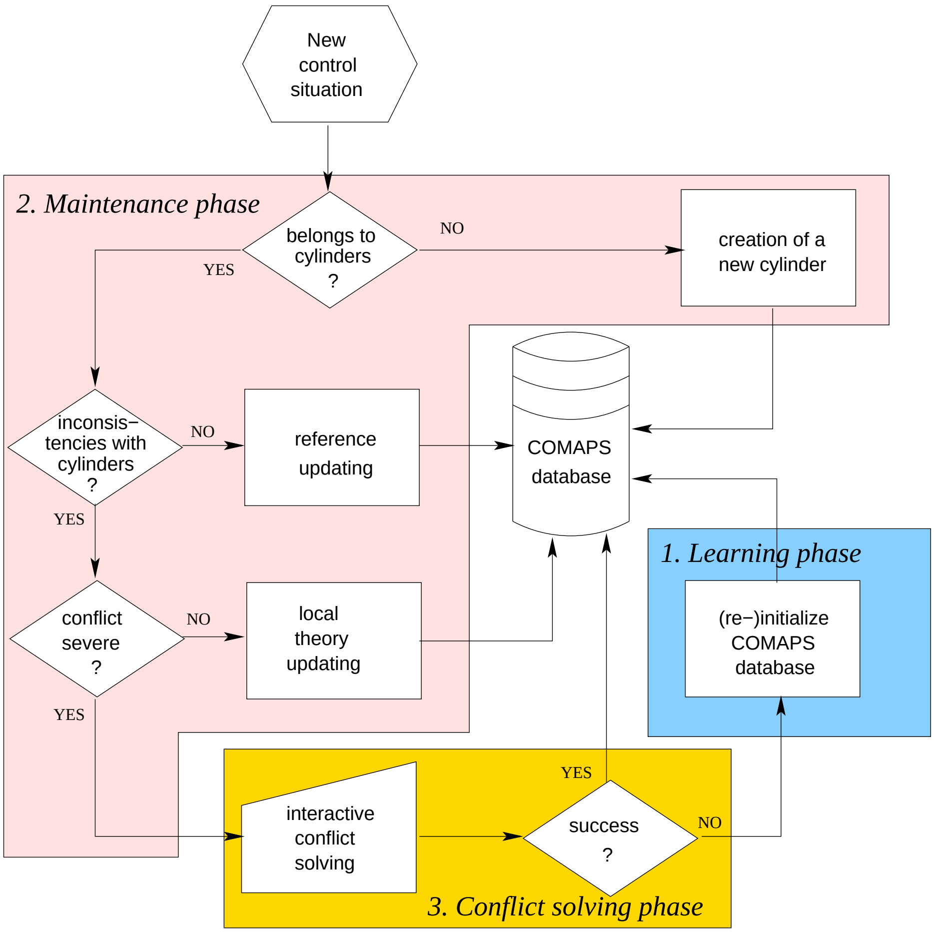

Figure 4.7: Synopsis of COMAPS algorithm
source: *Faure* (1997), *Le Saux* (2000)

The COMAPS algorithm is made of three different phases (see Figure 4.7):

1. A **learning phase** that will infer, either from an available reference or from the decision maker's knowledge extraction, promising combinations of aspects, hypothetical admissible cylinders and possible priority relations on cylinders.

2. A **maintenance phase** that:

- will update the partition of $(\mathbf{X}, V^X)$ into admissible cylinders according to new observed control situations,
- will detect conflict between prediction computed from the reference and actual judgment behavior of the operator, and
- will evaluate the severeness of the conflicts and will automatically solve the "lightest" ones.

3. A **conflict resolution phase** that is started whenever the intervention of the operator becomes necessary to help solve severe conflicts between the COMAPS representation of the control expertise and the apparent ongoing control practice.

The learning phase

The general framework of the algorithm to apply during the learning phase consists of three parts: The first one is dedicated to finding some promising combinations of aspects (with at most four aspects). The cylinders are computed in the second part on each combination of aspect previously extracted. In the last part final cylinders are computed, corresponding to remaining unclassified samples of the reference. But efficient heuristics must be applied to face the NP-hard problems mentioned above.

ML-techniques can provide such an efficient algorithm when stopping the tree decomposition at depth level four. From a most promising attribute X_i, we thus obtain admissible cylinders. It will be then be possible to restart the algorithm considering another attribute and in restricting computation to yet unclassified control situations, and so on, until all samples of the control reference are classified.

A possible partial ordering relation on the cylinders may emerge from the learning phase. This relation will correspond to non-empty intersections between cylinders associated with different judgments computed on different bases (i.e. judgment bases involving at least two different attributes X_i and X_j).

We do not mention a possible inconsistency of the reference, but we have to keep in mind that the reference may reflect some evolution of the expertise. Eventual conflicts can be suppressed from the reference in a pre-processing phase. It could also be interesting to apply data analysis to the control reference in order to find out inconsistencies. Such an analysis could also give clues for choosing some promising combination of aspects. Expert questioning could even be realized in order to discover such promising combinations.

The maintenance phase

Let us consider the reference $\mathcal{R}_t$ at time t to be consistent and $\mathcal{C}_t$ be the set of admissible cylinders generated from the reference $\mathcal{R}_t$. At time t, a new control decision $p^t = (\mathbf{x}^t, \mathbf{y}^t)$ has to be processed. Three different situations may now occur:

1. p^t belongs only to cylinders $\mathcal{R}_t$-compatible with $\mathbf{y}^t$ or to cylinders with lesser priority than a cylinder $\mathcal{R}_t$-compatible with $\mathbf{y}^t$. The new control situation is then considered consistent with the current cylindrical paving.

2. $\forall \mathcal{C} \in \mathcal{C}_t$, $\mathbf{x}^t \notin \mathcal{C}$. The new control situation does not belong to any previously generated cylinder. A new cylinder is created for p^t.

3. $\exists \mathcal{C}_y \in \mathcal{C}_t$ / $\mathbf{x}^t \in B_{\mathcal{C}_y}$ and $\mathbf{y} \neq \mathbf{y}^t$ and $\forall\, \mathcal{C}'_{\mathbf{y}^t} \in \mathcal{C}_t$ / $\mathbf{x}^t \in B_{\mathcal{C}'_{\mathbf{y}^t}}$, $\mathcal{C}'_{\mathbf{y}^t}$ has not a higher priority than $\mathcal{C}_y$. This situation gives rise to a conflict.

Here, we consider only the third situation. The risen conflict may be of three different kinds: (1) inconsistency with generated cylinders due to the learning algorithm itself, (2) evolution of the process and (3) evolution of the expert. In the first case, the updating of the cylinders decomposition has to be performed on the basis of the new reference $\mathcal{R}_t \cup \{p^t\}$. This conflict could come from a "bad" cylinders decomposition or from a "bad" extraction of the ordering relation between cylinders. In the two latter cases, the conflict may involve a local updating of the admissible cylinders or a questioning of the expert, which corresponds to entering the third phase of the COMAPS algorithm, i.e. the conflict solving phase.

The choice between updating or starting the conflict solving phase, relies on a *conflict severeness indicator*, qualifying the importance of the currently risen conflict. It may be based on the number of control situations involved in the conflict, considering the admissible cylinders decomposition. We could also consider the number of rules concerned by the conflict.

It was considered "wise" to wait for several control situations to enter into conflict with one given cylinder before activating any modification of the admissible cylinder decomposition. This *threshold* was related to the R_t-volume of a given cylinder under conflict or to the number of cylinders involved in an updating.

In fact, the COMAPS algorithm was designed in order to operate even if no reference is available at initialization, which means that the learning phase cannot initially be launched. The maintenance phase, therefore, involved a continuous search for promising combinations of aspects and re-computation of cylinders even if no conflict appeared. In this sense, the maintenance phase represents a complete ML algorithm on its own[37].

[37] It is a posteriori funny to notice that the three research partners in the COMAPS , each one responsible for a specific algorithmic phase, implicitly managed with his respective industrial partner, to transform his algorithmic part into a potentially complete knowledge managing algorithm. The German partner considered the learning phase the essential part of the COMAPS project. For the Brestian team, the central maintenance part could, in the limit, provide on its own a complete operational COMAPS tool and, finally, for the Luxembourg team, the conflict solving phase, with emphasis on the cognitive managing of the official control theory, was considered the only industrially relevant part of the COMAPS project. Team work is apparently not always simple.

Conflict solving phase

This phase implies a feed back to the operator. The cylinders are expressed under the form of logical statements, or control rule sentences, which define the COMAPS output interface to the operator. These conflict solving phase outputs may be of two kinds: (1) new control rule sentences given by the operator, further translated in terms of admissible cylinders the case given inducing a modified control reference, consistent with the new admissible cylinders decomposition or (2) an updated control reference from which the operator may have suppressed out of date control situations inducing a new admissible cylinder decomposition.

In all cases of risen conflict, even slight conflicts not necessarily requiring the starting of the conflict solving phase, an updating of the underlying control reference has to be performed.

Updating the control reference

We shall always store, at each time point t, two control references : (1) A *partial* reference $\mathcal{R}_t$, containing only consistent (or a few inconsistent control situations whose frequency is under a given threshold) control situations, from which the actual admissible cylinder decomposition is derived and; (2) A *complete* reference $\mathcal{R}'_t$, trace of all the control situations that have occurred, including history used during the initialization phase. This reference should be related with a complete admissible cylinder decomposition history, where out of date control situations could refer to out of date cylinders, accounting for modification of the expertise or of the process for example.

The complete reference could be used for re-computing the actual admissible cylinder decomposition. This could stress some shifting between the admissible cylinder decomposition resulting from successive local updating and a corresponding cylinder decomposition generated from the whole control history, based on the learning phase algorithm. As the learning algorithm is time consuming, it cannot be performed in on-line situation. Off-line it may be used from time to time for critical inspection of the ongoing reference.

From the global design of the COMAPS algorithm, we shall now abstract the design of our CHECK AS YOU DECIDE device.

4.6.3 The "CHECK AS YOU DECIDE" decision aid

The information exchange between maintenance and conflict solving phases is formalized with three symbols: (1) The actual (time point t) cylindrical paving $\mathcal{T}_t$; (2) The actual underlying decision reference $\mathcal{R}$, i.e. the actual set of exemplary control situations underlying the paving; And (3) the current set of newly observed control decisions $\mathcal{D}$.

With the option of "CHECK AS YOU DECIDE " enabled, the COMAPS system will decorate the newly incoming control situations $p \in \mathcal{D}$ with following $d(p)$ annotations:

- green ($d(p) = 0$) current control decision is predicted and coherent with the actual cylindrical paving;
- blue ($d(p) = 1$) no cylinder covering the control situation;
- orange ($d(p) = 2$) potential conflict in the predicted decision of the control situation;
- orange ($d(p) = 3$) potential conflict due to possible multi-decisions without clear priority;
- red ($d(p) = 4$) referential conflict, the proposed decision is unsound with respect to the underlying control reference.

Noticing non-green decorations ($d(p) \neq 0$) when proposing his/her current decisions, the operator may ask to start the conflict solving phase of the COMAPS algorithm.

Upon operator request, the COMAPS system will construct a questionnaire allowing to resolve the potential conflicts in decreasing order of decoration; first the most severe ones ($d(p) = 4$) and last, the least severe ones ($d(p) = 1$). After each information exchange between the COMAPS system and the operator, the three current states of the system, i.e. the paving, the reference and the current annotation of the recent decision history will be automatically updated and if not interruptedbarring interruption by the operator, the system will continue to construct corresponding questionnaires until only green decorations are left.

The general conflict solving algorithm we propose is shown in Figure 4.8 on the next page. The main loop is conditioned either by the presence of a non-green, i.e. possibly conflicting decision situation, or by the operator prompt.

We shall briefly sketch the indicated sub-procedures with all possible decorations.

4.6.4 Automatic generation of a conflict solving questionnaire and coding the operator's reactions

To realize this step, we will closely follow a similar methodology as proposed in the SYSCOG case[38] but adapted to the specific COMAPS purpose. To every type of decoration observed on the situation $p = (x, y)$ there corresponds a specific methodology.

- *Referential conflicts*
  Let us first discuss the most severe case ($d(p) = 4$) concerning a referential conflict. Here we observe a control decision $p = (x, y)$ identical to one of our reference or exemplary decisions $r = (x, y')$ but differently labelled ($y \neq y'$). The questionnaire will simply conjointly propose the exemplary reference situation

[38] See Chapter 3.

$\mathcal{R} \leftarrow$ current set $\mathcal{R}_t$ of corresponding reference situations
$\mathcal{T} \leftarrow$ current cylindrical paving $\mathcal{T}_t$
$\mathcal{D} \leftarrow$ current set $\mathcal{D}_t$ of newly observed situations
user $\leftarrow$ *continue*
conflict_solving $(\mathcal{R}, \mathcal{T}, \mathcal{D})$
  while $(\exists p \in \mathcal{D} : d(p) > 0$ **and** *user* = *continue*)
    do
    $Q_p \leftarrow$ **generate_questionnaire** $(\mathcal{R}, \mathcal{T}, p, d(p))$
    $A_p \leftarrow$ *gather operator reactions* (Q_p)
    $(\mathcal{R}, \mathcal{T}, \mathcal{D}) \leftarrow$ **update** $(\mathcal{R}, \mathcal{T}, \mathcal{D}, p, d(p), A_p)$
    user $\leftarrow$ operator prompt for continuing
    enddo
  output $(\mathcal{R}, \mathcal{T}, \mathcal{D})$
  endwhile
endconflict_solving

Figure 4.8: COMAPS Algorithm: conflict solving procedure

and the newly observed similar situation to the operator and ask him to confirm the newly observed decision.

Two user reactions are possible: ignore the conflict (either a control error or an un-stabilized trial and error decision) or replace the reference decision. In the first case $A_p \leftarrow$ 'IGNORE', and in the second cases, $A_p \leftarrow$ '*replace* r *by* p *in* $\mathcal{R}$'.

- *Cylinder versus decision conflict*
  The second case appears as a potential referential conflict ($d(p) = 2$). Let $p = (x, y)$ be the observed situation and let $\mathcal{C} = (c, y')$ be the unique corresponding cylinder, with $c \geq x$ and $y \neq y'$ again. The theoretical or predicted decision action from our actual cylindrical paving cannot be identical to the observed one without being in contradiction with other reference decisions or cylinders.

  Two possible origins of the conflict have to be checked one against the other: The conflict indicates in fact an apparent equivalence of the corresponding decision actions y and y' en question; Or the conflict is again due to an unstable decision behaviour, conscious or not. The questionnaire will propose to confirm the situation p w.r.t. some reference situations supporting the concerned cylinder, covering p and to some similar predicated situations altogether situated "near" in the attribute space to the actual situation p.

  This time, the user reaction may confirm three issues: (1) Ignore again the conflict ($A_p \leftarrow$ 'IGNORE'); (2) confirm the apparent equivalence of the labels

$(A_p \leftarrow' (y = y')'$; Or (3) confirm the specialization of the cylinder $A_p \leftarrow$ 'add p to the actual reference $\mathcal{R}$'.

- *New potential decision context*
  The third case concerns a potential paving conflict ($d(p) = 1$). Let again $p = (x, y)$ be the observed situation and let us first suppose that no cylinder covers this observation, i.e. the decision appears decorated as green underlined. The operator may again confirm or not this new appearing decision context: $A_p \leftarrow$ 'IGNORE', or – $A_p \leftarrow$ 'add p to the actual reference $\mathcal{R}$'.

- *Cylinder versus cylinder conflict*
  The fourth case ($d(p) = 3$) distinguishes the conflict, where two or more cylinders $\mathcal{C}$ differently labelled may apply without any clear priority of application. The questionnaire will present referential and potential situations out of all admissible cylinders $\mathcal{C}$ which are near in the attribute space to the situation p, in order to make the operator, first, confirm or not the relevance of the situation, and secondly, an eventual priority in application of the covering cylinders. Formally, we will code the operator's answer in the following way: – $A_p \leftarrow$ 'IGNORE'),– $A_p \leftarrow$ 'ranking of $\mathcal{C}$ and add p to the actual reference $\mathcal{R}$'.

4.6.5 Updating the control expertise

Updating the control theory following the user reactions passes first through the updating of the underlying exemplary reference control situations.

- *Updating the control reference*
  The COMAPS general update algorithm is shown in Figure 4.9 on the following page. Two cases may appear: (1) Either a new control situation p is added to the control reference $\mathcal{R}$; (2) Or a previous reference control situation r is replaced by the new situation p.

  After the updating of the set of reference control decisions, we need to check and, the case given, update the current cylindrical paving.

- *Updating the cylindrical paving*
  The algorithm for updating the control theory, i.e. the actual cylindrical paving, is shown in Figure 4.10 on page 155.

  Five cases may be distinguished:

  1. A new exemplary situation p without any covering cylinder has been added to the current control reference and a new maximal covering cylinder has to created for it.
  2. Following a wrongly predicted conflict in the decision of situation p, a new specialized maximal covering cylinder has to created for it.

```
update (R, T, D, p, d(p), A_p)
    cases
    A_p = IGNORE
    | A_p = add p to R
        R ← R ∪ {p}
        T ← update_paving (R, T, p, d(P), A_p)
        D ← D − {p}
    | A_p = replace r with p in R
        R ← (R − {p}) ∪ {r}
        T ← update_paving (R, T, p, d(p), A_p)
        D ← D − {p}
    endcases
    output (R, T, D)
endupdate
```

Figure 4.9: COMAPS Algorithm: general update procedure

3. Two previously distinguished decisions y and y' are no more to be distinguished and the corresponding cylinders are joined.
4. A decision situation p generates a conflict through a wrong ranking of admissible maximal covering cylinders. We reorder these cylinders in consequence.
5. Finally, the actual control reference has been changed in the sense that a former exemplary situation r is replaced with a newer situation p. Therefore, a maximal covering cylinder for p is created and the old cylinder for r is removed.

The COMAPS algorithm represents at present the most complex design of operational hermeneutics. We shall come back to the practical implementation that followed this design at CIRCUIT FOIL in Chapter 6 where we shall discuss the practical application of the COMAPS tool.

Let us now conclude this case study.

4.7 Concluding the COMAPS case

This industrial case study has illustrated methods and tools for maintaining a given official control expertise over time. Main attention was given to the construction of a factual control history directly recorded from the on-going production control practice. This control history reveals, via a specific qualification procedure, the objectively underlying control reference, i.e. the extensional form of a given control expertise.

update_paving $(\mathcal{R}, \mathcal{T}, p, d(p), A_p)$
  cases
  $A_p = \text{IGNORE}$
  $\mid d(p) = 1 \land A_p =$ "add p to $\mathcal{R}$"
    $\mathcal{C}_p \leftarrow$ create new maximal covering cylinder for p
    $\mathcal{T} \leftarrow \mathcal{T} \cup \mathcal{C}_p$
  $\mid d(p) = 2 \land A_p =$ "add p to $\mathcal{R}$"
    $\mathcal{C}_p \leftarrow$ create a specialized cylinder for p
    $\mathcal{T} \leftarrow \mathcal{T} \cup \mathcal{C}_p$
  $\mid d(p) = 2 \land A_p =$ "$y = y'$"
    $\mathcal{T} \leftarrow$ join cylinders labelled y and y'
  $\mid d(p) = 3 \land A_p =$ "ranking of admissible cylinders $\mathcal{C}$, add p to $\mathcal{R}$"
    $\mathcal{T} \leftarrow$ update ranking of admissible $\mathcal{C}$
  $\mid d(p) = 4 \land A_p =$ "replace r with p in $\mathcal{R}$"
    $\mathcal{C}_r \leftarrow$ create new maximal covering cylinder for p
    $\mathcal{T} \leftarrow (\mathcal{T} - \{\mathcal{C}_r\}) \cup \{\mathcal{C}_p\}$
  endcases
  output $(\mathcal{R}, \mathcal{T}, \mathcal{D})$
endupdate_paving

Figure 4.10: COMAPS Algorithm: update_paving procedure

Official control rules (the intentional form of the same control expertise) could be critically checked against this objective control reference. A cognitive confrontation between this extensional and intentional expertise, organized following hermeneutical principles, allowed us to design an algorithm for validating, adjusting and maintaining these official control rules along the ongoing control practice.

In case the preceding process renders rather stable formal control rules a CHECK AS YOU DECIDE device has been presented that may provide an on-line decision checking tool for unexperienced or novice controllers. In such a way the CHECK AS YOU DECIDE device "embodies" the regular control expertise and allows to transfer it to less experienced controllers.

The COMAPS case study mostly illustrates operational tools that allow to manage a regular (solid) decision expertise. The next chapter (see Chapter 5) will now present a case study that tackles an industrial fault diagnosis and repairing problem where it is operationally important to distinguish between regular, well mastered decision decision situations and critical ones, where the expert knowledge becomes intuitive and unstable.

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Chapter 5

The ADAC case: Designing a Production Fault Diagnosis and Repairing Wizard

"*As the etymology of the term* theory *suggests, theoretical thinking is the mode of thought that seeks to problematize the very relation between what can be seen (Greek,* theorein, *"to view, to look, to regard, to survey") and what can be thought about what one has perceived from the vantage point of perception.*"

FIGURAL REALISM: STUDIES IN THE MIMESIS EFFECT, (WHITE, 1999, P. VIII).

Contents

5.1 Summary of the ADAC case

The «Aide au Diagnostic des Actions Correctives en cas de défauts de surface» (ADAC) case study results from a collaboration with the Service de Statistique et des Méthodes Quantitatives de Gestion (directed by Marc Roubens), Institute of Mathematics from the University of Liège (Belgium). It concerns a fault diagnosis and repair problem proposed, again, by the CIRCUIT FOIL Luxembourg S.A. company. The study was undertaken by Sándor Jenei, a young Hungarian mathematician who visited our "Statistics and Decision" lab at the Centre de Recherche Public –Gabriel Lippmann from September 1996 to March 1998 and under the scientific direction of M. Roubens and R. Bisdorff[1].

The following description of the ADAC case is largely based upon technical reports by S. Jenei (Jenei, 1997, 1998a,b), officially delivered to the Ministère de l'Education Nationale et de la Formation Professionnelle in the context of his research grant.

5.1.1 Description of the fault diagnosis and repair problem

The study is focused on the design of an operator assistance tool for maintenance of the treater phase, a production phase following the copper plating phase described in the COMAPS study (see Chapter 4), in case of surface defects.

The production of copper foils can basically be divided into two major steps:

1. The *plating* phase, i.e. the production of the raw copper foil with the help of the plating machines presented in Figure 4.2 on page 104 and;
2. The *post-treatment* phase, where the previously obtained raw foil is equipped with special surface treatments.

[1]The ADAC project was supported through a BFR (bourse de formation recherche) grant from the Luxembourg Ministère de l'Education Nationale et de la Formation Professionnelle.

Several types of base materials and surface treatments are proposed depending on the thickness of the foil and the type of the finished product. During the treater phase, a complex production process involving several electrolytes and cleaning baths with multiple winders, some more or less severe surface defects such as dots, nodules, winding faults o.a. may be observed, which make the final product outcome eventually being rejected for sale.

In case of such a surface defect, a most critical operational goal is then to characterize and locate the origin the defect, so as to proceed as quickly as possible with adequate repairing actions, in order to continue normal production again.

5.1.2 The experienced decision-maker

In this problem the decision maker has a two-fold identity again:

- On the one hand, we have an experienced engineer responsible for the design of the diagnosis and repairing strategies. He is our experienced decision maker in this case;
- And, on the other hand, we have shop floor operators who supervise constantly the outcome of the treater phase. In case they observe some surface defect, they are in charge of executing the diagnosis and repairing strategy recommended by the quality engineer.

At the beginning of the ADAC study, the quality supervisor of the treater phase at CIRCUIT FOIL , had already established a detailed written description for defect diagnosis and corresponding repair actions, the so-called "*expert system*"[2]. The content of it is the following:

- Some connections between the appearance of the surface defect and some suitable repairing actions;
- A guide line which explains some technical expressions and procedures with pictures and samples of defects;
- And a check-list, in fact a questionnaire, which gives a hand to the shop floor operators in finding the origin of a defect via ordering them to follow consecutively a given set of precisely described steps.

5.1.3 Institutional context

In the CIRCUIT FOIL production process, the treater phase constitutes a rather complex physical and mechanical production step. Product outcome defects, i.e. foil

[2] In fact a thick paper file with standardized descriptions of all known defects followed by a detailed technical description of the necessary repairing actions

defects, cosmetic surface problems through oxidation for instance, winding irregularities resulting in faults etc, are difficult to early detect and subsequent indeterministic repairing actions may often lead to eventually long lasting production shortcuts.

The shop floor operators are supposed to use the above mentioned "expert system", which is different for each type of surface defect, in order to guide their diagnosis and the subsequent repairing actions. But, in practice, the "heavy" filer is rarely consulted in an on-line situation. Indeed, either the defects observed are commonly known with their corresponding regular repairing strategies, or the defect is not known and then a more or less ad hoc "trial and error" repairing process is followed. It is especially in this last case that more "intuitive" knowledge about successful repairing strategies, coming either from the shop floor operators or from the quality engineer himself, may be observed. But here, organized and well-formulated strategic knowledge is crucially missing.

The R&D Department of CIRCUIT FOIL, therefore, started the ADAC project with the major aim to reduce production shortcuts in case of surface defects through a more consequent use of the existing "expert system". The idea was to put it on-line so that the operators could be more efficiently guided in the diagnosis and repairing process.

5.1.4 The results of the ADAC project

The ADAC study was very successful, from the methodological as well as from the practical point of view. S. Jenei designed in Prolog the prototype of an *incremental generic operator assistance knowledge system* featuring:

- An *interactive support* for characterizing the observed defects;
- And a *dynamic on-line support* for the corresponding repair actions.

Following the Jenei prototype, a consequent software development[3] was undertaken and currently CIRCUIT FOIL uses commonly a complete generic ADAC tool in several real industrial production situations.

5.2 The ADAC diagnostic and repairing problem

5.2.1 Organization of the ADAC expert system

During his study S. Jenei was supported by the main author of the so-called ADAC "expert system"[4]. This basic operational guide for diagnosis of surface defects is organized as shown in Figure 5.1 on the next page.

[3]The implementation was realized by Francis Barba, CREDI Department, Centre de Recherche Public – Gabriel Lippmann, CREDI

[4]The production expert for the ADAC project was René Lanners, a technical engineer, responsible for the diagnosis and repairing activities concerning the treater phase

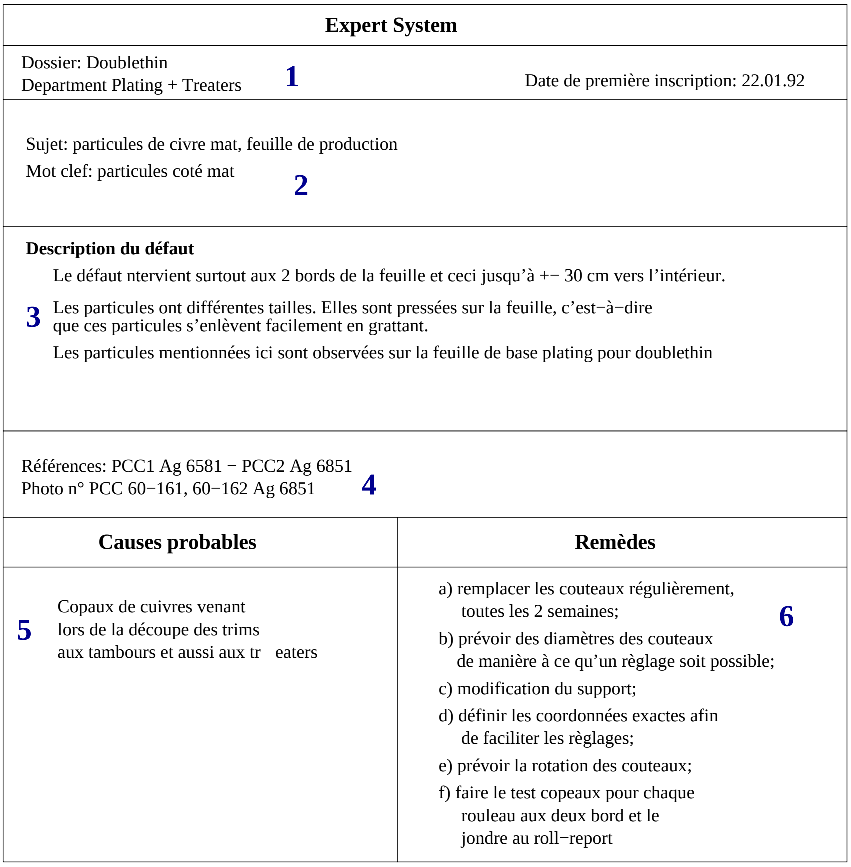

Figure 5.1: A sample entry from the ADAC expert system

The entries are separated for each product type: here *doublethin* foils (see Number **1** in Figure 5.1). The observed surface defect is given a title and a keyword (Number **2**). A precise and detailed description for exact diagnosis follows (Number **3**). References to technical material and to photos of the characterized defect are provided for further information if needed (Number **4**). Plausible causes for the observed surface defect are described (Number **5**) and finally, a detailed list of recommended repairing actions is given (Number **6**).

This user manual is supposed to be used by shop floor operators in case they observe surface defects on the outcome of the treater.

5.2.2 The ADAC problem is indeterministic

Unfortunately, the general diagnosis and repairing problem, as actually observed at the treater phase, is indeterministic by nature. Indeed:

- The performance of a repairing action is not always perfect. These actions are executed by human operators and mistakes are always possible;

- It is possible that the source of the defect is found and the appropriate repairing action is done in a correct way but, nevertheless, the defect does not disappear. This might happen e.g. when the defective part of the treater is replaced by a piece that itself is defective again.
- The defect might disappear by itself without any plausible connection with a particular repairing action;
- In case of rare defects, it is sometimes difficult to know, from the operator's local point of view, if the defect has presently already disappeared or is still present;
- The defect is previously unknown and no repairing actions are presently known.

5.2.3 Regular versus critical diagnosis and repairing processes

We may generally distinguish two separated phases in the diagnostic and repairing activities:

- a *regular* phase, where a known defect is observed and the corresponding repairing actions are undertaken, and
- a *critical* or "*trial and error*" phase, following a regular phase (in case the given surface defect has not disappeared and no more regular diagnosis and repairing actions are known).

Supporting the diagnostic and repairing process in the critical phases was one of the major goals of the ADAC study. In this phase, it is indeed particularly important to avoid unnecessary repetitions of same repairing actions again and again. This could happen e.g. after an operator shift where the following operators did not know for instance, if a certain repairing actions had already been tried or not, and with what result. In addition, it may happen that a given shift would not trust the previously made diagnostic and repairing actions.

The overall tracking and reporting of the repairing process appeared thus as a second major goal of the ADAC project.

5.3 Jenei's incremental operator assistance knowledge system

The IOAK (Incremental Operator Assistance Knowledge) system for fault diagnosis and quality control was designed by Jenei in a very generic way. Its overall goal is to help human operators to find and eliminate the source of a given production fault. It organizes the fault search at a strategic level in the regular phase of the repairing process and gives advice on how to proceed during a critical phase. This advice is based upon a historical learning feature.

The IOAK system consists of two modules: (1) A knowledge base and (2) an algorithm as shown in Figure 5.2.

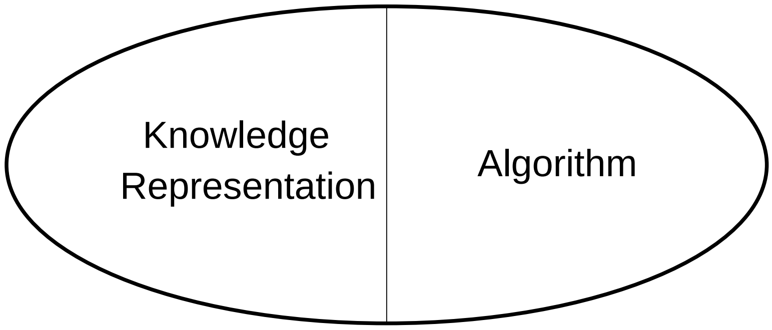

Figure 5.2: The basic modules of the IOAK system
source: *Jenei* (1998a)

The knowledge base module consists of two parts:

- The regular repairing strategies for known defects represented as a di-graph;
- And the historical knowledge reported from occurring critical repairing phases.

5.3.1 The regular knowledge graph

The first part, i.e. the graph representation of the regular diagnosis and repairing strategies (see Figure 5.3 on the following page), is previously created by the experienced operator or supervisor of the diagnosis and repair problem. The syntax of this graph structure is the following:

- The set H of nodes which have more than one consecutive node is composed of two types of nodes:
  - A set D of decision (question) nodes (represented as yellow "lozenge" $\diamond$);
  - A set $M = H - D$ of nodes starting concurrent repairing processes (represented as blue box $\square$).
- Leaves , i.e. nodes without any subsequent node, where we distinguish two types:
  - A set S of "*solved*" leaves (represented in green $\bigcirc$). We may actually consider the diagnosis and repairing process successfully completed upon reaching this type of node;

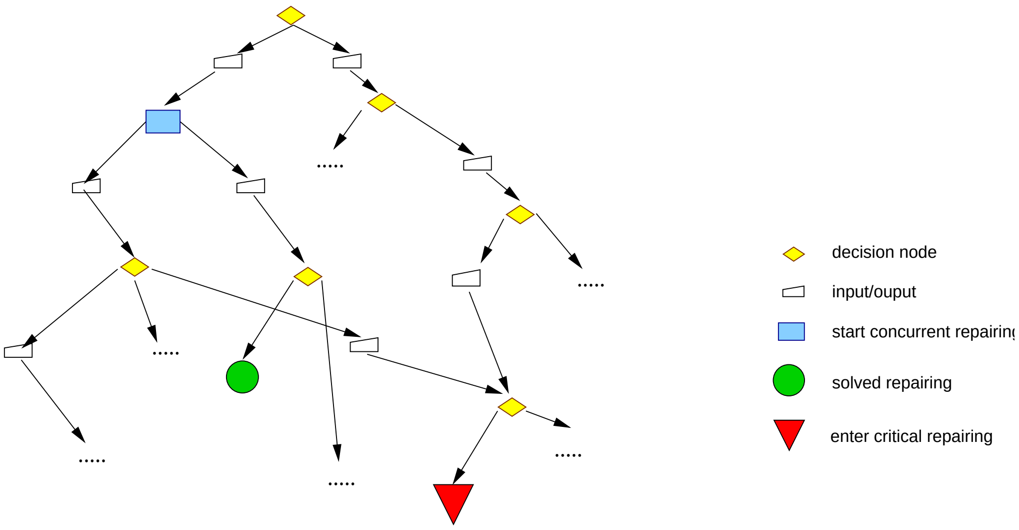

Figure 5.3: Regular repairing actions organized as di-graph
source: *Jenei* (1998a)

- A set C of "*unsolved* leaves, (represented in red ▼). After this latter node, the diagnosis and repairing process generally goes in its critical phase.

- The set A of consecutive nodes following a decision node, which represent in fact all possible answers to the decision (question). This set A is normally disjointed from the set D of decision nodes. These answer nodes may be associated with a linguistic scale: *sure*, *almost sure*, *probable* denoting, the case given, the operator's opinion concerning reliability of the answer in question.

Each node of the graph may be labelled with a corresponding textual information such as:

- *Doublethin production: spots on the treated side observed after TrTw: check if the fault is present at the unwind or only at the rewind of TrTw?*;
- *It is visible after Tr8 (unwind Tr7)*
- *Take samples at the unwind and rewind TrTw and give information to the shift leader and to operator on Tr8, that the defect remained on the foil!*
- *Has the defect disappeared?*
- ...

This graph is supposed to implement step-by-step the official process of diagnosing and repairing a given production defect. The best known regular investigations, tests and repairing actions from the experienced quality manager are written down step by step. Thus the knowledge base graph describes how the production expert would act in a fault situation. For each observed surface defect, a different graph may be used. It is worth noticing here that the knowledge graph is a pure passive syntactic structure without any deductive or inductive power.

5.3.2 The IOAK algorithm

The algorithm of the IOAK system consists of two consecutive parts: The *regular* phase and the *critical situation & learning* phase.

5.3.2.1 Regular phase

In the first *regular* part, the IOAK system guides human operators with the help of the regular knowledge graph, via a dynamic questionnaire, through the officially recommended diagnosis and repairing process. During this phase the evolving regular diagnosing and repairing activities are being *evaluated*, i.e. the operators' answers with their associated linguistic grades are recorded on the actual walk through the regular knowledge graph. This set of collected answers formally characterize in fact the production fault in question (see Figure 5.4).

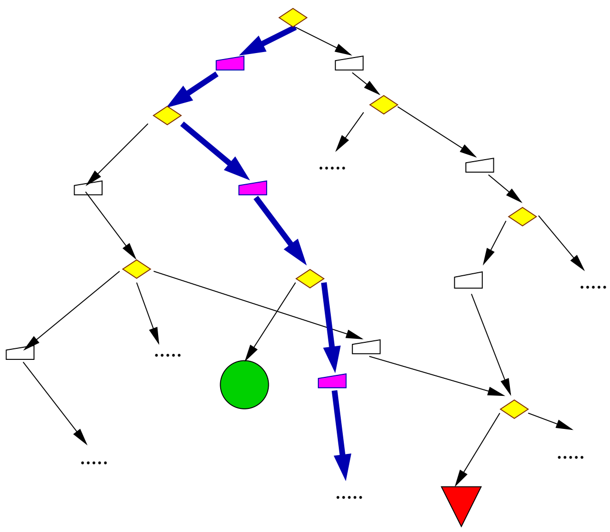

Figure 5.4: Recording a regular diagnosis and repairing process
source: *Jenei* (1998a)

Indeed, such a walk through the knowledge graph shows not only what the operators tried to do in order to eliminate the production fault, but it also shows the results of all investigations and tests with their associated degree of reliability of the results so far executed. In this way it carries essential information concerning the defect in question and it may be efficiently used for constructing a classification of the production defects.

In some situations, it may be reasonable to undertake concurrent independent repairing actions in order to solve the problem as quickly as possible. Therefore, the possibility to start *concurrent walks* is introduced as shown in Figure 5.5.

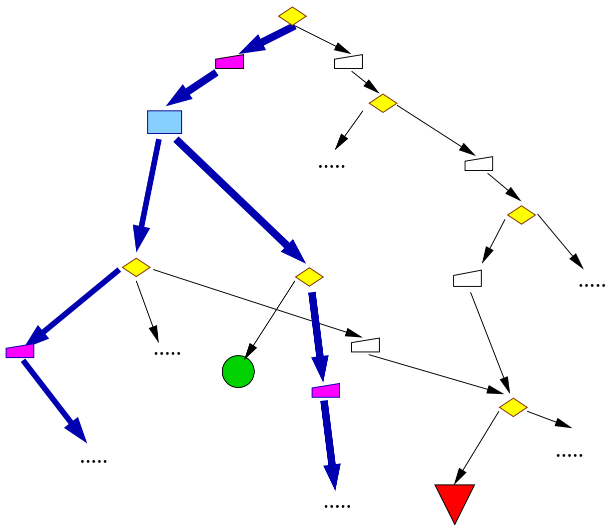

Figure 5.5: Recording concurrent diagnosis and repairing processes
source: *Jenei* (1998a)

If the production defect disappears during the regular phase, i.e. the walk through the regular knowledge graph arrives at a green ○ leaf, the IOAK algorithm is stopped. In the case of concurrent repairing actions it might be the case that one action has solved the problem and all ongoing concurrent repairing actions may safely be closed and/or cancelled[5].

5.3.2.2 Critical phase

If the observed defect has not disappeared, i.e. the walk through the regular knowledge graph reaches a red ▼ leaf, the second and *critical* part of the algorithm is activated.

Here, the guiding questionnaire is stopped and the current evaluation, i.e. the evaluated image of the unsuccessful repairing process on the set of answers nodes of the regular knowledge graph, is compared to a historical data base of previously recorded unsuccessful walks in order to detect similar evaluations with their eventual successful set of repairing actions (see Figure 5.6 on the next page). On the basis of

[5]Sometime a once started repairing action has to be necessarily followed by some other repairing actions in order to safely restart the production. A kind of transactional decoration of the repairing process may help implementing such technical dependences between the individual repairing actions.

this similarity, the IOAK system then proposes an ordered list of potential repairing actions (the most likely ones to solve the current defect, being listed first).

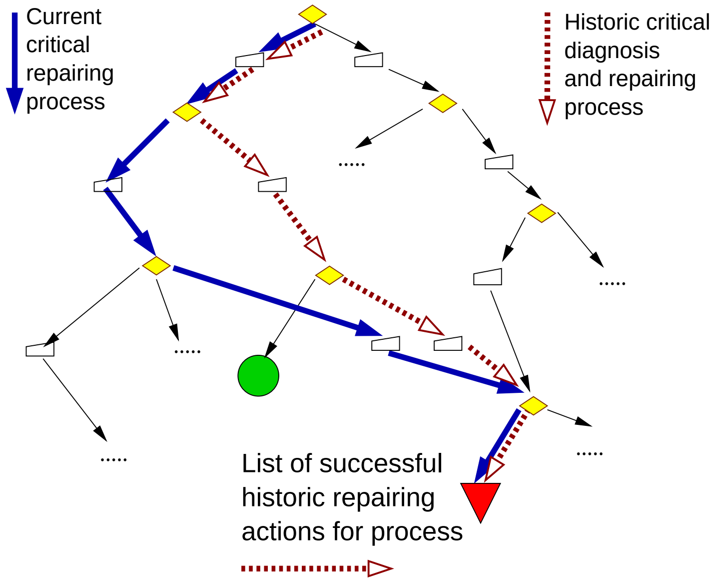

Figure 5.6: A similar historical critical repairing process with its associated list of eventually successful repairing actions

source: *Jenei* (1998a)

When the current defect is finally eliminated, the list of eventually successful repairing actions, as well as the initial formal regular evaluation, are added to the historical data base.

5.4 Critical study of the ADAC case

In this section we study in detail the formal properties of the IOAK system. First we analyze the cognitive requirement for using Jenei's system.

5.4.1 Cognitive requirements for using the IOAK system

The generic design of the IOAK system applies to a wide range of practical problems in fault diagnosis and quality control.

Primary cognitive input to the IOAK system is given via the basic description of each observed production fault. This description represents in fact the current state of the art of fault diagnosis and quality in the given industrial setting. It generally requires the presence of an experienced engineer in order to prepare the regular knowledge graph. But the syntactic structure of this graph is completely independent of any technical or industrial domain. Only the layout of the regular graph, with its recommended diagnosis and repairing strategies has to be established.

In the ADAC study, the establishment of the regular knowledge graph represents the main cognitive challenge, the experienced decision maker is facing. Although only one precisely delimited type of surface defect was actually chosen for experimenting with the IOAK system, it soon appeared that the print of the corresponding complete developed knowledge graph would covered practically a whole office wall. To follow within each detail the precise repairing strategies appeared to be rather tricky from an operational point of view.

The necessity to develop an efficient graphical user interface (GUI) for designing and maintaining the regular knowledge graph became evident, and the major part of the industrial software development, following the ADAC project, was indeed concentrated on the implementation of such a suitable GUI. Professional C++ graph classes allowing to visually manipulate the graph, but also to print parts or the whole of the graph were integrated into the final ADAC tool (see Section 5.5 on page 175 and Figure 5.7 on page 176)

It is, however, a positive point for the IOAK system that no minimum level of initial regular knowledge is required. This allows its use for organizing fault diagnosis and repairing strategies on newly starting production installations, where such a regular knowledge is still very poor.

But in any case, the actual regular knowledge graph represents the official and certified strategies for fault diagnosis and repairing. It contains normally the best expert's usual investigation and repairing activities in an algorithmic, i.e. executable description. Thus the graph describes how the *best* expert would act in a fault situation.

In the ADAC problem, the visual appearance of a surface defect is generally not sufficient to conclude on its possible cause. Special tests and investigations, depending naturally on the type of the observed defect, have to be done in order to precisely locate the place in the treater phase where the defect is apparently appearing. Depending on the results obtained from these investigations and tests, the fault search may be completely different.

These investigations and tests can be sometimes very expensive and/or the production has to be interrupted for a more or less long period of time. That is why the more or less optimal, or at least satisfactory, organization of the diagnosis and repairing process plays a major role. An it is precisely this "optimal" organization that is hard coded into the regular knowledge graph. It is worth noticing that for the actual graph designer and maintainer, it is not necessary to deeply understand the technical and physical causes of the defects. It is sufficient to simply integrate the best known and useful "conjectures" in a purely syntactic way.

In the design of his Prolog prototype, Jenei has provided some software tools for checking the syntactic structure of the knowledge graph.

```
check_structure :-
     not bad_multipoint, not answer_and_decision_situ,
     not bad_solved_point.
     bad_multipoint :-
          multi_walk_startpoint(N),
          not has_more_than_one_son(N),
          writeln('There is a multi_walk_startpoint which has only'),
          writeln('one outcoming node!'),
          writeln('The expert system stops running !').
     answer_and_decision_situ :-
          decision_situ(N),answer(N),
          writeln('answers can not be decision situations!'),
          writeln('The expert system stops running !').
     bad_solved_point :-
          solved(N),has_son(N),
          writeln('There is a point labelled by SOLVED which has an'),
          writeln('outcoming node!'),
          writeln('The expert system stops running !').
```

Following abnormal constructions are being detected:

- No multiple walk start point my have a single outgoing edge;
- No answer node can be simultaneously a decision node;
- Solved nodes can only appear at a leaf of the graph.

The knowledge graph has necessarily also a unique root node, denoted N_0, representing the common starting point of all regular diagnosis and repairing strategies.

Furthermore it appears clearly, from the operational purpose of the regular diagnosis and repairing strategies, that each strategy must eventually stop on either a solved or an unsolved leaf and this after a finite number of steps. As the graph contains necessarily a finite number of nodes, it is, therefore, necessary to guarantee that the regular knowledge graph be *acyclic*, i.e. that same tests and investigations are normally[6] not repeated.

Proposition 5.4.1. *Let* $G = (N, E)$ *be the acyclic graph underlying a given regular knowledge graph, where* N *represents a finite set of nodes and* E *represents a relation on* N*, in fact the edges of the graph.* E *gives a semi-*$\vee$*-lattice with* N_0 *as upper bound.*

It follows that the necessary acyclicity condition may be easily checked. As the graph is finite, there may only exist a finite number of different walks. For each such possible walk trough the graph, we have to check that it has at most a length of n, the finite total number of nodes of the graph.

[6] In case a given repairing action has not not been executed with a high reliability, it may happen that it is recommended to repeat it. We come back later to this point.

5.4.2 Supporting the regular diagnosis and repairing process

These structural properties allow generation during the regular execution of the IOAK system of a finite dynamic questionnaire according to the oriented graph by using the textual labelling of the nodes (see Subsection 5.3.1 on page 165).

The IOAK system gives commands/instructions to the operators, puts questions and establishes the next question or command accordingly to the answer given at the previous question node.

Definition 5.4.1. A *walk* in the regular knowledge graph $G = (N, E)$, is a finite sequence of labels attached to an oriented path $\pi = (w_0, w_1, \ldots, w_i, w_{i+1}, \ldots)$ where $(w_i, w_{i+1}) \in E$ for $i = 1, \ldots$ and $w_0 = N_0$, the root node of the graph.

Sometimes it is indicated to follow conjointly parallel repairing actions. They are started by a special multiple walk node N_m present in the graph. A multiple walk starting at such a node N_m is simply the *union* of of more than one *sub*-walks having the node N_m as root node.

The coordination between such parallel strategies is graph driven: If two parallel walks come again together at a certain node, the corresponding node label should indicate "*Wait for all parallel actions to get here!*" or "*Inform the other operators to stop their actions*", depending on the required official strategy at this point of the process.

The actual direction of the fault search can be different depending on the result obtained from a test or an investigation in a decision situation. Therefore, at a decision node N_d, the operator has more possibilities described in the knowledge graph with the help of a set of answer nodes. All such possible answer are interactively proposed to the operator and the system waits for the answer. The operator then has to choose between the offered alternatives and the walk continues according to the chosen answer.

Furthermore, the system offers the possibility of evaluating the reliability of certain answers, through a confidence function coding the more or less "*sureness*" of the answer. The motivation for this feature comes from the following situation: The effective observation of a requested test result may not be evident or the investigation may be more or less well realized. Thus the operator has the possibility to ponder his judgment about the sureness or not of the observation of a given state or result with the following linguistics grades: *sure*, *almost sure* or *likely sure*, *somehow not sure* or *no confidence*.

This linguistic (fuzzy) evaluation of the answers plays a crucial role in the critical phase of the IOAK system. But it may also play such a certain role during the regular phase itself. Upon arriving at an eventually unsolved leaf node, these evaluations may be used in order to implement an intelligent backtracking feature in the IOAK system that allows the operator to restart, the case given, the regular diagnosis and repairing process at a node in the regular graph where such an unsure answer was previously reported.

It appears from the above presentation, that the regular knowledge graph, as designed in the IOAK system, represents in fact some kind of explicit trace graph following the precise execution of the official diagnosis and repair strategies. In this sense, the graph has some resemblance with assembler programming where every single execution step of the processor has to be hard-coded. It would be interesting to investigate whether macro-instructions and pre-processing features such as `#define` and `#if ...#else` constructs usual in C and C++ development, could not possibly enhance the overall design of the knowledge graph. Designing, furthermore, a generic scripting language for the regular phase of the IOAK algorithm certainly remains one of the interesting challenges for future developments of this system.

But, let us now turn our attention to the critical phase.

5.4.3 Supporting the critical diagnosis and repairing process

Reaching an unsolved leaf may be due in practice to following reasons:

- The regular knowledge base is not complete or not properly elaborated. An authorized expert may easily modify and enhance the basic knowledge graph by inserting new methods and/or updating other ones;
- The diagnosis and repairing process is un-properly executed, i.e. in some decision situations wrong decisions have been taken. The systems allows, in fact, to backtrack to such an unsatisfactory decision node and to redo the repairing process from that node on;
- Or the regular knowledge diagnosis and repairing knowledge has arrived at a critical situation.

In this latter case, a given production fault cannot be corrected with the help of the regular diagnosis and repairing strategies and the IOAK algorithm enters in the *critical phase*. Arrived in such a *critical situation*, the IOAK system suggests an ordered list of potential repairing actions in decreasing order of relevance. This suggestion is computed from the learned historical knowledge and from the current evaluation.

The interaction with the operators stops then until the origin of the production fault has been found and the defect has been removed. Indeed, the IOAK suggestion is only a hint and the operators have to solve the problem on their own in this critical phase.

When finished the operators return to the IOAK system in order to record the list of repairing which helped to eliminate the current production fault. Each such record presents a couple (X, Y) where X is a function from N, the set of nodes of the regular knowledge graph to $[0, 1]$ tracing the evaluated walk of the diagnosis and repairing process, and Y is a list of repairing actions. A same relation (X, Y) may be recorded multiple times.

In order to measure the dissimilarity d_{ij} between two such evaluations X_i and X_j, Jenei uses the p-power of the L_p norm of their difference, defined as follows:

$$d_{ij} = \sqrt[p]{\frac{\|(X_i - X_j)\|^p}{|X_i \vee X_j|}}, \tag{5.1}$$

where $|X_i \vee X_j|$ computes the fuzzy cardinal of the union of both walks. Taking the strong negation $1 - d_{ij}$ of this dissimlarity index gives a corresponding degree of similarity $s_{i,j}$.

For practical application, this similarity measure has to be tuned by choosing:

- Adequate numerical values for the linguistic grades of the sureness indicator characterizing some of the answers collected through the walk;
- And the power p of the distance measure d_{ij} .

From a semantic point of view, Jenei's similarity index gives some kind of fuzzy *Jaccard*[7] index, i.e. the ratio of common nodes to the union of nodes in both evaluations.

$$s_{ij} = \frac{|(X_i \cap X_j)|}{|(X_i \cup X_j)|}.$$

Following this idea, the power could be chosen equal to 1 and the fuzzy sureness grades could be evenly distributed on the line $[0, 1]$.

Generally the production has to be stopped at the beginning of the critical phase. As it is expensive to restart the production, several potential repairing actions are realized in parallel. As a consequence, it is not always possible to determine which particular repairing action eventually solved the production problem. Hence, a smaller set Y of repairing actions carries more information about the correct repairing actions to do than a larger set one. The larger the set Y, the "noisier" the recommendation will be.

In order to take into account this noise, Jenei proposes to weight each element $r \in Y$ as follows:

$$\omega_Y(r) = \frac{1}{|Y|}.$$

Let H represent the set of historical recordings and let X_c represent the regular evaluation of the current critical repairing process. The overall weight of every potential repairing action $a \in Y$ appearing in one possible historical record $(X, Y) \in H$ is computed as follows:

$$\omega_H(a) = \sum_{(X,Y)\in H} \omega_Y(a) \cdot S(X_c, X).$$

The more a past repairing process X is similar to the current process X_c, the more relevant the formerly successful repairing actions Y become.

[7] A detailed discussion by G. M. Roux of the similarity indexes commonly used in classification may be found in (Roux and Roux, 1976, TIC n.).

Theorem 5.4.2 (Jenei). *For any critical evaluation X_c , the order of the proposed repairing actions – defined by the ω_H weighting function defined above – converges to a limit order with probability* 1.

Following the proof of Jenei, one may assume that subsequent production faults are independents events and the probability that a certain repairing action $a \in Y$ solves the problem of a critical situation is considered a constant value. In this setting, by applying classical results from probability theory, Jenei could prove (Jenei, 1998a) that $\frac{\omega_H(a)}{n^2}$ converges to a limit for any repairing action a, a historical record H of cardinal n and a given current critical evaluation X_c.

This limit-order reveals essential information about potential enhancements that could be added to the regular knowledge graph. This introduces the general problem of updating problem the regular knowledge graph.

5.4.4 Updating of the regular knowledge graph

It follows from the very generic design of the IOAK system that any correctly formulated diagnosis and repairing process can be used. This allows a.o. the expert to easily modify the content and/or the outlay of the regular knowledge graph.

But here appears also the problem of inheritance of the learned critical knowledge through updated regular knowledge graphs. Upon changing of the regular graph, some historical walks may become completely meaningless, others may become partly meaningless.

The proposed definition of the similarity index (see Equation 5.1 on the preceding page) allows to compute without any problem similarities between a current critical walk and a set of historical critical walks made on a different regular knowledge graph. If the actual graph is very different from the old one then all the previously recorded evaluations will be strobly dissimilar to the new evaluation. But in case the actual graph is only slightly modified, there is a chance that a large majority of historical walks might still show a close similarity to the actual critical walk, and the ordered list of potentially successful repairing actions remains pertinent for the operator.

5.5 Implementing the IOAK system

Following Jenei's design study, the CIRCUIT FOIL authorities, entirely convinced by the demonstration on the Prolog prototype, decided to undertake a consequent software development with the CREDI, the "Cellule de Recherche, d'Etude et de Dévloppement en Informatique" of the CRP–Gabriel Lippmann.

The development was done in C++ by Francis Barba who used for the manipulation of the complex regular knowledge graph professional graph classes. A view of

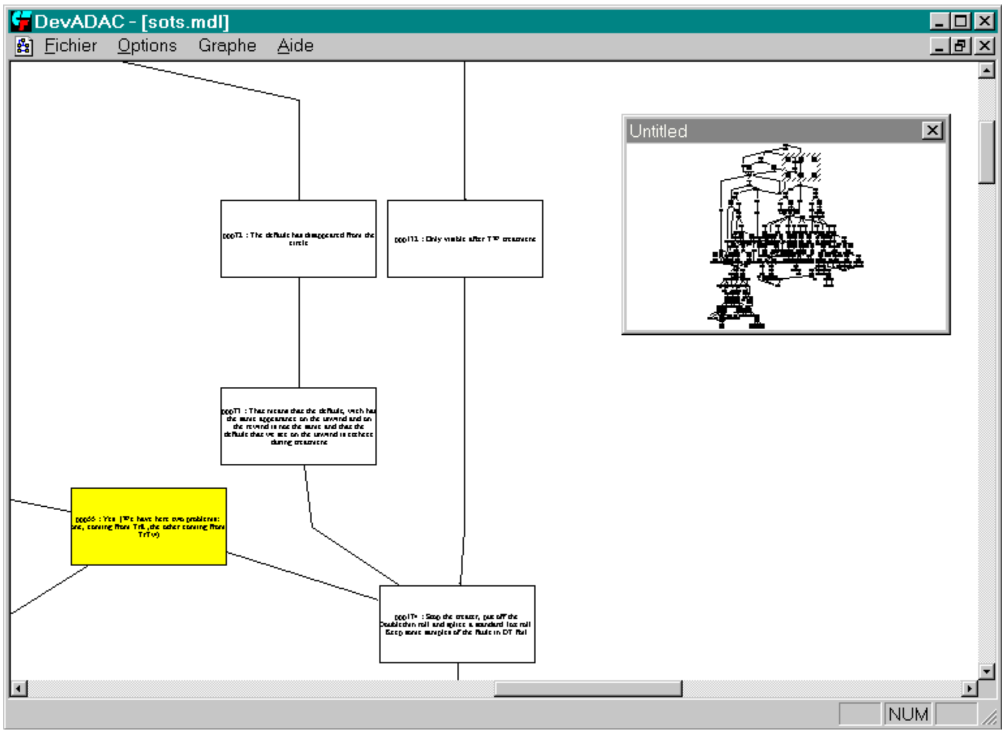

Figure 5.7: The ADAC software: A view on the regular knowledge
source: *DEVADAC user manual, F. Barba* (2000)

the graphical outlay is shown in Figure 5.7[8].

More advanced graph layout functions are provided as is visible in Figure 5.8 on the next page.

The next Figure 5.9 on page 178, shows the interface when starting a regular diagnosis and repairing process, whereas Figure 5.10 on page 179 shows the concurrent working on a double walk.

[8]Francis Barba has kindly supported us by providing screen snapshots from the graphical user interface of the ADAC software.

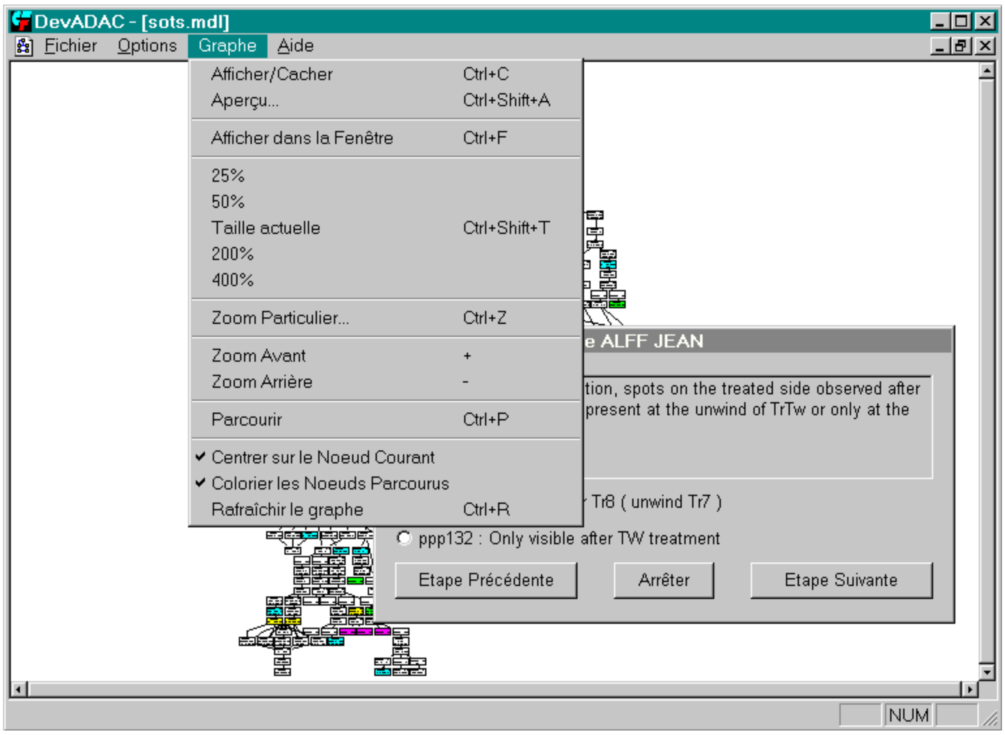

Figure 5.8: The ADAC software: menu for knowledge graph manipulation
source: *DEVADAC user manual, F. Barba* (2000)

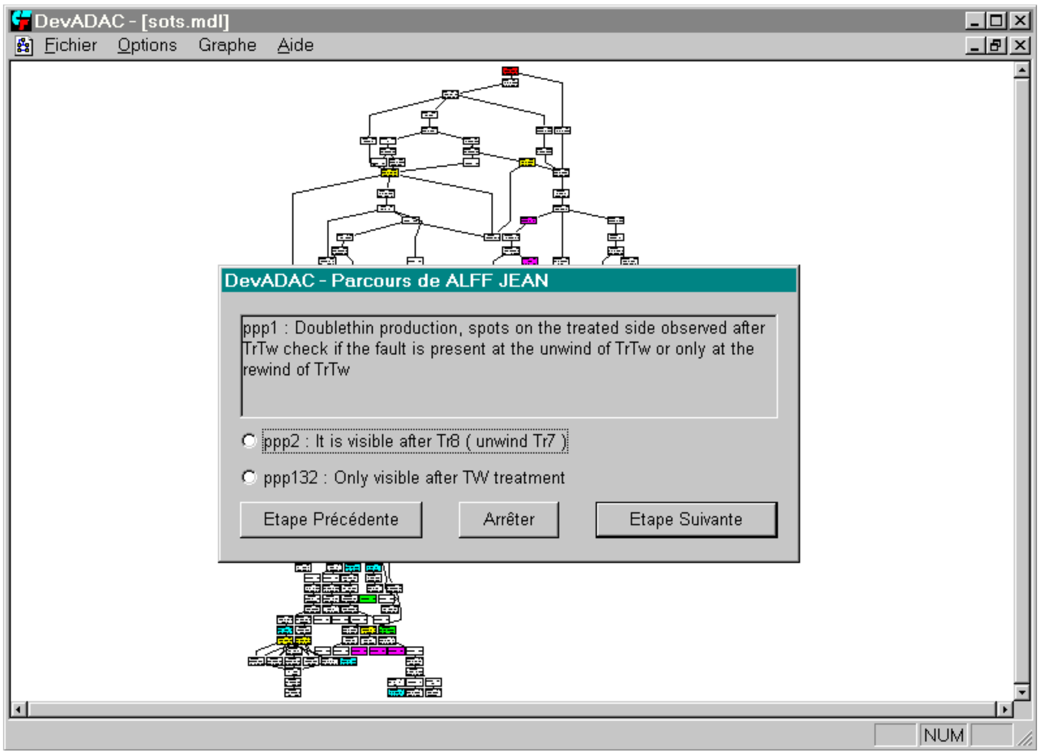

Figure 5.9: The ADAC software: starting a guided diagnosis and repairing process
source: *DEVADAC user manual, F. Barba* (2000)

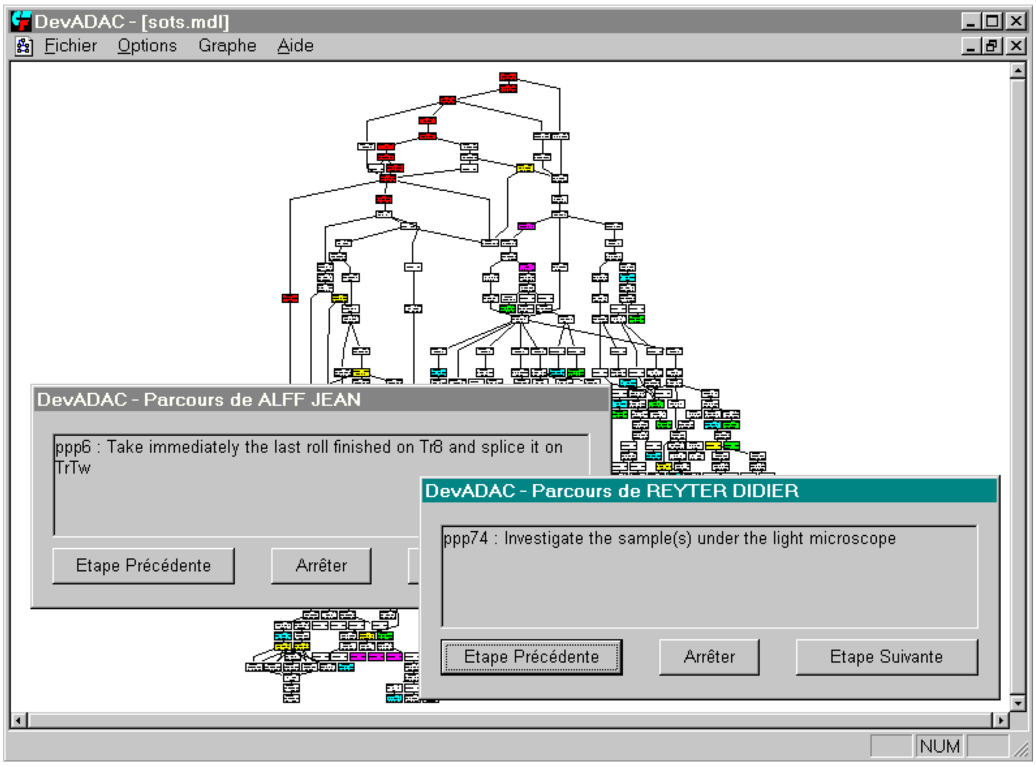

Figure 5.10: The ADAC software: concurrent guidance of two parallel repairing processes

source: *DEVADAC user manual, F. Barba* (2000)

5.6 Concluding the ADAC case

To conclude the ADAC case let us briefly summarize the operational advantages the IOAK system provides for solving the ADAC problem.

- *Genericity of the model*: the IOAK design allows universal application in various industrial contexts.
- *Domain independent operational representation*: the diagnosis and repairing knowledge appears under the form of a trace graph that may be operationally described with the help of any adequate formal scripting language and therefore may be used for guided execution of regular, official diagnosis and repairing strategies.
- *Historical records* of critical situations, i.e. a regular strategy has not been able to solve the production fault, are consequently stored and may be thoroughly analysed.
- *Operational guidance*: Less experienced operators may effectively guided through the repairing process, based upon regular, official guide-lines. This guidance prevents also unnecessary repetitions of same investigations, tests or repairing action by subsequent shifts.
- *Automatic learning*: The historical database about critical situations is automatically updated via usage of the system. The more varied the IOAK system is used, the more efficient its advice in the critical phase will be.
- *Parsimonious learning*: The learning of the IOAK system starts at a high and critical level, where the regular, already clearly formulated knowledge becomes incomplete, uncertain and fuzzy.

This concludes also the second part of or work. After detailed and self-contained presentations of each of our three industrial case studies: the SYSCOG , the COMAPS and the ADAC study, we shall now discuss, in a third part, general validation issues of the HECDA approach.

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Part C

Practical and scientific validation of human expertise centred decision aid

Part C : Practical and scientific validation of HECDA

Abstract

In this last part of our work, we discuss validation issues with respect to the knowledge appearing through our HECDA approach.

Following Roy[9], we may notice the fact that, though a given application of HECDA has been accepted by a decision maker and has given him satisfaction, that is by no means to be taken as a scientific validation of the concepts, models, methods, tools and results we have presented in detail in the previous part of our work. With a similar argument, may the failure of an application not be seen as a scientific falsification (in the sense of Popper) of the HECDA methodoloy.

Validity of the methodological framework provided by the HECDA approach and by the practical results thus elaborated in a constructive way, must be attested on the basis of two minimal conditions:

- First, there exist real decision making contexts, in which the practical efficiency of the HECDA approach has been demonstrated either in allowing to make "predictions" about a state of affair, or allowing to stimlate or inhibit certain phenomenas (manifestations, events, real experiences) in relation with the actual decision. This issue will be in the center of the discussions in Chapter 6 on page 187;
- And second, there exists a research community large enough who is interested in the HECDA approach and who sees in these concepts, models, tools and results a fruitful contribution to the scientific field in question – i.e. decision aid and OR. We shall discuss this issue in Chapter 7 on page 203.

[9]The overall layout of this thrid part is largely inspired here by an important contribution by Bernard Roy concerning the difficulty to validate, from a scientific and pratical point of view, a decision-aid science whose objects – "*quest for working hypotheses*" – cannot "*be rooted in the path of realism*". (B. Roy, 1993).

Chapter 6

Human expertise centred decision aid at work

"I need a life full of things," I said. "*Full of facts.*"

"*Facts,*" said Ormerod Goode. "*Facts.*" He meditated. "*The richness,*" he said, "*the surprise, the shining* solidity *of a world full of facts. Every established fact – taking its place in a constellation of glittering facts like planets in an empty heaven, declaring* here *is matter, and* there *is vacancy – every established fact illuminates the world. True scholarship once aspired to add its modest light to that illumination. To clear a few cobwebs, No more.*" ,

THE BIOGRAPHER'S TALE, A.S. BYATT[1]

Contents

[1] Chatto & Windus, London (2000).

6.1 Introduction

In this chapter we shall discuss practical efficiency of our HECDA approach on the basis of their respective industrial impact.

In a first section, our three industrial case studies will be revisited from the point of view of the practical impact they had on the ongoing real life decision making process. Apart from our three illustrative case studies of applied HECDA, we briefly present in a second section similar studies conducted at the IASC laboratory in Brest. In the presentation of this work we shall follow a path from low to high interaction with the experienced decision maker.

6.2 HECDA facing real problems and data

It is time now to report the practical impact all three industrial studies, i.e. the SysCog , the Comaps and finally the Adac project, have had on their respective decision making context.

6.2.1 Industrial impact of the SYSCOG project

The industrial impact of the SysCog project may be analyzed along two arguments: First, the enhancing of the production outcome; And second, the cognitive decision assistance we could provide.

6.2.1.1 Good industrial results

From the beginning to the end of the project, a reduction from 11% to 6% , i.e. around 50%, of the overall production scrap was observed. The amount of scrap production is directly linked to physical and chemical parameters characterizing the transitions between following production campaigns (See Section 3.2.3 on page 62 in Chapter 3). Even if it is difficult to associate this good result with some precise intervention of ours, it remains that the cognitive assistance of the plater operator greatly enhanced his technical scheduling ability.

This good practical result contrasted with the managerial reception our study received.

6.2.1.2 Cognitive decision assistance

The plant manager was quite unsatisfied with the results of the SysCog study. He attributed the reduction of the overall scrap to a knowledge they certainly knew prior to the intervention of the SysCog team.

His initial interest in the SysCog study was, in fact, based on the expectation to obtain eventually a "push button" software that would allow him to exhibit automatically better production plans than the actual ones elaborated by hand by the plater scheduler. Unfortunately, no such completely automated scheduling procedure could be proposed, and thus he was deeply disappointed. On the contrary, the plater operator gained new efficiency in his argumentation against the plant manager.

Due to this hierarchical conflict, a major part of the interesting partial automatizations we had achieved with the help of the CHIP programming environment (Bisdorff et al., 1995) could not be properly acknowledged by the operational staff at the TrefilARBED plant.

But this apparently negative result concerning the overall failure of the SysCog project from an institutional point of view underlines the otherwise extremely positive outcome of the cognitive study, namely the pertinent cognitive assistance we could offer the plater operator and the confirmation of his real and socially recognized decision expertise. This fact was naturally confirmed in private by the plater operator.

6.2.2 Industrial impact of the COMAPS project

The impact of the Comaps project is analyzed, first, on the European level and second, at Circuit Foil Luxembourg.

6.2.2.1 General industrial impact

The Comaps project originated from the Brest Thomson plant where the co-ordinator G. Coppin was working at that time. Industrial interests, at least at a strategical level, were clearly expressed. Unfortunately, the effective involvement of Thomson's operational staff in the Comaps project, apart from the efficient project management part, appeared rather difficult and no lasting industrial impact could be initiated.

At the second industrial site involved in the Comaps project, i.e. Textar in Leverkusen near Köln, strategic interests in the Comaps approach appeared rather late. Indeed, for the operational staff at place, the Comaps project was, in a first stage, seen as something abstract allowing simply to pump subventions from the EU Commission without any concern with their immediate industrial interests.

When we visited the Textar plant at a later date, we could, however, convince the quality control managers to record and study the objective history of some of their effective control practice. It is still, at present, astonishing for us, to remember the "naive" belief of the production control managers in the fact that their operators were naturally following exactly what is officially prescribed in order to control the production installation. How great must have been their surprise when they discovered, with the help of the COMAPS tool, that their operators did generally not follow precisely these official rules and that they noticed quite noticeable differences in control expertise among their operators. Thus they changed from indifferent to unconditional fans of the COMAPS approach, and further industrial developments around the COMAPS methods and tools were planned to follow the actual COMAPS project.

6.2.2.2 The COMAPS project at CIRCUIT FOIL

At CIRCUIT FOIL Luxembourg, the general COMAPS project was considered of strategic importance and a consequent involvement of CIRCUIT FOIL in the project could be noticed from the beginning on.

However, motivation and final goal, both of the COMAPS team and of the R&D Managers at CIRCUIT FOIL may not have been exactly the same. The overall goal of the COMAPS project was to develop a system for maintaining, on-line, a given production control expertise (see Section 4.1.4 on page 101 in Chapter 4), whereas the managers of CIRCUIT FOIL rather looked for a system to guide and guard the actual production control with the help of official production rules. This latter goal appears naturally as a practical sub–goal of the more ambitious general COMAPS goal, so that no essential divergence between the respective goals appeared during the project.

Nevertheless, a certain irritation, when confronted with the complexity of the COMAPS algorithm (see Section 4.6.2 on page 144) rapidly appeared. Continuous automatic updating of the control expertise as a consequence of using the COMAPS tool on-line in the ongoing control practice, as proposed by the COMAPS team, was not considered acceptable from the industrialist's point of view. The official control theory was to be considered a de facto stable production standard that has to be applied as best as possible. Periodic updating of this standard may be envisaged, but, in no case, should the normal control practice automatically adapt and change it. Only the specific quality manager is allowed to consciously alter, and only in coordination with all concerned authorities, the official production control rules.

It is clear, therefore, that the "CHECK AS YOU DECIDE " device was primarily imagined at CIRCUIT FOIL and that it is essentially the guarded production control aspect that mostly interested the CIRCUIT FOIL managers from a practical point of view. Consequently they undertook a specific software development to implement the "CHECK AS YOU DECIDE " device, but solely in the context of a static control theory. Updating of the actual control theory, if required at all, has to be done by hand by the corresponding R&D engineer responsible for the actual production process of the plant.

This split of the practical problem into, on the one hand, the common daily problem of operator assistance through the "CHECK AS YOU DECIDE " device based on an official Circuit Foil control theory, and , on the other hand, the periodic problem of updating these official control rules, is mostly relevant. The first, highly repetitive problem has easily been solved with the help of adequate software development, whereas the second problem remains one that has to be tackled *consciously* by a human expert, here the engineer responsible for the quality of the overall production process.

The presence of a R&D engineer in the daily control meeting (see section 4.1.3 on page 100) may be efficiently replaced by the presence of the Check as You Decide device which incorporates the official control theory and puts into practice a corresponding control guarding. Automatically recording in a "*back office*" manner, the evolution in time of the performance of the operators in terms of observed quality of the production outcome with respect to following or not the official control theory, allows to manage both the quality of the production controllers but also of the control expertise as given by the official control rules. This stage of practical exploitation of the Comaps tools has currently started at the Circuit Foil plant in Luxembourg.

6.2.3 Industrial impact of the ADAC project

Finally, clearly distinguishing between a given *regular* and, therefore, compliant knowledge concerning diagnostic and repairing of common production defects, and a *critical*, i.e. unstable, knowledge that may only be considered as more or less recommended, represents the industrial strength of the Adac project from the pragmatic point of view.

As mentioned in Section 5.5 on page 175 in Chapter 5, a consequent software development followed the Adac project and practical tests of this software, on several different production installations, are at present conducted at the Circuit Foil plant. Results are encouraging and further studies should give more insight into the pragmatic pertinence of this tool.

It is worthwhile mentioning here, that the Adac tool, more specifically the graph layout tool for describing the regular repairing actions (see Figure 5.8 on page 177), could be favourably used for describing and maintaining the official control rules appearing in the Comaps problem. It is astonishing how long it took the author to understand this evident pragmatic correspondence between the Comaps and the Adac project. When a production engineer claimed in the early stage of the Adac project, that this latter project was essentially the same as the Comaps project and that we should concentrate all on the Adac project, we protested energetically, principally invoking the complex cognitive problem tackled in the Comaps project, i.e. the continuous maintaining of the control expertise against the "simple" cognitive problem of using a static, regular knowledge as proposed in the Adac approach.

Considering at present the pragmatic range of both tools with the benefit of hindsight, we must admit that the practical intuition of this engineer must be brought out.

This intervention again supports the important fact that the CIRCUIT FOIL goal in the COMAPS project was clearly not focused on an automatic, on-line updating of the official control rules, but rather more on the assistance for formulating and applying the actual regular knowledge of the production in every day production practice.

Before discussing this strategic conflict which comes here to light between the COMAPS team, and more specifically the Brest team around J.-P. Barthélemy, and the CIRCUIT FOIL managers, let us briefly present related HECDA work developed in Brest.

6.3 The HECDA approach developed at the IASC

In this section we present related work, contemporary to our three industrial case studies, that was realized at the IASC laboratory in the context of the JADAR research program and under the scientific impulse from Barthélemy and Mullet (1995; 1994; 1996).

6.3.1 The JADAR research program

The JADAR research program, running roughgly from 1993 to 1997 at the IASC Departement at the ENST de Bretagne in Brest, was devoted to the design of interactive systems for decision aid and knowledge acquisition. The aim was to study the cognitive processes at work in judgement activities and to use them for elaborating corresponding decision aid tools such as: Automatic rules acquisition based on some heuristics for decision making; Cognitive systems for decision aid applied to environmental protection; Cognitive systems for decision aid applied to quality control of industrial processes; Methodology for extracting and analyzing judgement processes and; Decision aid applied to banking and financial problems.

Following researchers were involved: Jean-Pierre Barthélemy, Pascal Boldini, Michel Briand, Pascale Kuntz, Benoît Archieri, Gilles Coppin, Fabrice Guillet, Sarhan Hichéri, Jean-Daniel Kant, Christine Lapébie, Philippe Lenca, Emmanuel Pichon, Jan-Wei Wang.

Cognitive systems for automatic rule learning was the key element of this research and six Ph'D theses were conducted in the context of this project: Gilles Coppin: *Target tracing*; Fabrice Guillet: *Control of industrial processes*; Jean-Daniel Kant: *Connectionist approaches to decision heuristics*; Christine Lapébie: *Decision heuristic implementation*; Philippe Lenca: *Decision in savings products*; Emmanuel Pichon: *Industrial process planning*; And J. Wang: *Decision rule extraction*.

The very first work concerning the emerging idea of the HECDA approach represents an alternative approach compared with classic machine learning techniques such as decision trees and rule extraction approaches (Archieri et al., 1994). Essential difference to these more classic methods lies in the fact that the algorithmic development is driven by the MBH model of the decision maker's expertise (Barthélemy and Mullet, 1996; Pichon et al., 1994b).

Formal requirements underlying this early approach are:

1. That the decision maker supports a stable and consistent formal representation of the decision problem, a fact we denote as "*Galoisian*" (see Figure 6.1) and that a historic set of observed decision situations is provided and;

2. Decision making concerns non cyclic ordinal categorical judgments semiotically based upon multiple aspects from discrete ordinal attributes.

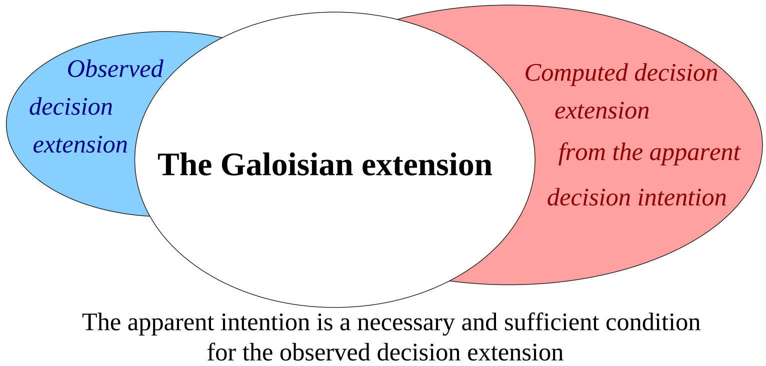

Figure 6.1: The "*Galoisian*" decision maker

We call "*Galoisian*", a decision maker, who utters a formal decision intention that is equivalent, in terms of its corresponding computed decision extension, with his observed decision making extension (see Figure 6.1).

6.3.2 The polynomial calculator

A first implementation of the approach is discussed in Wang (1995). From the structural architecture of this tool, shown in Figure 6.2 on the following page, we may notice that, in these early realizations, the cognitive aspect of the HECDA approach is directly anchored in the MBH model, i.e. a polynomial representation consisting of an addition (disjunction) of monoms (conjunction) of aspects (see Section 2.3.4 on page 42 in Chapter 2 on page 29), chosen as mathematical model for representing and extraction the decision making expertise.

The application concerns the observation of 14 clinical psychologists with respect to their usual pedagogical orientations and recommendations, a case study provided by Mullet (1996). The test persons were participating on a voluntary basis, asking only for a cognitive feedback once the apparent decision strategies were computed.

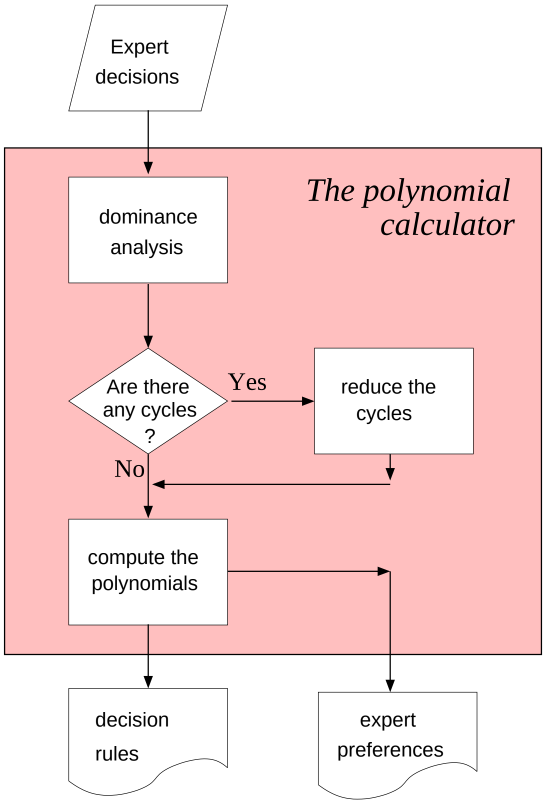

Figure 6.2: Structural architecture of the polynomial calculator
source: *Wang* (1995)

From the overall design of the calculator, we may easily see that this *behaviouristic* approach to HECDA relies mainly on a mathematical tool which provides a description of the apparent decision making expertise on the basis of a given extension of decision situations without any direct cognitive intervention of the decision maker. Formal outcome is a, generally, small set of apparent decision rules that support dominance based decision making strategies in the sense of Montgomery. The polynomial calculator represents, in fact, a specialization to ordinal attribute domains of our most general decision theory algorithm (see Section 4.4.3 on page 128 in Chapter 4). In this sense it may appear essentially as a *critical investigation* tool in the context of the HECDA approach.

Working hypotheses are, as mentioned above, a *Galoisian* decision maker, admitting non-cyclic ordinal dominances between polynomial categories and a given coherent decision reference, i.e. either reducing the decision history in case a small set of decision situations induce a cycle or grouping the concerned decision categories.

6.3.3 The Categ_ART tool

A second implementation of such a critical investigation tool, mixing this time sub-symbolic with symbolic elements, has been realized by Kant (1996). His neural net tool, CATEG_ART called, may be seen as a *psycho-mimic* approach to compute a given decision expertise from a given decision reference.

Let $\mathcal{L}_s$ be a symbolic language and $\mathcal{M}_c$ a cognitive model. Following Kant (1996, p. 60), we may say that a decision aid system is psycho-mimic with respect to $\mathcal{M}_c$ and $\mathcal{L}_s$, if and only if:

- Its architecture presents all functionalities necessary for taking into account the cognitive principles of the model $\mathcal{M}_c$;
- Outcome is expressible in the language $\mathcal{L}_s$;
- The operations that characterize its internal functioning, directly implement the cognitive principles of the model $\mathcal{M}_c$ and produce intermediary representations again expressible in the language $\mathcal{L}_s$.

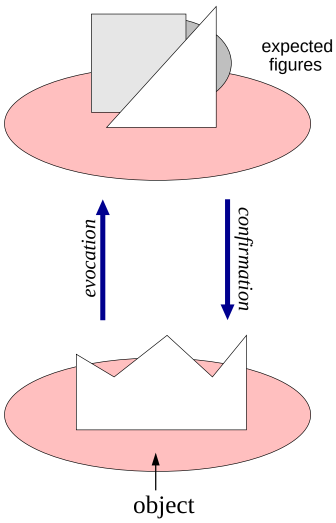

Figure 6.3: Illustration of the resonance-competition principle
source: *Kant* (1996)

Apart from the cognitive principles inherent in the MBH, the Categ_ART tool relies on a *competence–resonance* principle giving the abduction process which allows the decision maker to look for the right dominance structure to use with the less cognitive effort possible. This principle, illustrated in Figure 6.3, works as follows:

Resonance: Decision is triggered by resonance of a given action with a particular structure supporting the awaited shape an action must show in order to be accepted as *the* decision;

Competition: If several such structures may enter in resonance for a same given action and potentially induce contradictory decisions, a competition mechanism is used to choose one structure for the final decision.

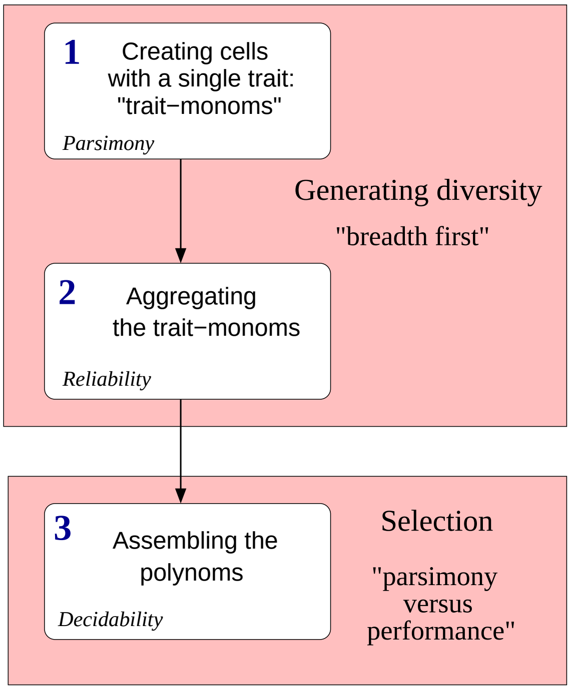

Figure 6.4: The three main steps of the learning algorithm implemented in the Categ_Art tool

source: *Kant* (1996)

The Categ_Art learning algorithm is divided into three main steps as shown in Figure 6.4. The first step implements the parsimony principle in order to construct atomic aspects (trait-monoms) through the resonance mechanism. In the second step, aggregation of trait-monoms is guided by the reliability principle in order to reduce bad classifications. Finally, the last step creates the polynoms (the actual classes) from the layout of the active connections elaborated in the neural net during the previous steps.

Kant has applied his Categ_ART tool to a marketing study in private banking. The goal was to uncover the apparent preferences, experienced customer would express with respect to a given set of placement products of the CMB (Crédit Mutuel de Bretagne).

6.3.4 Cooperative decision expertise extraction

The polynomial calculator used by Wang (see Section 6.3.2 on page 193) was originally designed to automatically extract decision rules from a given decision reference. Following an algorithmic result obtained by Pichon et al. (1994a)[2], it appeared interesting to incorporate the polynomial calculator into an interactive questionnaire, generating on the fly a minimal decision reference that is necessary to compute the apparent decision rules.

This approach resulted in a second generation of interactive implementation of the polynomial calculator:

- Leading first to the Asclepius tool as proposed by Guillet (1996).
- A second and similar experience was conducted by Lenca (1997), who proposed the Apache tool with a corresponding application in banking.

6.3.4.1 Application of the Asclepius tool

The underlying industrial case study concerns the description of a melting process control expertise. This industrial application represents the initial motivation for the Comaps project definition.

The practical objective of Guillet's study is to enhance the controllers expertise. The ordinal attribute space representing the control of the process was elaborated from interviews with an expert controller who was asked to specify the relevant attributes with their corresponding ordered modalities. Three attributes with 4 modalities and one with 2 modalities were used.

The decision problem appears as a selection problem concerning three ordered categories: Excessive (1); Satisfactory (2); Or insufficient (3) quality outcome. The cognitive task of the decision maker consists in classifying each proposed control setting in one of these three categories.

The practical session with the Asclepius tool generated 49 questions which the expert controller took 20 minutes to answer. At the end of the session, the knowledge extraction resulted in an exhaustive list of accepted control settings for each of the three categories. Evidently, the control settings gathered under category (2) represent the apparent control reference, i.e. the extension of the control expertise, whereas the corresponding anti-chain with its associated control rules represents the apparent intentional control expertise.

During the execution of the questionnaire, no cognitive feedback was delivered to the expert controller, who simply answered the automatically generated questions. At

[2] Computing the decision rules corresponding to ordered categories in a multi-attribute space is formally equivalent to compute a maximal anti-chain representing the borders between the categories. This problem, computationally difficult in the general case, becomes computationally easy to solve in a monotone ordinal attribute space.

the end, the expert was at first very astonished by the rather large number of satisfactory control settings he discovered in the computed control reference. After close inspection, he admitted that in his mind he had indeed never explored in such great detail all potentially satisfactory solutions. We find here a similar cognitive result, we noticed in the SysCog study, where the initial number of admissible production campaigns was very small compared to our computed reference (see Section 3.5 on page 85 in Chapter 3). In a second step, the expert controller was confronted with the outcome of the polynomial calculator, i.e. the apparent satisfactory control rules. After close inspection (10 to 30 seconds per rule) he concluded that all rules made sense and were in fact practically applicable. Similar to both previous cases, the Asclepius tool also requires the hypothesis of a *Galoisian* decision maker.

6.3.4.2 Application of the Apache tool

The Apache tool (Lenca, 1997), similar in its algorithmic design to the previous Asclepius tool, implements again an interactive version of the polynomial calculator.

Lenca's practical application concerns the extraction of saving strategies from three kind of persons: A regular saver familiar with usual financial products, a novice saver, not specially familiar with the usual product but potentially very interested in discovering adequate offers, and a specialist, a professional consultant in financial products. Similar to Pichon's work (1996), Lenca reports details of the working sessions with the Apache tool. For the novice saver, he could for illustrate quite interestingly a specific learning mechanism. Indeed, the tool could generate explicitly formulated rules for preferences, the novice user only knew "intuitively". The expert saver, well-aware of his saving strategy, could for his part see the Apache tool precisely confirm this particular strategy after the working session.

It is worthwhile noticing that in the Asclepius, as well as the Apache application, the decision reference underlying the apparent cognitive decision rules, is implicitly constructed in correspondence and in parallel with the computations of the polynomial calculator. In this sense, these tools generally represent knowledge extraction tools.

For experienced decision makers however, as was the professional consultant above, the tool may also be used as a formal validator tool for previously known regular decision strategies. Main working hypothesis for the correct practical application is again the *Galoisian* decision maker condition. Decision extension, i.e. the exemplary decision reference, matches the uttered decision intention.

6.4 Conclusion

Let us conclude with a general view on all these practical applications from an HECDA approach's point of view.

6.4.1 Computing the decision expertise

Unfortunately, both the initial "batch" version of the polynomial calculator as well as the Categ_Art tool, were not applied in a real every day decision making context outside a University laboratory, so that it is difficult to thoroughly discuss practical validation in a properly pragmatic oriented decision-aid sense.

Nevertheless, these potential decision-aid tools appear as cognitive psychology oriented alternatives to classic machine learning techniques. Thus they may give some operational support for critical investigations concerning effectiveness and consciousness of a given decision expertise, similar to the methods and tools we have presented and used in the COMAPS case study (see Section 4.4 on page 125).

Kant (1996, pp.159–172) has, for instance, been able to show that his psychomimic constructions: On the one hand, the aggregated monoms, may be seen as a conjunction of *typical* aspects shared by most of the objects of a same category (Rosch, 1973) and, on the other hand, the selected polynoms may be seen as formal disjunctive expressions of family resssemblances (Rosch and Mervis, 1975).

6.4.2 Collaborative expertise extraction

The interactive refinement of the polynomial calculator, as implemented in the ASCLEPIUS and APACHE tools, represents a major step forward in the direction of practically relevant HECDA tools. An important cognitive assumption nevertheless remains, i.e. they specifically address the Galoisian decision maker, in the sense that the computed decision rules are supposed to represent correctly both the decision extension as well as the decision maker's conscious intention.

The operational purpose of the IASC approach remains ideologically anchored in a decision-aid problematic similar to classic engineering problems. In terms of B. Roy (1992), we remain in the case of a "*quest following the path of realism*". The cognitive constructs in the mind of the hypothetic decision maker are indeed supposed to exist in a real world. We are going to describe them, after more or less complex computations, with the help of the MBH's formal language.

This basic epistemological position, resulting from a mathematical Psychology oriented view on decision making, may explain the latent difficulties we experienced with the IASC researchers when designing our COMAPS methods and tools. We will recover this discussion in the last chapter.

6.4.3 Collaborative validation of a given decision expertise

The cognitive decision-aid tools developed in the SYSCOG study all rely on a similar working hypothesis. The decision maker must again admit a Galoisian representation of his decision expertise but only, in an asymptotical sense, via the necessary converging in time of the validating hermeneutical circle. Indeed, the SYSCOG type decision aid makes sense if the validating circle admits some fix-point where decision extension (the decision reference) and decision intention (the decision theory) meet in a stable formal representation both of the decision problem and its solving strategies.

Up until now, the "*Galoisian* character of the decision expertise appears as timeless condition, applicable in a "hic et nunc" consideration. The operational objective of the COMAPS project, however, clearly puts the question of validating a given decision expertise in a general temporal horizon where learning and maintaining of solving strategies is in the center of the design. The Galoisian condition remains somehow required, but in a much weaker version. The matching of decision extension and intention may only appear necessary in the long run, after some more or less long time of consequent use of the COMAPS tool.

Effectively observing a conscious, slight divergence between an observed decision reference and the intentional discourse covering the corresponding decision practice, represents now the essential practical motivation for undertaking any decision aid study to reduce if possible this divergence.

We observe here a shift from a *classic* scientific quest concerning the description of "*real*" things existing in the world independently from the observer to a "*constructive*" science. This issue will be discussed in the last chapter.

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Chapter 7

On the way to a HECDA science

" ... It emerges [...] that a "decision science" [...] can only be rooted in the path of realism, which implies accepting postulates and hypotheses which have proved unusable in the practice of OR–DA. [...] By shifting the object for the quest for knowledge, it nonetheless appears possible to speak in terms of a "decision–aid science". However [...] the validity and viability of the body of knowledge produced remains sources of further questions."

BERNARD ROY, DECISION SCIENCE OR DECISION AID SCIENCE (1992)

Contents

7.1 Introduction

In this chapter we show that the study of human expert decision making is gaining more and more importance amongst a whole range of scientific disciplines such as cognitive psychology, knowledge engineering, cognitive sciences, history and epistemology.

Each such connection to a neighborhood science of Operations Research will only be shortly sketched, as the overall objective of this chapter is to outlay a future research program aiming at validating, but also enriching, the palette of methods and tools that we have illustrated all through our three industrial decision aid cases.

In order to not overload our work, this last chapter will only be sketched. Several points that we are going to introduce would in fact need deeper investigation. That would however delay too much the final release of our work. May the reader see it hints for further, ongoing research on the topic of human expertise centred decision aid.

First we turn our attention to related work in general Psychology.

7.2 The psychological point of view

After a general historical overview[1], showing the ever lasting prevalence of the concern about "human reasoning" in psychology, we turn in a second section our attention more precisely to recent research in cognitive psychology.

7.2.1 From general Psychology to Behavioral Sciences

Starting with Hume's inquiry concerning human understanding we see that "*there appear to be only three principles of connection among ideas, namely, Resemblance, Contiguity in time and place, and Cause Effect*" (Hume, 1739). This *associationism*, continued by Hartley (1749), first points to the necessarily procedural constitution of human expertise. Indeed, Hartley distinguished two forms of associations between ideas: successive and simultaneous. The first are built up when train of ideas, regularly follow one another and get bound together, whereas the second are built up between ideas that regularly come together at the same time. What has now to be considered is the effective observation of any decision expertise.

Here Watson's *behaviourism* comes to our rescue (Watson, 1913), in the sense that he integrates Okham's parsimony principle with Hume's associationism, but instead of considering expertise as mental capacities, he focuses on effectively observable behaviour. Decision expertise is not primarily a mental capacity but rather more an *expert behaviour*.

[1] This part is extracted from a recent paper (Barthélemy et al., 2002)

Such expert behaviour is only conceivable in the context of a pragmatic approach towards decision problems. Here James, with his attempt to construct a psychological science that will teach a person how to act is pointing at the horizon (James, 1892). Meaning of ideas is found in terms of their possible consequences, in our case here, in terms of observable satisfactory decision behaviour.

But it is not a new kind of operant conditioning, in the sense of Skinner (1950) that we are interested in, but instead we rely on modern *Cognitive Psychology* where cognition is mainly studied from the *information handling* standpoint. Where classical behaviourism completely ignores consciousness, we reintroduce *states of consciousness* as one essential component of human centred processes we are going to design. Indeed, the behaviouristic concept of direct simple linkage between environment and behaviour appears unsatisfactory. Human operators are active and intervening participants in their environment and human memory is not a simple store of past situations, but is organized so as to efficiently assist complex adaptive behaviour in real life.

Another root of classical behaviourism may be found amongst the Utilitarists theorists (Bentham, Mill, ... but also J. Bernouilli [1738]). Utilitarism is based upon the requirement that a human decision maker tends to chose his/her most "attractive" alternative. This approach involves the so called "rationality principle" that can be stated as follows:

- The decision maker is able to generate exhaustively all the scenarios relative to decision situations;
- He(she) is able to evaluate attractiveness of each of them;
- He(she) is able to aggregate these local evaluations in a global one and;
- Finally, (s)he chooses alternatives with the most favourable global evaluation.

These four points are assumed in the classic utility theory, as axiomatized by Von Neumann & Morgenstern (1944). Further developments, taking into account more realistic behavioural facts, lead to various models within Behavioural Sciences like prospect theory (Tversky and Kahneman, 1981, 1992), stochastic choice and random utility models (Luce, 1969) and more recently media theory (Falmagne, 1996) .

The classical OR approach to decision aid, but also the multicriteria decision analysis developed by the European school (see Chapter 1 on page 15) still strongly rely on this rationality principle. A critical perspective, coming from Cognitive Psychology, however, puts in doubt this commonly accepted rationality principle.

7.2.2 New insight from cognitive psychology

Recent research (Lundberg, 2000; Lundberg and Nagle, 2002; Lundberg and Svenson, 2000) in cognitive psychology, gets more and more concerned by the investigation of human decision making expertise when facing complex real world decision problems. We may observe here, similar to our approach, a qualitative shift from the investigation of simplistic decision making tasks, as usually discussed in this discipline, towards more complex decision making processes, generally involving experienced decision makers facing real and, mostly, very complex problems.

This kind of research results now directly concern the psychological investigation of the cognitive validation step (see Section 2.2.2 on page 37), we have presented in Part A. Decision theoretic research is here focusing on post decision processing, i.e. how experienced decision makers may implement subtle consolidation and differentiation strategies (Svenson, 1992, 1996) in order to reduce dissonant cognitions by re-evaluating and reconsidering them. It appears that such post decision restructuring of the decision problem focuses on the most important attributes, leaving the less important attributes unaffected (Svenson and Benthorn, 1992).

A critical study of this scientific literature in a conjointly pragmatic and hermeneutical perspective, as underlying our HECDA approach, is a worthwhile consideration. The EURO HCP working group on "Human centred Process"[2] will certainly provide a lot of opportunities for future work on this issues[3].

But a similar evolution may be directly observed in the field of Cognitive Sciences when considering the description of cognitive systems in general.

7.3 From a Cognitive Sciences point of view

Again a historical review allows us to put into perspective the origins of the formal representation such as the MBH underlying our HECDA approach.

7.3.1 Contesting the classical rationality principle

The common rationality principle, as proposed by the classical utility theory, has been strongly attacked by H. A. Simon (1955; 1983).

"*... It is easy to construct conceptual abstractions – like those in the literature of economic and statistical theory – that describe decision making as a process of choosing among possible states of the world. Whatever their value for conceptualizing certain aspects of the theory of choice, these abstractions cannot be taken as description of actual decision making systems, since they ignore a central fact of this decision–making process: that it must be carried out by an information processing system whose computational powers are poor in comparison with the complexity of the environment with which they must cope. Factorization of the*

[2]See `http://www-hcp.enst-retagne.fr`

[3]Gustav Lundberg actually chairs the international Programme Committee of the 14th Mini EURO forthcoming in May 2003 in Luxembourg and organized by the author. Olav Svenson is foreseen as one of the invited guest speakers for this conference.

complexity by the device of selective attention is an indispensable adaptive mechanism ..., (Simon, 1977, p. 159). The *bounded rationality principle* he introduced, assumes that the decision maker is able to optimize but only within the limits of his(her) representation of the decision problem. Such result is fully compatible with many results in the psychology of memory (see Section 2.1.2 on page 31 in Chapter **2**): An experienced decision maker, using solving strategies compiled in long-term memory, solves a decision problem with the help of his(her) short-term working memory.

Inheritances of this bounded rationality principle may be listed:

- Decision making involves *heuristics* like the satisfaction principle (Simon, 1977), representativeness and availability Kahneman et al. (1982) as well as framing effects Tversky and Kahneman (1981);
- Decision making appears to be close to *problem solving* (Huber, 1982);
- Decision making involves *global evaluation* of alternatives that are supported by short-term working memory and that must be compatible with various kinds of *attractiveness scales* (Svenson, 1979, 1983);
- Finally, decision making can be viewed as an achievement of a more or less complex information process and anchored on the search for a *dominance structure* (Montgomery, 1983). The decision maker updates his(her) representation of the problem with the goal of finding out a case where one alternative dominates all the others.

This leads us again directly to the mathematical model of human decision expertise as proposed by the MBH (see Section 2.3 on page 39 in Chapter **2**).

We do not have the place here, to investigate, in detail, the scientific roots of the MBH and to thoroughly discuss the important place this mathematical formulation of human decision expertise occupies in our methodological approach. But again, forthcoming events in the context of the EURO HCP working group[4] will certainly provide occasions for discussion and developments.

Besides the theoretical considerations, Cognitive Sciences, similar to our concern, consider generally a pragmatic dimension supporting a mimic reconstruction of human (natural) intelligence.

7.3.2 About cognitive systems in general

Modern cognitive sciences provide us with the insight that cognitive systems, in general, are an association of a *physical working device*. That is, they are environment sensitive through perception and action and they possess a *mind* generating mental activities designed as operations, representations, categorizations and programs leading to efficient problem solving strategies.

[4]See the Web site `http://www-hcp.enst-bretagne.fr`

Mental activities inside the system act on the environment who. itself. acts again on the system through perceptions producing by the way representations. This synergy with an environment leads a cognitive system to develop autonomous abilities of auto-organization (structuring of representations, categorizing through factorization of the environment *a.o.*).

Designing and implementing human centred systems for planning, control, decision and reasoning, therefore, requires the study of the operational domains of a cognitive system along three dimensions:

- An *environmental* dimension where first, *actions* performed by a cognitive system may be observed by the way of changes in the environment and secondly, *communication* is an observable mode of exchange between different cognitive systems;
- An *internal* dimension where mental activities, i.e. *memorization* and *information processing*, generates changes in the internal states of the system. These activities are however influenced by partial factorizations through the environment (planning, deciding and reasoning, change the course of the world) that appear essentially as stable cognitive constructs;
- And an *autonomous* dimension where *learning* and *knowledge acquisition* enhance mental activities by leading to the notions of self-reflexivity and consciousness.

The reader may easily recall the presence of all these specifications in the cognitive systems that were put into practice within our three industrial case studies. The systematic exploration of scientific literature concerning the design and implementation of general cognitive systems has still to be done. The question to be asked would be: can the study of our HECDA approach be related to the emergence of a *science of cognitive systems*?

We now turn our attention towards the general science of history.

7.4 From a meta-historical point of view

As well illustrated trough all the three industrial cases shown in Part **B**, the very nature of human decision expertise objectifies itself in a complex historical reconstruction of the decision practice of the experienced decision maker. This historical work has to be confronted to relevant issues, as discussed in the context of the science of history, ie.e *Meta-history*.

It seems to us that two important issues have to addressed: On the one hand, the symbolic coding step (see Section 2.2.2 on page 37 in Chapter **2**) which necessarily prefigures the decision practice in order to capture the semiotics of the decision making process and, on the other hand, the abstraction of the decision reference from the qualifying of the decision history.

7.4.1 About prefiguring the decision practice

Concerning the necessary coding of the observed decision practice, we may recall with H. White that, "*before the historian can bring to bear open the data of the historical field the conceptual apparatus, he will use to represent and explain it, he must first* pre*figure the field – that is to say, constitute it as an object of mental perception. This poetic act is indistinguishable from the linguistics act in which the field is made ready for interpretation as a domain of particular kind, That is to say, before a given domain can be interpreted, it must first be construed as a ground inhabited by discernable figures. The figures, in turn, must be conceived to be classifiable as distinctive orders, classes, genera, and species of phenomena. Moreover, they must be conceived to bear certain kinds of relationships to one another, the transformations of which will constitute the "problems" to be solved by the "explanations" provided on the levels of emplotment and argument in the narrative.*"(White, 1973, p. 30).

Heavy discussions between the members of the COMAPS team were concerned with this problem and major methodological differences appeared during the COMAPS project between the Brest team and the Luxembourg team. In Brest, under the direction of J.-P. Barthélemy, the ad hoc formal implementation of the decision practice as constructed by the COMAPS tool, was seen as a pure mathematical artefact without any cognitive relevance for the decision maker. The MBH compliant formulated decision expertise inside the COMAPS tool generally does not bare any cognitive relevance outside the COMAPS algorithm. On the contrary, in Luxembourg, and especially at CIRCUIT FOIL, these formulations, constructed and maintained by the COMAPS tool, were considered as the proper socially accessible and accepted formulations of the official decision rules underlying the decision expertise. The argument above in this sense supports the Luxembourg position.

Again, time and space limits prevent us in this work to progress on this problem, but future research and discussion is necessary to really master this issue in the context of our HECDA approach.

A second issue, generally tackled by Meta-history, concerns the all important distinction we have made between the concepts of decision *history* and decision *reference.*

7.4.2 Abstracting a decision reference from the decision history

Indeed, as noticed by H. White, ".. *there does, in fact, appear to be an irreducible ideological component in every historical account of reality. That is to* *say, simply because history is* not *a science, or is at best a proto-science with specifically determinable nonscientific elements in its constitution, the very claim to have discerned some kind of formal coherence in the historical record brings with it theories of the nature of the historical world and of historical knowledge itself which have ideological implications for attempts to understand "the present", however this present is defined. To put it another way, the very claim to have distinguished a past from a present world of social thought and praxis, and to have determined the formal coherence of that past world,* implies *a conception of the form that knowledge of the present world also must take, insofar as it is* continuous *with that past world. Commitment to a particular* form *of knowledge predetermines the* kinds *of generalizations one can make about the present world, the kinds of knowledge one can have of it, and hence the kinds of projects one can legitimately conceive for changing that present or for maintaining it in its present from indefinitely.*"(White, 1973, p. 21).

It is essentially the pragmatic dimension of the decision aid that contains the keys that allow us to qualify a past decision practice in order to abstract from it the exemplary decision situations we install as decision reference. And this step, has to be validated with this pragmatic dimension in mind.

Before closing the discussion, we would like to question the "cognitive responsibility"[5] (Pepper, 1966) of our human expertise centred decision aid approach. The perspicuous reader may have noticed that the ethical issue, of great importance for validation of any decision aid, but even more for a human expertise centred one, has apparently not gained our attention.

7.4.3 Cognitive responsibility

Why should we be so much concerned by a rather "*intuitive knowledge*" when technical knowledge and computational capacities of our civilization appear so tremendously convincing. Think of the plant manager in the SysCog case, who wants a "push-button" solution in order to impose his point of view against a competent human expert. Likewise, a guarded decision device such as a "Check as You Decide " device, may easily be transformed in a *restricted* or *confined* decision making, a temptation some managers, basically convinced of the necessary correctness of their regular knowledge, surely will not withstand to put into practice.

More fundamentally, what allows us, in a critical perspective, to put artificial, computed decision theories against corresponding "*natural*", i.e. more or less intuitive solving strategies proposed by a human expert? Does it makes scientific sense to compare computed control rules in the Comaps tool for instance with the official

[5] Pepper introduces the notion of *cognitive responsibility* to distinguish between philosophical systems committed to rational defenses of their world hypotheses and those not so (see White, 1973, n12, p. 23).

control rules in use at CIRCUIT FOIL? The discussion was heavy within the COMAPS team about this issue. Pure behaviourism doesn't allow to accept neither as something "*real*" besides the objective decision practice.

For our part, we would like to put forward a "*cognitive responsible*" HECDA approach, which does not alienate the decision maker's natural decision expertise in a way that it gets confined and eventually vanishes in front of an automatic decision making device.

In our technical world, human decision making, essentially seen as not being reliable and stable, is being, as far as possible, replaced by robots and machines so as to guarantee a faster, more stable and apparently formally correct decision making practice. For those who would easily stand up for this apparently rational issue, let us close our work with following *true* story.

> Beginning the nineties, a group of German economists and journalists visited Japan in order to consult the Japanese business community about the advancement of the new information technologies in their activity field. The German group also visited the old Tokyo Fish market guided by the old director. Looking at the apparently chaotic bidding with hundreds of people shouting, making signs and running around, one German guest asked the director whether they had not yet thought of perhaps supporting the bidding operations with a computerized system. "*Well*", answered the old director, "*in fact we had already put such a system into practice some time ago, but we have had to switch back to our traditional system mainly out of two precise operational reasons.*" And he continued to explain that first, the computer assisted bidding was definitely to slow. Human handling coupled with visual communication by far outranks in speed any keyboard or other mechanical input device based bidding system. But this reason was not essential. The second reason he gave was more serious and irreducible. The market traditionally keeps a solidarity fund to cover bidding errors, which insures fishermen as well as fish handlers against financial disasters induced by an erroneous bid. In case of an error, it is generally not possible to know precisely who's fault it was. With the computerized system however, it became now too easily apparent who made the error, the fisherman, the handler or the broker. With the consequence that the market solidarity could no longer be invoked as easily as before, eventually threatening the existence of the solidarity fund and even of the convivial community around the traditional old fish market.

7.5 Conclusion

In this chapter we briefly sketched some connections to neighbour disciplines of OR such as general and cognitive psychology, cognitive sciences and meta–history in order to show: First, that our major concern, i.e. modelling human decision making expertise, has a long standing tradition in these fields; And secondly, many of our arguments may go back to original insight developed in these fields.

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Chapter 8

Conclusion

> "... *So läuft die Bewegung des Verstehens stets vom Ganzen zum Teil und zurück zum Ganzen. Die Aufgabe ist, in konzentrischen Kreisen die Einheit des verstandenen Sinnes zu erweiteren. Einstimmung aller Einzelheiten zum Ganzen ist das jeweilige Kriterium für die Richtigkeit des Verstehens.*"
>
> VOM ZIRKEL DES VERSTEHENS. HANS-GEORG GADAMER (1959)[1]

In the preceding pages we have discussed design and implementation of decision aid systems that specifically address the experienced decision maker.

We started our discussion, in a first part, by recalling the classic Operations Research approach to decision aid, as well as the methodological paradigm switch from mathematical optimization techniques to multi-criteria decision aid, with the intention to illustrate that both these decision-aid approaches are not adapted to situations where the involved decision maker shows a certain amount of decision expertise.

To address the experienced decision maker – a situation we generally meet when trying to tackle industrial decision aid problems – we therefore introduced a specific human expertise centred decision aid (HECDA) approach, a methodology for decision aid addressing the experienced decision maker. It is mainly the refined consideration of a given decision making history, where the decision expertise is objectively reflected. That last point makes up the distinguishing feature of the HECDA approach. In this

[1]"... *So runs the movement of understanding from the whole to the part and back to the whole. The task is, through concentric circles, to widen the unity of the captured meaning. According all details to the whole, represents the respective criterion for judging correctness of the understanding*". in *Hermeneutik: Wahrheit und Methode.* Gesammelte Werke, 2. Band, H. G. Gadamer (1986)

methodological framework, the Moving Basis Heuristics (MBH) is introduced as major alternative for modelling cognitive solving strategies of experienced decision makers.

In order to illustrate the proposed HECDA methodology on work, we presented in a second part three illustrative applications of human expertise centred decision aid: The SysCog application: a cognitive decision aid laboratory designed for uncovering and checking the solving strategies of an experienced human operator confronted with a complex production scheduling problem; The Comaps project: a guarded production control system based upon the exploitation of a large history of expert production control; And finally, the Adac study: a guided production fault diagnosis and repairing system.

In a third part, we discussed first practical validation issues with respect to the knowledge appearing through our HECDA approach. Related work conducted by research workers from the IASC department at the ENST de Bretagne is briefly introduced and discussed from the point of view of its relevance for practical application. Finally, a last short chapter briefly sketches some perspectives for further scientific validation through the exploration of connected disciplines such as Cognitive Psychology, Cognitive Sciences and Meta-history.

Appendix

All references used through all chapters are gathered in the general bibliography below.

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