depending on whether one asks people directly or their liquor stores. (It was done, and the second value turned out to be twice as high as the first.)

1.5 Organization of the Thesis

The work begins with an introduction to the most important psychological models in human cognition that are relevant to understand the exchange of information between people and computers (Chapter 2). This chapter is also dedicated to mental models, i.e. how the user *visualises* the system he deals with.

In Chapter 3 is introduced the concept of system complexity. The computer is considered as information interface between user and process in order to reduce and match the complexity of the process and of its operations to human cognitive limits.

Practical suggestions for the design of the user interface with particular consideration to the organization of screen page layouts are contained in Chapter 4. The design of the user interface of a satellite control station, is described in Chapter 5; here the interface is also critically evaluated on the basis of the information presented in this work. The conclusions of the Thesis are reported in Chapter 6.

In Appendix 1 the most important guidelines and standards for the design of user interfaces are listed. Appendix 2 contains a critical evaluation of two papers in the field of human-computer interaction.

research on human planning in manufacturing systems, she indicates how an increasing amount of work is widely dispersed, and many researchers are not aware of one another's work. In her own words

> "With a few outstanding exceptions, papers in this area tend to suffer from shortcomings of procedure and reporting which jeopardise their impact as severely as do conceptual inadequacies. These include poor justification of independent variables, problems with choice of subjects, the number of subjects, task pacing, and poor rationale for the dependent variables chosen. [...] It is appropriate to pause and ask what the manufacturing sector really needs from human factors. Otherwise we may be providing answers to questions that might not be relevant."

The recollection of my own experiences designing database applications and user interfaces has helped me considerably to evaluate the literature, that was sorted according to a simple subjective criterion: as *useful* (e.g. experiments about the handling of complex systems by humans and that give insight to the question), *neutral* (e.g. articles about the importance of metaphors in the user interface) or *useless* (e.g. psychological models that do not build on an experimental basis and are not related to real human behaviour).

As good as it might be, the published literature can give only partial insight to issues in human-computer interaction. This theoretical information can be extended by testing real interfaces on one's own. A method I like is trying to operate vendor machines without reading the instructions and figuring out the way they work from the aspect of the panel. In this way I once lost a Bankomat-card, that was retained by the ATM-machine.

In some of the fields where computer control is used (and abused) the users have made their complains heard. Collecting this information directly was also part of the background work to prepare this Thesis.

In fact, computers are used by millions and millions of people world-wide. These people represent a much better pool of information than a dozen test subjects in a room. We need new methods to search for knowledge in the real world in order to extend the results gained from more restricted experimental settings. After all, an investigation on the consumption of alcohol would lead to different results than graphical interfaces and that are published a few years after the introduction of Apple Macintosh and graphical desktop interfaces for DOS machines? By then, the customers have already decided by themselves.

Modern tools support the development of high-quality graphics on computer displays. Symbols are first generated on screen pages and are then connected to process values; the state of the process controls the appearance of the symbols on the screen. With the help of these tools one can produce neat and clean but also disorganised and cluttered process pictures. The decision about *what* to display and *how* to display it - once a certain tool is given - is made by the process engineer. This Thesis wants also to address the question of what information is needed to select and organise the content of an user interface.

1.4 In Search of an Approach

The study of human-computer interaction is a very young discipline and as such it suffers of a number of problems. One of the most important of them is the lack of an established methodology. The subject calls for an interdisciplinary approach; the problem cannot be defined and solved from one point of view only - be it psychology, computer science, neurobiology or else. The majority of authors agrees on this in principle, yet this is easier said than done.

Most published research focuses on just a few themes, mostly military applications (in particular aircraft cockpit design) and of course personal computers ("how do we build a very user-friendly word processor?"). Unfortunately, there is not very much about the human-computer interface in process industry and the use of monitoring, supervisory and control systems.

Another drawback of the current literature is that several of the publications and papers have a very abstract perspective ("bridging the gulf between the user and the application", "manipulating a virtual reality") and present little evaluation of real case studies. Probably due to the novelty of the subject, much work is still dedicated to *label* rather than to *explain* facts.

The problems with current work in human-computer interaction for process-control applications are pointed out by Sanderson (1989). In a comparative

The main hypothesis made in this work is that every human-computer interaction problem is actually a cognition problem of dealing with an unknown, complex system (not all systems need to be complex; simple systems can be considered as special cases of the more general problem). The **user interface** acts then as **complexity interface**. A technical process has an intrinsic complexity and its operation is perceived more or less difficult by the human user depending on several conditions. We will examine ways how - on the base of the original system and human cognitive limits - the complexity of the *comprehensive* system consisting of the original process and its control computer can be reduced to less than the complexity of the original process alone. In such a case the use of the computer interface is warranted.

We witness today a wide discrepancy between theory and praxis in many fields, and human-computer interaction theory is one of those. On the one hand, there is a wealth of very specific knowledge, mainly reported on scholarly publications (*Ergonomics*, *Human Factors*, *IEEE Transactions on Systems, Man and Cybernetics*, etc.). Conferences on this topic are organized and their reports are published in thick volumes; "user-friendly" has even become one of the established mode words in the computer field. On the other hand, what is done in practice depends largely on what is available on the market, so that at the end a few companies in Japan *de facto* decide on what hardware we will use and similarly a few companies in the USA decide about how our software will look like.

A simple example to explain this point better. Since 1988 there is a standard in Germany, DIN 66234, "*display work places, principles of ergonomic dialogue design*", (see Appendix A1). I might have been an inattentive observer in that country, but I never heard of a single instance in Germany where software was praised to be "DIN 66234-conform". As known, "IBM-compatible", DOS, UNIX, MS-Windows dictate in reality much more the aspect of solutions. Even if MS-Windows were not up to the requirements of the DIN standard, it doesn't matter. It would sell anyway, in Germany as in the rest of the world.

This does not mean that MS-Windows or similar software are poor products. Rather, research work should be closer to real-life to be of use in order to produce interfaces that are really oriented to the needs of the users. What is the use of experiments to test whether alphanumeric displays are better or worse result in higher strain on the operator or in a more complex user interface. Therefore, the requirements of the technical process including the way work is carried out *together* with knowledge of the cognitive capabilities of the user must provide the frame on which the user interface is built.

We are focusing here on the human-computer interaction, but this should not leave the process computer and the technical process out of scope. The user wants to get a result by the *entire* system he interacts with, not just to have a nice-looking interface. However, we must count that for a long time many systems will still be designed to be complex and the user interface will be the only element that can make operations simpler. In this, at least we have an advantage: a computer-based interface is software, and software is the most ductile material at man's disposal - it depends on how we use it.

Finally, it should not always be implicitly assumed that all process control tasks must be carried out by computers. A correct and comprehensive theory for human-computer interaction should provide a frame to recognize when a computer-based user interface is actually needed and when not.

1.3 Goals and Results of this Thesis

This work focuses on the application of process computers (monitoring, supervisory and control systems) as interface between technical / physical processes and their human operators. The main question stated in this Thesis is

"*What indications can we get from psychology / cognition science in order to configure the operator interface in a process control system?*"

To answer this question, current theoretical information from the literature is structured and organized in a form suitable as practical guideline for design. In this work no new experimental results are presented, but experiments that are already documented are evaluated in consideration of their relevance for practical applications. The design of a modern satellite control centre in Germany is then evaluated on the basis of the presented theory.

goal} must therefore be designed in such a way that the user remains in control of the goal.

This aspect raises the question of **transparency**, often simply stated as such (as we did earlier), that the monitoring and control computer must be transparent to the user and the technical process. But in an automated or supervisory system the computer cannot be transparent by definition. For example, when do the operator commands represent actual controls and when set-point signals? In a supervisory system, the user ends up working with a new process (tool) represented by the combination of the original technical process with the process computer.

The question of transparency can be exemplified by Figure 1.3. Between the user and the goal are the technical process and the control computer. The technical process and the technical functions in the control computer are defined by the nature of the process and fixed (i.e. not under the control of the user interface designer).

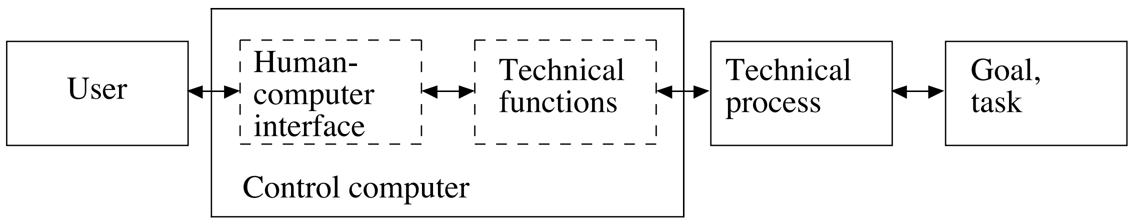

Figure 1.3 Systematic relation between user, computer, process, and goal

To draw an analogy with system science, the technical process may be denoted by **S** and the control functions by **R**. In order to reach complete transparency between the user and the goal, the human-computer interface must then perform the function $(\mathbf{RS})^{-1}$ or $\mathbf{S}^{-1}\mathbf{R}^{-1}$. This work focuses primarily on the configuration of the user interface, i.e. on the design of $(\mathbf{RS})^{-1}$. We will also examine here to what extent transparency is desirable.

If there is an intrinsic mismatch between the computer system and the process to be controlled, e.g. because of a poor selection of sensors and actuators, this will

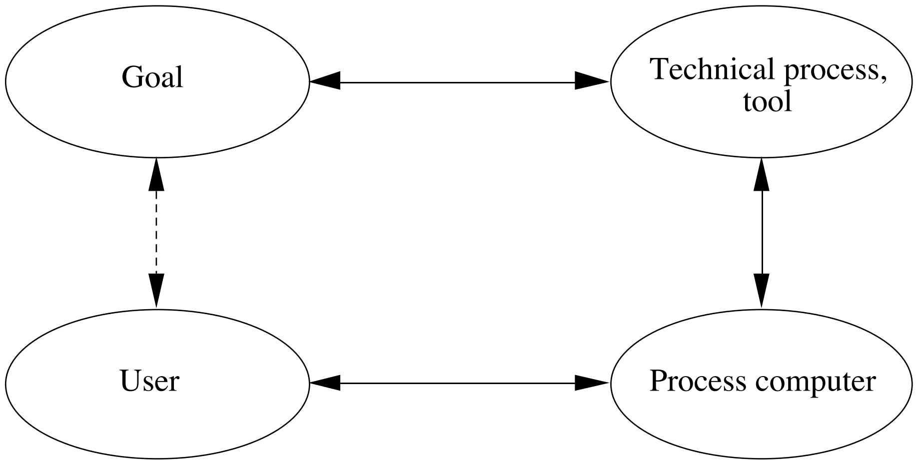

Figure 1.2 Use of the process computer in the control of the technical process

interacts with the technical process at a higher level, defining goals and subgoals rather than the actual commands to reach them. **Control** means that the computer can influence the technical process and **automated control** that the selection of the signals to influence the process is made autonomously by the computer. Many automated and regulation functions can be performed without computers, although computers tend to be used more and more to replace earlier techniques. In many cases, especially in large and complex plants, there is a combination of all these methods.

Whatever the process computer is - a monitoring, supervisory or automated control system - it remains no more than "the tool to use the tool" and must therefore not be confused with the process goal itself. For long time though, because of an inadequate and not fully mature computer technology that generated at least as many problems as it was supposed to solve, human operators not seldom had to dedicate more attention to the computer systems than to the applications the computers were intended for. But ultimately the user wants to see the fulfilment of the goal and does not want to concern himself with the process computer for its own sake. On the other hand, the user can only interact with the technical process via the process computer. The interaction {user <-> process computer} and {process computer <-> technical process <->

to user and goal. In practice the tool is never transparent, and the human has to learn how to use it by experience, relating how its operation leads to the desired results.

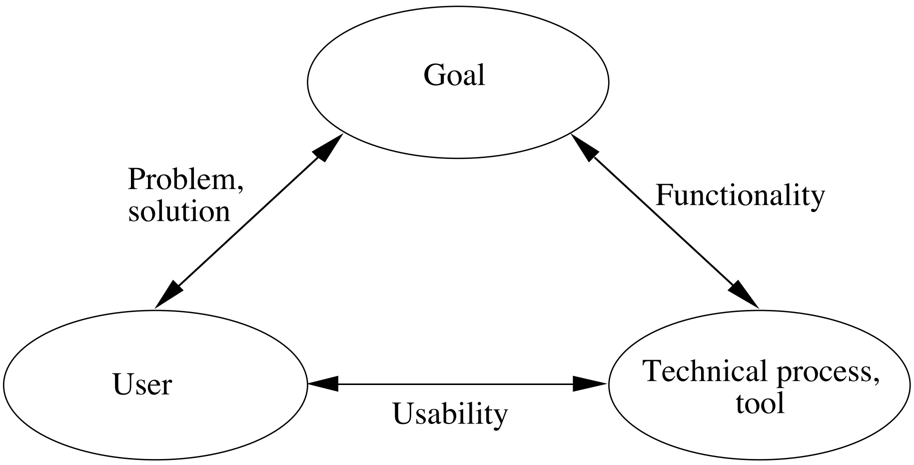

Figure 1.1 The three major entities of every technical process

When computers are used to control the process (the initial "tool"), the model represented in Figure 1.1 is no longer valid and must be extended in order to encompass the technical process itself and the computer control system (Figure 1.2). The user still wants to reach a goal, but can reach it only indirectly, with the help of the technical process. Yet also the technical process cannot be manipulated directly, but only through the control computer.

The user ends up working with two tools in order to reach the primary goal. If the process computer is not correctly adapted to the technical process, this makes the operation more difficult for the user, because he now has to conceptualise the technical process itself, the control computer and also the way they both interact. Computers can be used in different ways in process control. We will use the term **process computer** to denote any kind of computer connected to technical processes. A **monitoring system** collects process data and presents it to the operator in a suitable form. A **supervisory system** performs some automated functions or regulation tasks. With a supervisory system, the human operator

Different terms are used to denote the "contact point" between humans and machines: *User Interface*, *Man-Machine Interface*, *Man-Machine Communication*, etc. We will use in the following **Human-Computer Interaction** (**HCI**) and **User Interface** for two reasons. **Interaction** is a broader term than **communication** and describes better the whole range of different aspects in the interplay between people and computers. Moreover, communication implies that humans and machines are cognitively at the same level, and that is not the case. "Human" is of course more general than the restrictive "man". Finally, we focus here mostly on computer-based interfaces and not on the use of artefacts and machines in general, although many of the considerations may hold also in the more general case.

1.2 The User Interface for Process Control

Let us consider the purpose of technical processes. A *technical process* is a combination of physical components (and their operations) performed in order to act on, and change, something in the physical world. Movement, chemical reactions and heat transfer are all processes in this sense. Examples of processes are any industrial or chemical production, room conditioning (i.e. the control of the physical variables temperature and humidity), and transportation, which consists in the controlled change of speed and position in a vehicle. Three entities can be identified in relation to every technical process (Figure 1.1):

- user
- goal
- technical system/process (tool)

The user wants to reach a certain result and to do this he uses the technical process (tool). The tool acts therefore as the *interface* between user and goal. For a simple goal, like fixing a mechanical part, a simple tool is sufficient, the screwdriver (this does not mean that the invention of the screwdriver was a simple task). The production of large quantities of chemicals is a different goal and also the "tool" is different, in this case a large and complex plant. In general, the tool should be built in such a way that the user can concentrate on the goals and not be distracted by the way the tool itself works, i.e. the tool is *transparent* control panels and the aspect of commands to be entered by the user. The information presented by the computer to the user (and that is mostly defined by the system designer) must be easy to understand, even in complex situations, so that the user can make the correct operational decisions.

This does not mean that there is agreement about the scope of human-computer interaction; in fact the confusion is still widespread. Quite often "user friendly" is understood as "many colours on the screen" or as the use of some national language. Not many designers or users look at the interface in terms of complexity reduction, matching mental models, task fulfilment and the like. This is an indication of a more complex problem, namely that many end users cannot define their own needs and therefore want interfaces that address the *appearance*, but not the *essence* of the problem.

These problems in human-computer interaction derive from the fact that this discipline is not based on a few well-defined parameters the same way Newtonian mechanics and electrical theory are, but rather on much more elusive aspects that only in part are related to experimental criteria. Yet from the theory of human-computer interaction is requested a practical contribution to interface design.

This raises the question of what kind of knowledge we are looking for. Artists work unconsciously in a way that cannot be described as a formal set of instructions. A picture can be well balanced, stimulate imagination and - most important of all - convey a message. The same can be said of a book, a piece of music, a movie or an advertising blackboard. Yet there is no set of rules about how to write a good book or make a good movie. There are, however, sets of rules that, if broken, lead mostly to poor pictures, books, music and movies. This might also be the role of human-computer interaction at the present, to provide the basis to analyse and guide the design of user interfaces, without acting as an immediate blueprint.

Human-computer interaction theory will therefore be a powerful tool to determine where the boundaries are, i.e. what *not* to do rather than what to do, but alone it will not ensure the quality and completeness of a result. There will still be a dimension that cannot be confined to any handbook or list of rules, and where the human designer will retain the most important role.

During the 1970s and 1980s, microelectronics made possible the diffusion of computers on a large scale; this led to the impact of the computers with a large, non specialist population. It was no longer possible to require hundreds of thousands of people to become experts; the computers had instead to be designed to be easier to use. Ergonomic principles were used to investigate the particular aspects of computer use: this field is so important that it has turned into a discipline of its own, **Human-Computer Interaction** (**HCI**).

Today most complex technical systems and processes are controlled to some extent with help of digital computers. The initial intention was to simplify and optimize system operations, but it turned out later that it was not always the case. In fact, it has already been observed that the problem with computers is that they do what we *tell* them to do, not what we *want* them to do. The goal of human-computer interaction is to bring the two aspects closer, where the means is the design of the user interface.

The importance of ergonomics in process control applications is now well understood also from the general public. The accidents in the nuclear power plants at Three Mile Islands (USA, 1980) and Chernobyl (USSR, 1986) have drawn enormous public attention to the consequences of the operations of complex systems that are poorly engineered, especially in consideration of the role played by humans.

Computers are used to collect data and present it in suitable form to the human operators, as an interface for control and even to carry out automated operations. This has led to important consequences on how work is performed. For example, operators in charge of chemical processes used to read data from some instruments and then intervene on the process by manipulating control devices. In automated plants they are responsible over larger part of the technical process by *observing* how computers and automated controllers carry out the task.

The control system engineer faces the problem of human-computer interaction as user or as designer. As a *user*, he should know how to approach a system, what to look for, what to expect and how to quickly recognize the general operational principles for a process. If a system is built on consistent and logical rules, the user will be able to operate it in a short time. As a *designer* of a control system, he has to define how the process-related data is presented on terminals and

1 Introduction

1.1 The Need for a New Approach to Human-Computer Interaction

The design of the user interface has become one of the most important aspects in the development of computer systems. The purpose of this interface is to facilitate the exchange of information between the user and the machine (computer or technical system) to be controlled. A well designed user interface fulfils several purposes: it makes work conditions more pleasant, helps to reduce errors (and thus possibly to limit the extent of damage to the system under control) and finally enables the user to understand the function of the technical system. This type of knowledge is necessary when unforeseen actions have to be performed, e.g. in the case of emergencies. All these aspects are treated in the present work.

The history of the use of a methodological approach to study the interaction between humans and machines goes back to World War II. A new discipline, called **human factors**, was used to select the personnel in relation to the task to be accomplished. Yet it soon turned out that with the growing complexity of some systems, like e.g. aircraft, some tasks became too complicated to be performed even by specialists. The perspective of human factors therefore changed to investigate also how to fit the job task to the person.

Human factors is known in Europe as **ergonomics**. Traditionally, the European approach has always been more oriented to study how the work environment can be configured to adapt best to human workers than selecting the humans to fit the environment. Ergonomics is an interdisciplinary science that integrates knowledge from fields as different as engineering, physics, physiology and psychology.

Since the beginning of computer development and for a long time, the object of attention has always been the machine. Computers were most of all designed to work effectively with the available technology; they were not designed to be easy to use. In order to operate a computer, the human user had to be a specialist with detailed knowledge of the internal workings of the machine.