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PRAVDĚPODOBNOSTNÍ PORADNÍ SUBSYSTÉM JAKO SOUČÁST DISTRIBUOVANÉHO ŘÍDICÍHO SYSTÉMU SLOŽITÉHO PRŮMYSLOVÉHO PROCESU

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PROBABILISTIC ADVISORY SUBSYSTEM AS A PART OF DISTRIBUTED CONTROL SYSTEM OF COMPLEX INDUSTRIAL PROCESS

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Prohlášení

Předkládám tímto k posouzení a obhajobě disertační práci zpracovanou na závěr doktorského studia na Fakultě aplikovaných věd Západočeské univerzity v Plzni. Prohlašuji, že jsem tuto práci vypracoval samostatně s použitím odborné literatury a dostupných pramenů uvedených v seznamu, který je součástí této práce.

V Plzni, 15.2.2018 Ing. Ivan Puchr

Abstrakt

Složité průmyslové procesy jsou obvykle řízeny pomocí sofistikovaných řídicích systémů. Řídicí systémy garantují základní fungování procesu, avšak část odpovědnosti za správné nastavení některých parametrů je ponechána na operátorovi. Vzhledem k tomu, že nastavení těchto parametrů může značně ovlivnit chování celého procesu a případně i kvalitu výroby, je žádoucí vybavit operátora podpůrným nástrojem, který mu pomůže vyvarovat se nesprávného nastavení těchto parametrů. Jednou z možností je nasazení počítačového poradního systému.

V této práci je diskutován pravděpodobnostní poradní systém a jeho integrace do celého řídicího systému. Protože fungování poradního systému je značně závislé na dostupnosti kvalitních technologických dat z procesu, je věnována velká pozornost sběru, přenosu a uchovávání dat v distribuovaném řídicím systému a také některým technikám pro posouzení kvality signálů a pro jejich případné vylepšení.

Zpracování technologických dat pro účely poradního systému za použití Bayesovské teorie pravděpodobnosti je v práci diskutováno též.

Řešení jsou v práci demonstrována na příkladu složitého průmyslového procesu, konkrétně na válcování ocelového pásu.

Klíčová slova: distribuované systémy řízení, komunikační sítě, meziprocesní komunikace, sytémy pro podporu rozhodování, zpracování dat, data mining, shluková analýza.

Abstract

Complex industrial processes are usually controlled by advanced control systems. The control system guarantees basic functioning of the process, but a part of responsibility for the setting of several parameters is left to operators. As the settings of these parameters can substantially influence the behaviour of the whole process and possibly the quality of production, it is reasonable to provide the operator with a support tool that can help him to avoid improper settings of these parameters. One possibility is to provide the operator with an advisory system.

In this work, a probability based advisory system and its integration into the whole control system is discussed. As the advisory system is highly dependent on the availability of process data of a good quality, attention is devoted to data acquisition, transfer and storage within the distributed control system together with some techniques for signal validation and quality enhancement. The processing of data for the purposes of the advisory system, in this case based on the Bayesian probability theory, is discussed in detail further in this work.

For better understanding, the problems and solutions are explained by using of an example of complex industrial process—metal strip rolling.

Keywords: distributed computer control systems, communication networks, inter-process communication, decision support systems, data processing, data mining, cluster analysis.

Contents

1 Introduction

Up-to-date control systems of industrial processes can manage to control the particular process even without substantial help of an operator in many cases. Yet, there exists a set of applications where operator's involvement in process control is unavoidable. There are several reasons for this. Let us quote the most frequent one: process is affected by influences that are not or even cannot be measured, and the operator uses his experience and intuition to replace the missing information.

In this situation, an experienced operator can be, at least temporarily, quite successful, but it is a hard work for the operator in any case. The quality of control and thus the quality of production is highly dependent on operator's long-term experience and on his actual psychical and physical condition. With change of this condition or with change of the operator for a less experienced one, the quality of production can vary significantly. The reason need not be subjective ability of the operator only, but also objective reasons such as for example that operator cannot follow all measured variables at the same time. It is usually presumed that people can continually follow five values at most [1].

To help the operator and to minimize the variation of production quality, advisory system can be introduced as an extension of control system. Development of the probability based advisory system takes advantage of results of several research projects aimed to utilization of probabilistic theory for industrial applications. Projects are listed in the following table:

Period	Acronym	Name	Partners	Grant	Program/Call
2000-2002	ProDaCTool	Decision Support Tool for Complex Industrial Processes based on Probabilistic Data Clustering	University of Reading (UK), ÚTIA AV ČR, Trinity College Dublin (IRL), KOR Rokycany, COMPUREG Plzeň, s.r.o.	IST-1999-12058	IST-Shared cost RTD (FET)
2005-2011	DAR	Data Algoritmy Rozhodování	ÚTIA AV ČR, COMPUREG Plzeň, s.r.o, FAV ZČU, ...	1M6798555 601	MŠMT PP2-DP01
07/2009-06/2012	ProBaSensor	Probabilistic Bayesian soft sensor—a tool for on-line estimation of the key process variable in cold rolling mills	COMPUREG Plzeň, s.r.o, ÚTIA AV ČR, Josef Stefan Institute (SLO), INEA d.o.o (SLO)	E!4632	EUREKA-Eurostars, MŠMT
01/2013-12/2015	ProDisMon	Probabilistic distributed industrial system monitor	COMPUREG Plzeň, s.r.o, ÚTIA AV ČR, Josef Stefan Institute (SLO), INEA d.o.o (SLO)	E!7262	EUREKA-Eurostars, MŠMT

Table 1 Research projects concerning the advisory system.

Author of this document has cooperated as a team member of COMPUREG project partner on all these projects.

For illustration and for better understanding of particular problems and solutions of the advisory system, an example of complex industrial process with distributed control system is used—metal strip rolling.

Reasons for development of an advisory system are presented in chapter 2. As the research and development process started several years ago and because the advisory system is relatively complex, not all details will be described in this work. Attention will be paid mainly to key parts of the system—data acquisition and data processing. Recently added signal validation and quality enhancement functions are described in final chapters.

Chapter 3 brings a survey of various approaches to the solution of advisory systems, together with several examples of different types of applications.

Development of the system can be roughly divided into several stages. Process data is to be acquired within the distributed control system. All available data that can hold information about the controlled process are useful. This topic is described in chapter 4.1.3., while hardware and software structure of the advisory system can be found in chapters 4.1.1 and 4.1.2. Attention is devoted mainly to inter-process communication within the distributed control system.

The key part is data processing of the acquired data with the use of methods based on Bayesian probability theory. Key principles of the theory are the topic of chapter 4.2.1. Chapter 4.2.2 is focused on the theory of mixtures of probability density functions, which is the basic tool for the processing of acquired data.

Presentation of outputs of the advisory system to operators is described in chapter 4.3.

Data processing methods are calculation-intensive. Performance issues are the topic of chapter 4.4.

Advanced functions of the advisory system concerning the signal validation and quality enhancement are described in chapters 4.5.

2 Reasons for Development of an Advisory System

As mentioned in chapter 1, there is a set of processes and their control systems where direct and continuous involvement of operator in control of the process is unavoidable. Typically, these processes are complex, controlled by a control system with a relatively high number of input and output signals. Control system is usually formed by a set of cooperating subsystems that control local parts of the system and at lower hierarchical levels. These local control tasks can be managed quite easily because of their low-dimensional nature and because low-dimensional problems can be modeled relatively easily with the aim to find suitable control strategy ([2] page 15). Principles and technical realisations of these local control subsystems have been elaborated usually in detail and realized successfully during the past decades.

Operator controlling a complex industrial process has usually a lot of variables available. These variables may describe the behaviour of the process sufficiently but the operator is not able to follow them in their complexity. His physical and psychical conditions influence the performance and results substantially [3]. On the other hand, operator can use his intuition and involves into the decision even the extraneous influences that are not available to the control system (for lack of sensors) [1].

On the contrary, a computerized control system, that would replace the operator, would have the following advantages and disadvantages:

+ the ability to follow almost unlimited number of variables,
+ operation with almost stable performance,
– no intuition,
– cannot involve conditions that are not supported by input signals.

This obviously results in not to supersede operator by a computer but to take advantages of both and support operator by a computer—by an advisory system.

3 State of the Art

In the following subchapters, sources of information are concentrated that are related to the investigated theme of advisory systems. Principles of related projects are summed up here. Evaluation and categorization of principles used in these projects and their relation to our approach are summarized finally.

3.1 Decision Support System for Value Engineering in Flour Mills

In [4], a decision support system is described that helps the operator to adjust parameters of flour mill control system close to optimum from the point of view of selected criterion. The decision support system is designed for a special industrial application, the control of mixing of dozens of material streams (input streams) with different technological properties into a substantially smaller number of final (output) streams. Output streams are required to have specified properties, which are reached by suitable combination of input streams. There are some limitations, e.g. not each input stream can be directed to each output stream from topological reasons. On the other hand, there exist usually several combinations of input streams that can produce required output stream properties.

The solution formulates the problem as linear optimization or linear programming problem. Linear combination of input streams should reach selected criterion under several conditions that must be met. There exist several algorithms that solve linear programming problems but in this case, some obstacles prevented straightforward solution. The main obstacle to overcome was high complexity that resulted in too high computational performance requirements. The problem had to be simplified in several aspects. During the development process, methods of integer linear programming (input stream attributes were quantified by integer values) and binary (zero-one) linear programming were used besides continuous value linear programming. Acceptable solution with reasonable computation time was find in the end. Decision support system was successfully tested in a real industrial environment. Interface to the operator is a special graphical user interface. It offers several possible computed adjustments (combinations of input streams that meet the requested criterion) the operator can choose from. Operator uses his experience and possibly other aspects not known to the advisory system to select among the offered combinations the right one.

From the point of view of developed probabilistic advisory system, following properties of the linear programming based decision support tool should be taken into account:

- Solution with a help of linear programming needs the problem to be described by a linear function, that is to be minimized or maximized, and a set of constraints. This is a limitation that cannot be overcome in all considered applications.
- The use of the described decision support tool is limited to a special industrial process.
- As the solution of the general linear programming problem took much computational time and power, the general linear programming problem had to be simplified with a good knowledge of the industrial process to get reasonable time delays.
- The graphical user interface of the decision support system may be inspirational as it offers not only one possibility but lets operator choose from several acceptable settings. An expertise knowledge based on experience of the operator can help him to make the right choice.

3.2 An Architecture of a Multi-Agent System for SCADA, Dealing With Uncertainty, Plans and Actions

In [5], the authors deal with the problem how to extend a standard SCADA (Supervisory Control and Data Acquisition) system by a possibility to assist operator in making decisions under uncertainty. As application example, control of electrical power generation, transmission and distribution is given. The system is designed to help operator to control balance between power generation and consumption, while information from multiple sources is uncertain.

Handling of uncertain information is based mainly on Dempster-Shafer theory. This approach is similar to Bayesian statistics approach described in next chapters. Dempster-Shafer theory is specific in that respect that instead of probability of a proposition it uses the notion of *belief*. The difference is that belief that proposition is true plus belief that proposition is false need not be equal to one in Dempster-Shafer theory. In other words, the Dempster-Shafer theory handles also the situation that we have not enough information to express either the probability that the proposition is true or the probability that the proposition is false.

Another approaches to handling of uncertain information (e. g. possibility theory) are used in the multi-agent system for SCADA project too. The project exploits also fusion rules for combination of uncertain information from several sources.

The project aims mainly for specific applications characterized by relatively slow processes in an environment with high uncertainty.

3.3 Framework of a Machining Advisory System with Application to Face Filling Processes

In [6], a specific advisory system for the use in the field of machining processes is described. Users of this advisory system are manufacturing engineers who face the problem to plan the production of a new product with a machine tool. Production parameters, machine tool settings are to be adjusted to new conditions. In the article, situation is demonstrated on face milling operation. Inputs of the advisory system are machining parameters such as speed, feed, depth of cut etc., further cutter geometry and material constants. Outputs are cutting forces, workpiece vibrations and spindle vibrations. The advisory system works basically with model of the face milling process in cooperation with some heuristic rules. The system is designed for offline processing. The operator inputs all requested parameters and after a calculation phase, system displays output parameters. The system is not intended as an online advisory system for the operator of the machine tool.

Features of the advisory system can be summed up as follows:

- Advisory system is based on a model of the investigated process. So the model of the process must be known, which is a request that is not always possible to be fulfilled.
- Some properties of the investigated process not included in the model are described with a set of heuristic rules.
- Solution is an example of a grey box model approach.
- Advisory system is not suitable for online support of operator controlling the machinery tool.
- Designed for one specific application only.

3.4 Improving Drilling Results with a Real-time Performance Advisory System

In [7], an advisory system is described that is used in oil industry. Operator-driller is supported by the advisory system during the process of drilling of an oil well. As the advisory system is an example of a commercial product, information about its principles is very limited. Generally, the system is based on model of drilling process. The model is probably adjusted for each location conditions, especially geological parameters are taken into account. This model is created offline during the planning phase days before drilling actually starts. During the drilling phase, the advisory system compares actual drilling conditions with the planned ones in online mode and offers the operator possible adjustments. Data acquired in the online phase are then used for upgrade of the drilling process model. Thorough attention is focused to presentation of information to the operator. 3D and simplified graphic objects are used to attract operator's attention and to let him to recognize the meaning in the wink of an eye. It is especially important in harsh environment of the rig.

In short:

- Grey box model based.
- Model repeatedly adjusted with the use of newly acquired data.
- Heavy duty operator panel due to harsh environment.
- Simplified visualization readable even under bad weather conditions.

3.5 Research and Applications of AHP/ANP and MCDA for Decision Making in Manufacturing

In [8], the author introduces the use of AHP/ANP and MCDA methods for the support of decision in manufacturing. MCDA (Multiple-Criteria Decision Analysis) is an approach to solution of problems where the best alternative is chosen not on the base of one criterion but multiple criteria are taken into account. Criteria are dependent or independent. The dependence of criteria brings the necessity to optimize them as a complex and to cope with possible contradiction of criteria. The most precise machine is usually not the cheapest one, e.g. that is why, solution of these problems is instead of one best possibility a set of most suitable alternatives.

AHP (Analytic Hierarchy Process) is a method for solving of MCDA problems. Problem is decomposed to sub-problems. Sets of alternatives and criteria are chosen and composed to a hierarchy. All alternatives are evaluated by a number in relation to each criterion. The importance of criteria in relation to final goal is evaluated by a number for each of them. The evaluation advances from lover to higher level in hierarchy. In the end, alternatives are evaluated by numbers that enable to choose the most suitable alternative with the respect to desirable goal under selected criteria.

ANP (Analytic Network Process) is a method similar to AHP, but alternatives and criteria are generally taken as independent of each other and are not composed to a hierarchy but to a network.

The author states examples of applications of this approach and draws attention to articles describing the use of MCDA methods in following areas:

- How to reach a competitiveness of a manufacturer on the market

- How to choose the right type of a power plant
- Enterprise profitability analysis
- Risk analysis for improvement of safety of manufacturing system
- And others.

An interesting example of using the MCDA methods for decision support in document printing field can be found in [9].

There exist several software products on the market that support operator in solving MCDA problems. These software tools communicate with operator in the manner of a dialog which is given by the nature of the MCDA problems. The operator have to specify basic initial information and requested goal together with criteria and their weights. The software offers alternatives and enables the operator to experiment with criteria and their weights while displaying how the priorities of alternatives may change.

This type of problems and the approach to the solution of them is not fully compatible with our intended operator support system but it is inspirational. For example, there may exist more than one way how to get from one operating mode of a machine to another one. One way may be to increase the value of parameter A and then to decrease the value of parameter B. Another way may be the reverse order of parameter adjusting. Because both the ways may not be equivalent in consequences, operator than faces the decision which way to choose. MCDA approach may help to solve this problem.

3.6 A Multi-modal Teaching-Advisory System using Complementary Operator and Sensor Information

[10] offers an example of an specialized advisory system used for support of operator teaching an industrial robot to do an operation. The teaching is done by generation of commands for the robot by the operator. The main contribution of the advisory system is the joining of information that is available to robot (inputs from sensors) and of information the operator has available (intuition, experience, the goal of teaching). There is no special mathematical theory support according to information available. The advisory system just presents a concentrated information to the operator and supports him in reaching more precise teaching results.

This advisory system is interesting in it that it uses, besides usual visual interface, an audio output too. This enables the operator to keep watching robot's tool and to be more precise in navigating this tool.

3.7 An Integrated Transport Advisory System for Commuters, Operators and City Control Centres

[11] describes interesting application of advisory system for users and operators of city transportation system. This application is interesting in that respect that traffic control is one of fields which was used for evaluation of developed probabilistic principles in the above mentioned DAR project.

The transport advisory system has three categories of users: passengers, vehicle drivers and operators in control centres. Especially, the use of the advisory system by operators in a control centre and data acquisition are interesting from the point of view of the developed system. The most frequently used information in this system is geo location of transportation vehicles and passengers. As the system is intended for heavily populated cities where there is no problem with Internet connection of mobile devices, no GPS is used for the purpose of localisation of passengers and vehicles. The system uses HTML5 geo location services provided by third party for this purpose. This enables to monitor locations of passengers' mobile devices and build in driver's consoles in vehicles in real time. Acquired location data are concentrated in control centres and create the main base of information for decision support of the advisory system users.

As it is not known what amount of resources the system will need but it is known that high scalability is necessary, the system is not built on a special hardware but it exploits, at least in the development stage, Amazon cloud computing services. The use of cloud computing services may be inspirational because demands for relatively high computing power are expected in our project too, especially for advisory mixtures of probability density functions.

Another interesting moment is how the advisory system tries to reduce amount of transmitted data. The principle consists in grouping of passengers' requests and system replies and suggestions. For example, passengers boarding the same vehicle or waiting at the same bus stop are most probably interesting in the same information.

3.8 Development of an Integrated Decision Support System to Aid the Cognitive Activities of Operators in Main Control Rooms of Nuclear Power Plants

In [12], support tools for operators of a very complex industrial process, nuclear power plant, are described from the point of view of main problems of this specific field. Similarly to other complex processes, the operator faces the problem that he has all necessary information available but he is not able to follow all sources of information simultaneously, recognize all non-standard situations, find solution and carry out proper actions.

The importance of the operator support is demonstrated in the article by the statistics showing that almost in one half of incidents in US nuclear power plants a human error was involved. Another interesting information is that experiments proved that operator supporting system may decrease operator's awareness in special cases. This stresses the importance of proper design of the operator support system. The design of the decision support system in [12] is based on detailed knowledge of human cognitive process.

The support functions of the system are divided into two categories in the article. Improvement of displays and indicators like colours, use of 3D technology and use of latest information presentation approaches like multimedia are called "indirect support". In other words, the ways information is brought to operator. The other category is called "direct support" and comprises means that bring information with added value to the operator. This category consists of advisory and decision support systems, expert systems and knowledge-based systems.

A part of described decision support system is worth noticing. One of subsystems validates operator's actions. Operator after evaluation of information and after making a decision makes a plan of actions that e. g. should return the process from an unstable state to a standard one. Validation subsystem checks the sequence of planned actions and warns the operator or even interrupts the intended action plan with the aim to avoid dangerous or otherwise faulty sequence of actions.

As far as the underlying theory is concerned, neural networks are mentioned in the article. Neural networks are used in fault diagnosis advisory system. To increase the reliability and credibility of generated advices, two neural networks are used. One network processes logical input signals concerning alarms and statuses of particular parts of the process. The second one processes analog input signals bringing similar information as the logical ones. Outputs of both networks are merged with the aim to increase the reliability of information presented to the operator.

3.9 A Hybrid Neural Network and Expert System for Monitoring Fossil Fuel Power Plants

In [13], authors introduce an operator support tool consisting of combination of a neural network model of power plant and a rule-based expert system. This hybrid system is designed to help operator to keep the power plant in standard conditions, especially the power plant boiler. The neural network model undergoes an adaptation to the particular power plant. This is called learning phase. The learning makes portability of this system to another power plant easier. On the other hand, the set of rules of the expert system must be changed substantially with an new power plant. This must be done by hand.

The concept with learning phase corresponds partially with the advisory system described in this work where the learning phase is replaced with the phase of data mining from historical data.

3.10 Intelligent Online Process Monitoring and Fault Isolation

In [14] article, besides standard principles of operator support based on an expert system, an important function of operator support tool for diagnostic purposes is highlighted. In case of an emergency situation of a controlled process, diagnostic systems produce usually an overwhelming amount of alarms, messages and other information. This can confuse the operator. The operator support tool should process all these sources of information, separate substantial information from less important one and present it to the operator with the aim to let them concentrate on really important corrective actions.

3.11 ALLY: an Operator's Associate Model for Cooperative Supervisory Control Situations

Authors in [15] offer an remarkable approach how to support operator of a complex process. In standard situations, process may be controlled by one operator, but under abnormal conditions, one operator cannot manage the situation. That is why more than one operator is usually in charge. This is not very effective because operators are underutilized in most cases. The key idea is to let one operator control the process and create a computer-based associate / assistant to human operator that will help the operator in abnormal situation of the process. The communication between operator and associate is based on human to human communication principles. Operator and associate cooperate in the manner of two humans, while operator has always the priority in making decisions. The operator can delegate a control function to the associate but the operator must have right to seize back the initiative under all circumstances.

This article is inspirational not in used technologies with respect to its date of publication, but mainly in the principles how the human operator cooperates with the advisory system.

3.12 The ANN (Assistant Naval Navigator) System

Assistant system described in [16] is a special purpose advisory / warning system. It is used for the support of operators of small vessels in US, especially recreational and small commercial. The necessity of this system arose from the number of deaths and severe injuries and amount of property losses in boat accidents. The ANN system has client server architecture. ANN clients are small handheld devices, equipped among others with a colour display, GPS module, wireless Ethernet interfaces and module for voice synthesis. ANN clients are present on the vessels operating in close-to-shore waters and communicate with a network of servers located along the coast. Servers acquire information from many sources like GPS position, speed and direction of particular vessels, weather conditions and forecast. Software modules are both knowledge based and operating on cybernetics principles and process this information with the aim to find possible collisions and other dangerous situations. Results are directed to ANN involved clients in the form of warnings and advisories.

In spite of the fact that this field is not related to our intent, we can find some similarities in that respect that the operator has enough information even without ANN system to navigate the boat safely but he is not able to interpret all the information correctly in a limited time period. The operator is usually provided with a set of navigation assistance instrumentation that provide relevant information but the operator is usually not able to navigate the boat by hand and follow and interpret all devices simultaneously, especially under dangerous conditions. The ANN client device presents the information to the operator in a concentrated form and based on significance priorities

3.13 EPAS: An Emitter Piloting Advisory Expert System for IC Emitter Deposition

Among knowledge based systems for support of operators, the expert system described in [17] can be named. The system solves a problem in the production of integrated circuits. A diffusion operation was parameterized by a set of parameters that influence the quality of operation substantially. In case of low quality of operation, operator had to call for an experienced production engineer that changed the set of parameters. The change was based mainly on the engineer's experience. There were some attempts to describe the relations between set of parameters and quality of operation by mathematical equations, which would enable to calculate the parameters. The attempts were unsuccessful and that is why a solution with an expert system was introduced.

The expert system was built with the help of a commercial expert system building tool. Experience of production engineers was transformed to objects and rules of the expert system. Irrespective of the date of publication, this article well demonstrates the reasons for introduction of an expert system:

- Process is too complex to be described by a simple model.
- Engineers with experience can reach relatively good results by application of a heuristic approach.

3.14 The Intelligent Alarm Management System

In this article [18], support of operator is described that helps him to better recognize what is important and what is not. The alarm management system improves the situation in control room of a large petrochemical plant where operator is overburdened by a big amount of alarms generated by a standard SCADA system. The number of alarms is typically 100 in 10 minutes.

The system acquires statistical information of occurrences of particular alarms, makes analysis of nuisance alarms and separates alarms connected with critical process variables. This information is processed online and as its output, system provides an interface to operator that enables him to set particular filters that enable to reduce the number of alarms while preserving important information that enable the operator to control the process and make appropriate actions to avoid any emergencies.

This is further example of a typical operator support system that helps the operator by reducing insignificant information presented to operator while keeping the substantial one.

3.15 Energy Management of the Multi-Mission Space Exploration Vehicle using a Goal-Oriented Control System

[19] introduces use of operator advisory system in the field of aeronautics. The system is used in space exploration vehicle both during the tests on earth and during the space missions. On earth, it is used for coordination of energy consumption and planed day's activities of the crew. For creation of the plan of activities, human-in-the-loop model of the vehicle with the crew is used. Advices generated by the advisory system are interpreted by astronauts. Astronauts are taken as smart actuators. The advisory system calculates predictions of energy consumption. Planed crew activities are taken into account, as different activities need different amount of energy. Actual environment conditions like temperature and terrain influence energy consumption calculations. Another interesting condition that is incorporated into power consumption model is the ability of the exploration vehicle to rescue the tandem vehicle if it gets into difficulties.

The article shows that even in NASA projects, not all software must necessarily be created as special-purpose but that generally used software may advantageously be exploited too. The example is Google Earth service that was used as a tool for route planning of the exploration vehicles.

GUI of the advisory system is surprisingly a standard simple screen using description and value labels complemented with a line chart that represents energy supply change during the mission. This shows that even a simple GUI can meet requirements of a prestigious project. On the other hand, the GUI would deserve at least some bar representation of numerical values for better readability.

3.16 Operator Support Systems in S&C of Large Technical Systems

In [20] article, general aspects of operator advisory systems can be found. In spite of the early date of publishing, the article brings classification of advisory systems and questions concerning operator's GUI that are valid up to now.

Alarm filtering systems are one category of systems for support of operators mentioned in the article. The main task of these systems is reduction of information presented to operator. This category is represented by [18] in our survey. Knowledge based advisory systems are classified as another category. These systems are used very often, in our survey are represented by [17]. Advisory systems based on neural networks form another category mentioned in the article. These systems are regarded as very promising because of the 'fuzzyness' and probability that can be incorporated in these systems. System described in [12] belongs to this category. The last category mentioned in [20] is formed by self learning advisory systems. Systems of this type exploit similarity of newly emerging situations to former ones. Operator acknowledges that newly emerged situation was recognized by the system correctly and that the system can remember (learn) it for next time use. Similar principle is used in [13], e.g.

As far as GUI is concerned, the article discusses so called Mass Data Display (MDD) principle. It is an approach how to present status of thousands of process variables to the operator. Each variable is represented by a small graphical object that changes its properties (shape, colour) according to changes of variable status. This enables to create a pattern of these small object on a screen. The pattern is perceived by the operator as a whole and operator can recognize its changes that indicate changes of the monitored process. According to the authors, tests showed that MDD must be taken as an additional tool for the operator only, not as a replacement of standard operator screens with objects like Pipe & Instrumentation Diagrams, numerical and bar graph representations of variables, trend curves and so on.

Further, the use of three-dimensional presentation of process status and multimedia use in control rooms are discussed in the article, but this information can be taken for obsolete with respect to the date of publication.

3.17 Data Mining Approaches for Sustainable Chiller Management in Data Centers

The [21] article deals with the problem how to help an operator to manage the cooling of a data centre. CAMAS (Chiller Advisory and MAnagement System) is described here. The authors stress the importance of this theme by giving example values that 1-2% of all electricity are consumed by data centres and that 30-50% of data centres electricity consumption is spent on cooling. So it is worth to optimize the cooling.

The CAMAS system does not use an model approach. There exist theoretical models of particular units of data centres but the use of these models is limited because of inevitable simplifications and big amount of necessary computational resources. That is why CAMAS exploits data-driven approach. Inputs of the system are data from sensors positioned around the data centre, in particular racks and in all cooling equipments. As a part of cooling system, a cooling tower is located in the open air. Sensors are positioned outside the data centre too, to measure ambient temperature and humidity. Cooling tower together with evaporator and condenser form chiller, where cooling water is produced. Other parts of the cooling system are Computer Room Air Conditioning (CRAC) units positioned in the data centre room. CRAC units cool air that is blown through computer racks. Power of the cooling system can be controlled.

Previous experience with operation of the cooling system showed that inefficiency of the system is caused mainly by the following issues:

- Frequent start / stop cycles of the cooling system cause degradation of reliability of the cooling system, MTBF (Mean Time Between Failure) decreases.
- Energy efficiency of chiller is low if cooling load is too low or too high.

- There exist unknown dependences between cooling system efficiency and environment conditions.
- Performance of the cooling system is influenced by factors that are not measured by sensors.

These problems cause that the cooling systems are usually operated and controlled on the base of heuristic rules and operator's experience. This is insufficient especially if cooling load changes frequently.

With the aim to find efficient working points of the cooling system, the CAMAS uses motifs. Motif is a time sequence of multivariate data values that form a typical pattern and the pattern occurs in data stream repeatedly. CAMAS utilizes special algorithms for finding motifs in data stream. Found motifs are taken as states of cooling system and are evaluated from the point of view of cooling system sustainability. Sustainability comprises power consumption, carbon footprint and amount of energy reserved for consumption regardless of whether is consumed or not.

Motifs cover a smaller part of time the cooling system is working. The rest of time periods, the CAMAS tries to cover by states with correlation to external conditions of the cooling system. For finding these states, clusters in multivariate data space are identified. Clusters are taken for states and transitions between states are investigated. In this respect, the whole operation of chillers in the cooling system is decomposed to sequence of states and transitions between them. This composition is then used to investigate the cooling system and to find principles how to operate it in an efficient and sustainable way with respecting the economical aspects.

The aim is to create a tool for support of administrators of data centres but further investigation is necessary according to authors of the article.

3.18 State of the Art Summary

The survey stated above is naturally not fully comprehensive but all main directions and trends of development in this field may be recognized from it. The incompleteness has several reasons. Operator advisory systems often have some properties of knowledge-based systems, expert systems and other decision support tools, which widens the field extremely. Other reason is that this course of study develops very quickly, especially rush computing power enhancements and network interconnection intensification enable the use of approaches that were inconceivable recently. Substantial part of information about achievements in this field is not available because it is often developed in corporate and not in academic environment, which causes the results to become commercial and not publicly available.

The survey shows that systems for support of operators can be broken up into several areas from different points of view:

1. Description of process behaviour:
    - Very often approach is the description of process behaviour based on a model. White box model describes the process completely with as little as possible of approximation. The model is represented by a set of differential equations usually. White box model is very rear and is used for simple processes only. The

reason is that it is very problematic and in most cases even impossible to find the appropriate representation. If we intend to develop the operator advisory system not for one particular process only but for a set of similar processes, the white box model approach is not suitable for us. It would be necessary to find the model for each particular process.

- In many cases, the white box model is replaced by grey box model (see [6], [7]). This approach is characterized by finding of a simplified model of the process controlled by operator. A reasonable amount of approximation is used. Special behaviour of the process not supported by the simplified model is covered by a set of parameters and circumferences. For grey box model approach to advisory system, constraints similar to white box model are valid too, in the respect of our intentions.
- An approach that often produces good results is to describe the behaviour of process by a set of heuristic rules and constraints only (see [4], [6], [17]). This strategy originates from natural idea to sum up the historical knowledge of experienced operators and exploit it in the operator advisory system. Principle is simple but it is usually a tedious and time consuming work to concentrate the historical knowledges of operators and transform them into a formal expression exploitable by computerized advisory system. And what is more, it must be repeated for each particular process.
- An example of another approach is given in [8]. In this case, decision problem can be described by a set of criteria and operator is to be advised in making right decisions in a hierarchy of alternatives with the aim to reach as good as possible result according to selected criterion. The methodology is called MCDA—Multiple-Criteria Decision Analysis. As mentioned in chapter 3.5, this strategy is not suitable for continuous control of process by operator, but it can help the operator to decide if the advisory system generates more than one way how to reach requested status of process.
- From the point of view of our intention, solution based on black box model (or data-driven solution in [21]) is interesting. Principles of process behaviour are mined out from historical data. This operation may be automated in principle and thus may avoid necessity of human professional formulating model of the process. Principles of this approach will be described in next chapters in detail.

2. Handling of uncertainty:
    - In cases where the behaviour of process controlled by operator is not fully known and exactly described, we must handle a certain amount of uncertainty. First example of theory for handling of uncertainty is described in our survey in chapter 3.2. The mentioned Dempster-Shafer theory with its key notion called belief is especially suitable for processes with high uncertainty and enables even to express that we do not know anything about a statement.
    - In [12], [13] uncertainty is handled with the use of neural networks.
    - In [21] Bayesian statistics is used as the key theory and that is our choice too, as it will be explained in next chapters.
3. Type of operator support:
    - The simplest way how to process available information and support the operator is a simple concentration of information and presentation in an ergonomic way. In this case no artificial intelligence or complex data processing is used. No new

information is added, the support system helps the operator to perceive more information at the same time (see [10]).

- An often used approach is intelligent prioritization of important and hiding of insignificant information. In this case the support system provides additional information to the operator in that respect that it decides what is important at a given moment and what is not (see [14], [16], [18]).
- Another special category of support systems create solutions that hold dialogue with operator. Main representative of this category are expert systems of various types ([17]). In this case, operator must actively communicate with the support system by asking questions and selecting alternatives.
- Another type of operator advisory system, that differs from expert systems to a large degree, is the system that online follows process status and operator's actions and generate advices for operator, to enable him to direct the controlled process to a desired status. This is the type of advisory system, development of which is described in next chapters.

4 Operator Advisory System

From the facts stated in the State of the Art chapter, it is obvious that there exist a lot of different approaches to the concept of a system that helps human to make better decisions. The solver's team of scientists and people from industry mentioned in chapter 1 had not the aim to find the "best for all" solution of the advisory system. The team aims to create an advisory system that is suitable for branches of human activity the research participants were interested in. It means industrial applications but with the respect to possibility to generalize results for the use in other fields.

From the integration point of view, the advisory system was composed not as standalone system but as an integral part of distributed control system consisting of several subsystems. It was mainly COMPUREG participant who defended the subsystem strategy, in spite of the fact that a standalone solution would have been much simpler. On the other hand, with the integration of the advisory system into the COMPUREG's distributed control system proved by several industrial applications, some advantages and even spare of development time were expected.

From the control theory point of view, "... *the adopted approach relies on black-box modelling. This orientation on building of universal data-based models is driven by the problem addressed. The modelled processes are so complex that grey-box or white-box modelling would be too expensive. Whenever possible, the grey-box approaches should however be used to complement the advocated approach. They can strengthen it, for instance, by providing prior physical information at factor and component levels*" ([2] page 20.), as will be shown in next chapters.

As far as mathematical theory is concerned, Bayesian decision making was chosen. Main reason for this was fact that ÚTIA participant had long term experience in the field of Bayesian statistics, proved by many publications and successful research projects, and that during the projects, this theory showed its big potential in the field of decision making support.

4.1 Integration of the Advisory Subsystem into Distributed Control System

As mentioned above the advisory system is composed as an integral part of distributed control system. A schematic layout of such a composition is drawn in the following picture.

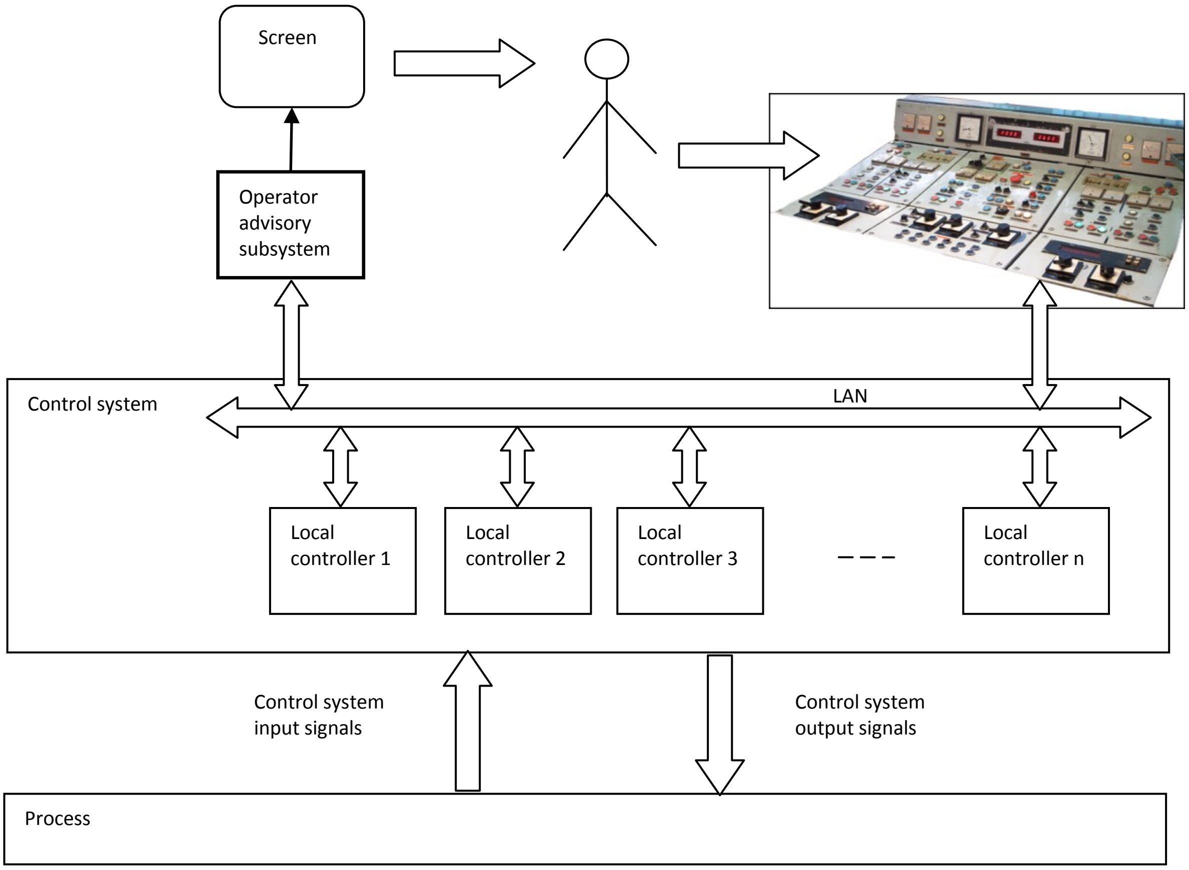


Figure 1 Integration of advisory subsystem into control system of a process

Process is controlled by a set of local controllers cooperating via local area network. Advisory system is connected to the same LAN as another peer. This enables the advisory system to share control system's data. Advisory subsystem presents results of its calculations for operator to the screen. Operator evaluates suggestions and recommendations of the advisory system and realizes results of his decision by control desk. Thus the control loop closes. (Control desk is in the figure connected to LAN which presumes that local controllers have remote IO's installed there.)

4.1.1 Hardware and Operating System Platforms

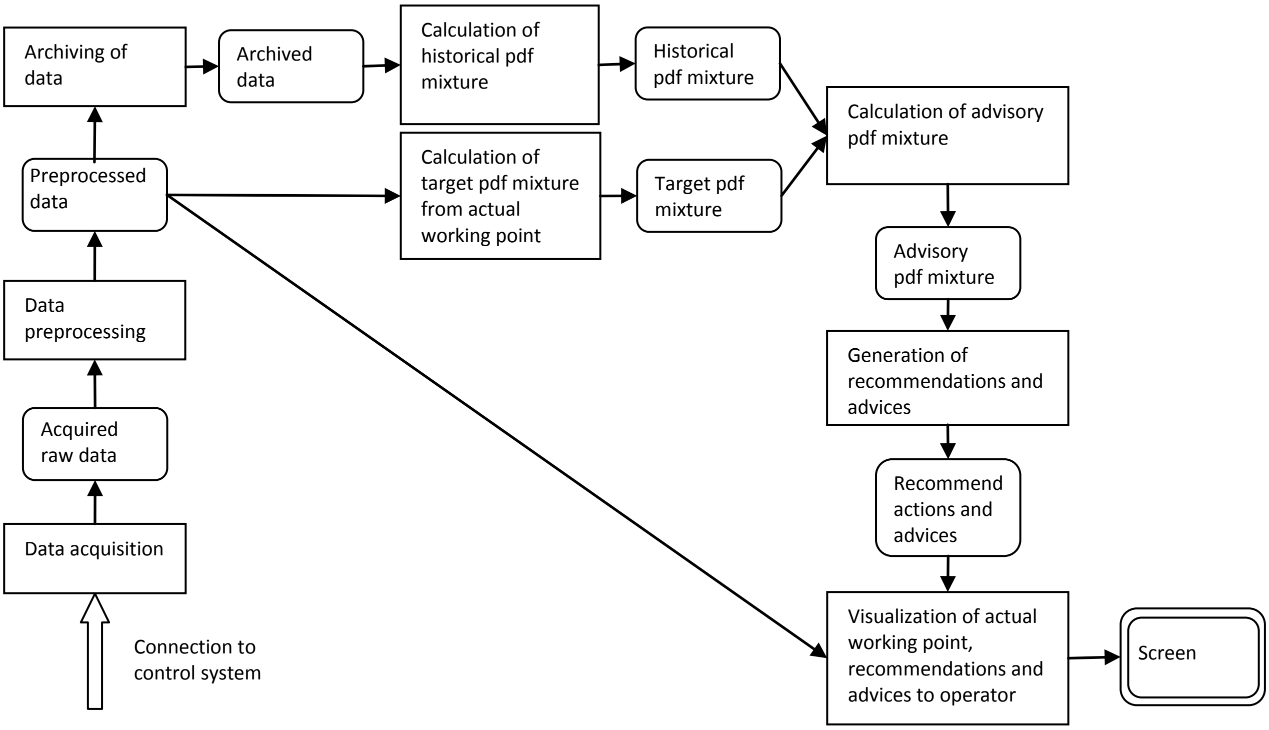
In the following chapters, explanations will be bound to a particular hardware and operating system environment sometimes. As mentioned above, the advisory system is intended as an integral part of COMPUREG's distributed control system. In this aspect, we will limit ourselves to hardware and software platforms used in these systems. They are characterised by the following item:

- industrial PC (IPC),
- Siemens PLC,
- Microsoft Windows,
- Linux with real-time extensions:
    - Xenomai real-time framework for Linux [22],
    - RTAI RealTime Application Interface for Linux [23].

4.1.2 Structure of the Advisory System

As mentioned in the previous chapter, the advisory subsystem is integrated into the control system of process which enables the advisory subsystem to exploit the control system's data. This is very important for the advisory subsystem because its functioning is fully dependent on the supply of quality data containing information about behaviour of the controlled process. In the concept of advisory system as a standalone one, it would be necessary to build new interface for input signal acquisition (interface cards, wiring and even new sensors) which may mean, depending on number of input signals, substantial additional costs for the advisory system. That is the reason, the concept of integration into the control system is preferred to the standalone solution.

If the concept of integration is adopted, a simplified logical structure of the advisory subsystem can be drawn as in the following picture. (Notion pdf mixture means mixture of probability density functions, it will be explained in next chapters.)



Archiving of data
Archived data
Calculation of historical pdf mixture
Historical pdf mixture
Calculation of advisory pdf mixture
Preprocessed data
Calculation of target pdf mixture from actual working point
Target pdf mixture
Advisory pdf mixture
Data preprocessing
Generation of recommendations and advices
Acquired raw data
Recommend actions and advices
Data acquisition
Visualization of actual working point, recommendations and advices to operator
Screen
Connection to control system

Figure 2 Logical structure of advisory system

Simplified schema in the picture shows information flow from the input of control system's data to output of information for operator to screen. Data acquired by means of control system are transferred to advisory subsystem via local area network connection. These, from the point of view of advisory subsystem, raw data are stored in real-time database inside the advisory subsystem. Real-time database (RDb) technology will be described in next chapters. Then, the turn of pre-processing of raw data comes. It means scaling, normalization, re-sampling, filtration and other methods of data (input signals values) improvement. Pre-processed data are archived. It is not only archiving in the form of disk files but also short history archiving in RDb memory resident database for fast access to historical data.

Now the data processing splits into two streams. From archived data, mixture of probability density functions (pdf) called *historical mixture* is calculated. This mixture comprises information about process behaviour in the past. Historical mixture is calculated during the offline (start up) phase and is updated continuously then. The other branch calculates so called *target mixture* that contains information about actual working point of the process.

From historical mixture and target mixture, *advisory mixture* is calculated then. The advisory mixture expresses the information how the process parameters should be set to reach process working conditions close to optimum from the production quality point of view.

As this is not the final output of the advisory system, advices and recommendations are generated leading the operator to reach the optimum settings via a shortest and trouble-free way.

Presentation of the advisory system outputs is carried out by visualization module. Beside the current values of technological variables, advices and recommendations are visualized to tell the operator in a comprehensible way what to do.

One possible physical realization of the logical structure can be found in the following figure.

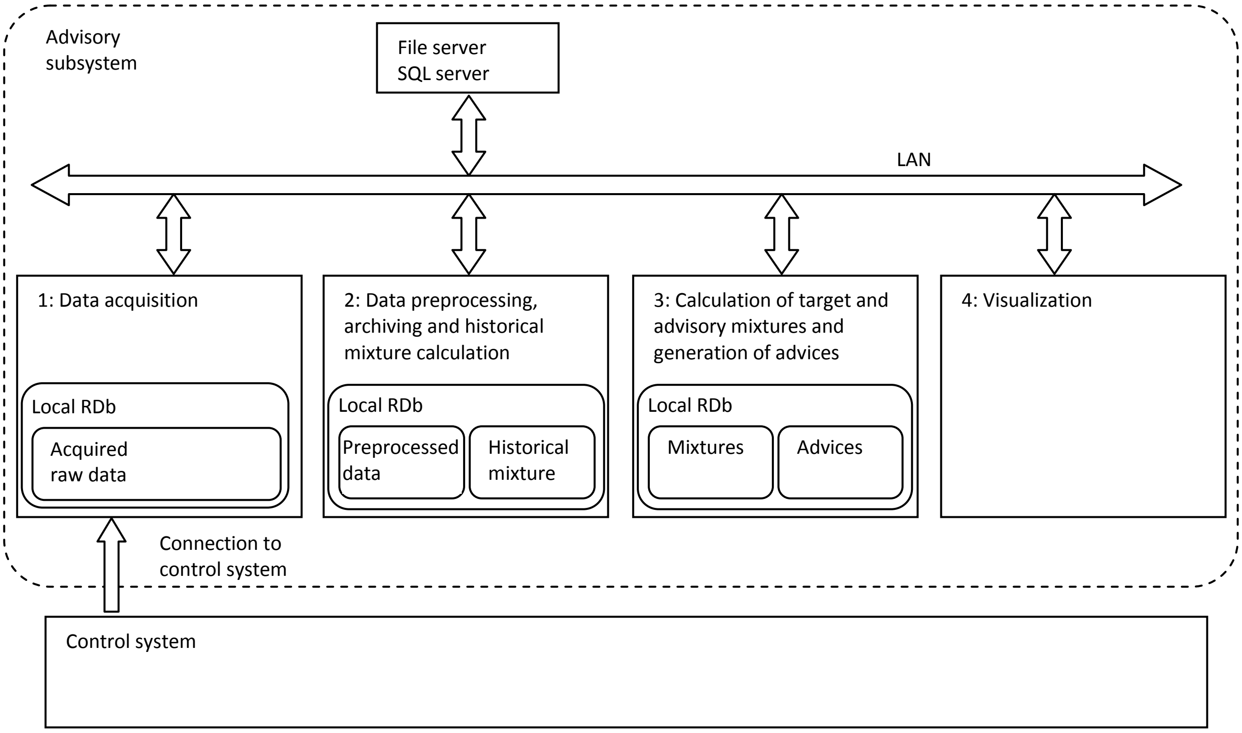


Figure 3 A possible physical structure of advisory subsystem

Advisory subsystem is created by a local area network segment with four separate nodes realizing particular functions of advisory subsystem. Special node is attached serving as file and SQL server for the purposes of archiving of historical data.

For communication between particular nodes, real-time database (RDb) technology is used. RDb is used for storing of intermediate results calculated in separate nodes and for exchange of data between nodes. It will be described in next chapters in detail.

4.1.3 Data Acquisition

Functionality of the advisory system is based on data mining algorithms. These algorithms need to be supplied with sufficient amount of quality data. And that is why data acquisition is one of the most important parts of the advisory system. First, data are acquired during the advisory system's start-up phase. In this phase, data are acquired to accumulate information that describes nature of the controlled process sufficiently (*historical data* in short). In this preparatory phase, the advisory system produces no outputs useful for operator yet.

In standard working phase, data are acquired for two main purposes. One purpose is the improvement of the historical data acquired during the start-up phase. A reason for this is that the more data the better evidently. Another reason is that the behaviour of the process may change in time and can differ from behaviour during the start-up phase. This may be caused by replacement of some parts of process or of control system's parts, e.g. Also new working modes may be introduced with production of products with new properties. Newly acquired data are also necessary for recognition of actual working mode of the process.

4.1.3.1 Sources of Data

Data are acquired from several sources. In case where advisory system is added to an existent control system of a process, data can be acquired from archives of the control system, especially in the start-up phase when historical data are acquired. In this case, data are usually available in the form of files of different formats. This can be easily overcome by unification of all formats with the help of conversion software modules. As the conversion output, the Microsoft Access file database format MDB is used. The reasons for selection of this format were as follows:

- The format is widely spread and easily accessible from all commonly used software platforms.
- This format enables to divide long history period recordings into several files and indicate in file name the time period they represent.
- With the division into files, database properties are not lost, especially indexing of records is kept.

In case of utilization of an existent control system as the source of data in the standard working phase of the advisory system, the control system must provide standard communication interfaces and enable connection of at least one other node. It is only a rear situation that existent control system provides one interface with a standard communication protocol with the possibility to acquire all necessary data. Therefore, it is often inevitable for the advisory system to make several communication connections to the control system. For the situation when all necessary data are not accessible via a communication interface, advisory system must connect to the process with the use of signal inputs and sensors. In the next figure, there are three main possibilities of configuration for the purpose of data acquisition.

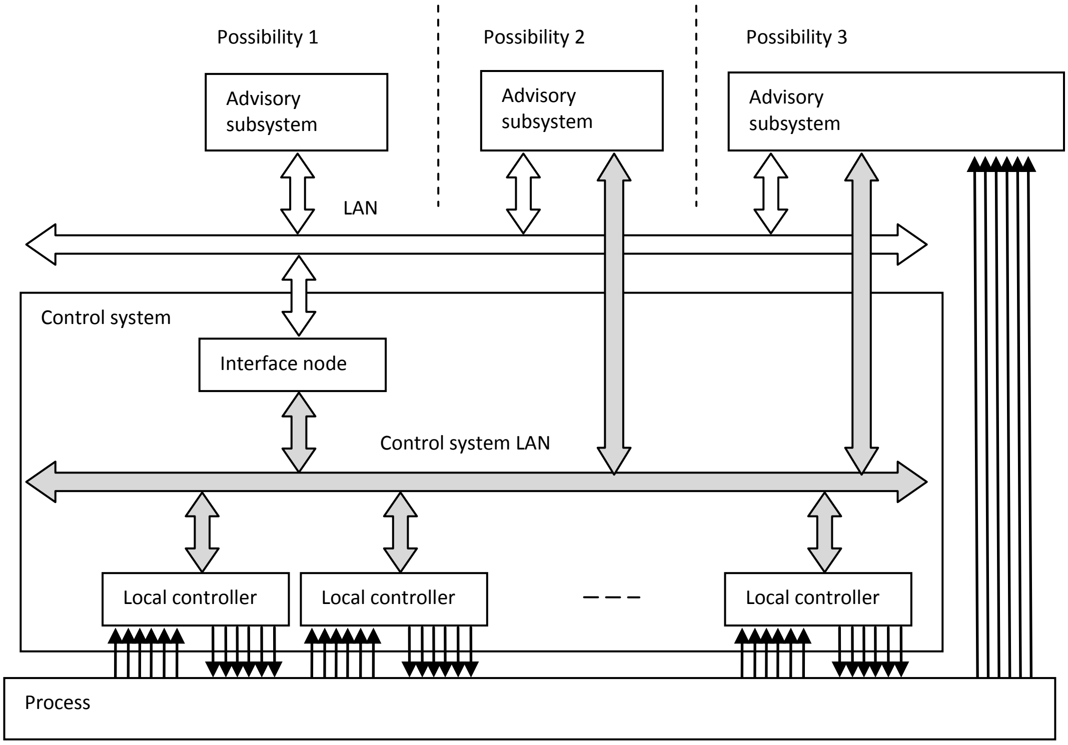


Figure 4 Three examples of connection of advisory subsystem to an existing control system for the purpose of data acquisition

Possibility 1 is the purest one because data come from one source, from interface node where control system publishes all data acquired from local controllers. Control system is not influenced by the connection of the advisory system. The interface node of up-to-date control systems usually provides standard communication protocols which enables easy connection of the advisory system. The most often used communication protocols for this type of connection in industrial applications is OPC (Object Linking and Embedding for Process Control [24]) protocol or its innovated version OPC UA (OPC Unified Architecture) [24].

Possibility 2 covers the situation where not all data required by advisory system are published by the interface node. In this case, the advisory system must make additional connections to control system's local controllers to acquire data. Control system is influenced by the new connections, timing on the control system's LAN may change to such an extent that it can degrade functionality of local controllers. At the factory floor level, such communication networks are usually used that provide deterministic timing of data exchange among communication nodes. Response time is calculated with the known number of peers and changes with addition of another one. Other problem may occur if the advisory system has to be connected to fieldbus type factory floor network with master-slave concept of communication media access control and especially if single master only is allowed. In this case, the advisory system should be the master to query local controllers (slaves) for requested data but single master is occupied by control system's node and no other master is allowed. Examples of industrial networks with deterministic timing are industrial clones of Ethernet network, so called real-time Ethernets (EtherCAD [25], PROFINET [26], etc.). Master-slave networks are mainly based on RS-422 or RS-485 physical layers respectively. An example of a network of this type is Siemens's PROFIBUS [27], often used in Europe. The advisory system should provide at least several of mentioned network interfaces to be able to connect to existing control systems.

Possibility 3 represents a situation where data necessary for advisory system are not all available either via interface node or direct connections to local controllers. In this case, advisory system must provide input cards for connection of input signals directly from the process using existing or newly added sensors. The usage of additional input signals does not influence the control system, but it represents substantial additional costs.

If the advisory subsystem is deployed together with control system, the integration can be more consistent. Some data acquisition subtasks are implemented directly in local controllers and cooperate with advisory subsystem's data acquisition node.

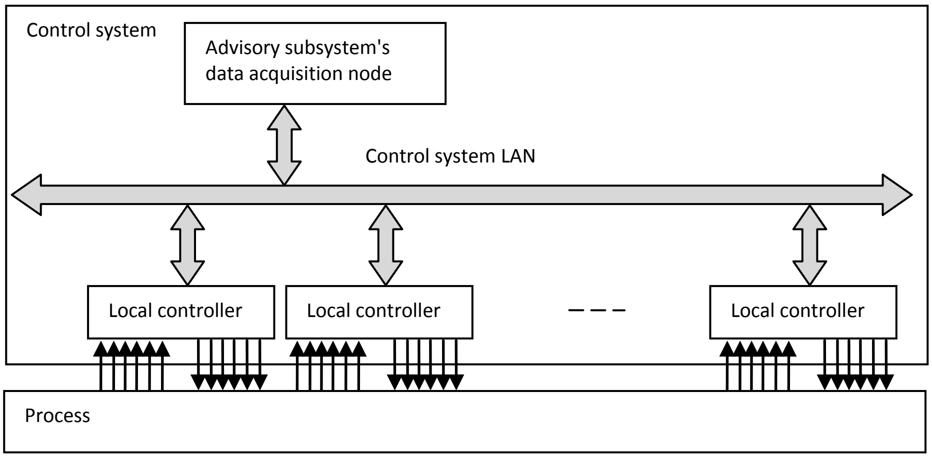


Figure 5 Integration of advisory subsystem's data acquisition node directly into the control system

Cooperation consists in data exchange and synchronization of local controllers and data acquisition node. For this purposes, Real-time Database concept is used.

4.1.3.2 Real-time Database Concept of Inter-process Data Exchange

Real time Database technology (RDb) was developed by COMPUREG participant in ProDaCTool and subsequent projects as by-product. Author of this document is author of the basic RDb concept too, and implemented and evaluated all basic data structures, mutual exclusion mechanisms and other functions in a real-time environment. Primarily, RDb was meant as a tool for tasks in multitasking environment to exchange data addressed by symbolic names. After further development, RDb is used for inter-platform integration too. It means that e.g. a task running under Xenomai, real-time framework for Linux, can write a value to a variable with a symbolic name, and another task running under Microsoft Windows Embedded Standard 7 operating system can address the same variable with the symbolic name and read the value (see [28]). (Here, the notion *task* represents an activity competing for access to shared data whether it is process or thread.)

RDb was developed not to replace generally used standard software technologies of this type as OPC e.g., but to cover a limited range of COMPUREG's applications of distributed control systems for fast industrial processes. Great emphasis was put on real-time aspects of the solution because RDb is used as standard part of local controllers running under real-time operating system. Requested real-time properties are met by accepting the following principles:

- simplicity of code,
- direct conversion of symbolic names to memory address, search operations used only in initialization phase,
- atomicity of most of operations ensured on instruction level, use of system calls reduced to minimum with the aim to minimize system overhead,
- system calls used for critical sections of manipulations with complex data structures only.

More detailed description of RDb technology can be found in 6Appendix 2.

4.1.3.3 Historical Data Acquisition and Storage

Features of RDb technology described above and in 6Appendix 2 are used advantageously for data acquisition of historical data for the purposes of the advisory subsystem of distributed control system.

4.1.3.3.1 Time Period and Sampling Strategy of Recordings

For further needs of the advisory system, series of data records sequential in time are necessary. The time period of data acquisition should be long enough to record as much as possible different states and working modes of the process. In practice, it means rather months than days. The time may be continuous from the beginning to the end of data acquisition period or series of continuous periods separated from each other by breaks with no data acquisition can be used. First alternative is used e.g. in a case of an continuous production process like power generation in a power plant or water purification in a water treatment plant. The data acquisition with breaks is, on the contrary, used if the nature of the investigated production process is discontinuous. An example of such a process is the steel strip production on a reversing rolling mill. In this case, it is reasonable to stop the data acquisition in time periods when rolling direction is changed or when finished strip coil is replaced for a new one.

In both cases of data acquisition strategy, it is pretended that data samples are equidistant in continuous time periods. The term "equidistant" need not mean equidistant in time in all cases. There are processes where coefficients of quality production are not linked with time of production. As an example of such a process, we state the steel strip production here again. The quality coefficients are measured or calculated not in relation to time instants of production but in relation to the current length of produced strip. In this case, the acquisition of another data sample is triggered not by a time tick but when a certain strip length section has been rolled, when the measured strip length changes by a certain increase.

It is apparent that both the continuity of acquisition and the triggering of sample acquisition influence the calculation of statistical coefficients substantially and that is why the proper strategy must be selected according to the nature of the investigated process. As an example, we present here plots of two different recordings of the same time period of production and calculation of mean value of signal representing position of rolls in a rolling mill. In the first case, ending phase of a steel strip production is recorded with the sample triggering by each 37.88 millimetres. In the second case, the same strip part production is recorded but samples are triggered by time ticks of 5 milliseconds. Comparison of both the recordings and an example of calculated statistical coefficient is demonstrated in the following figure.

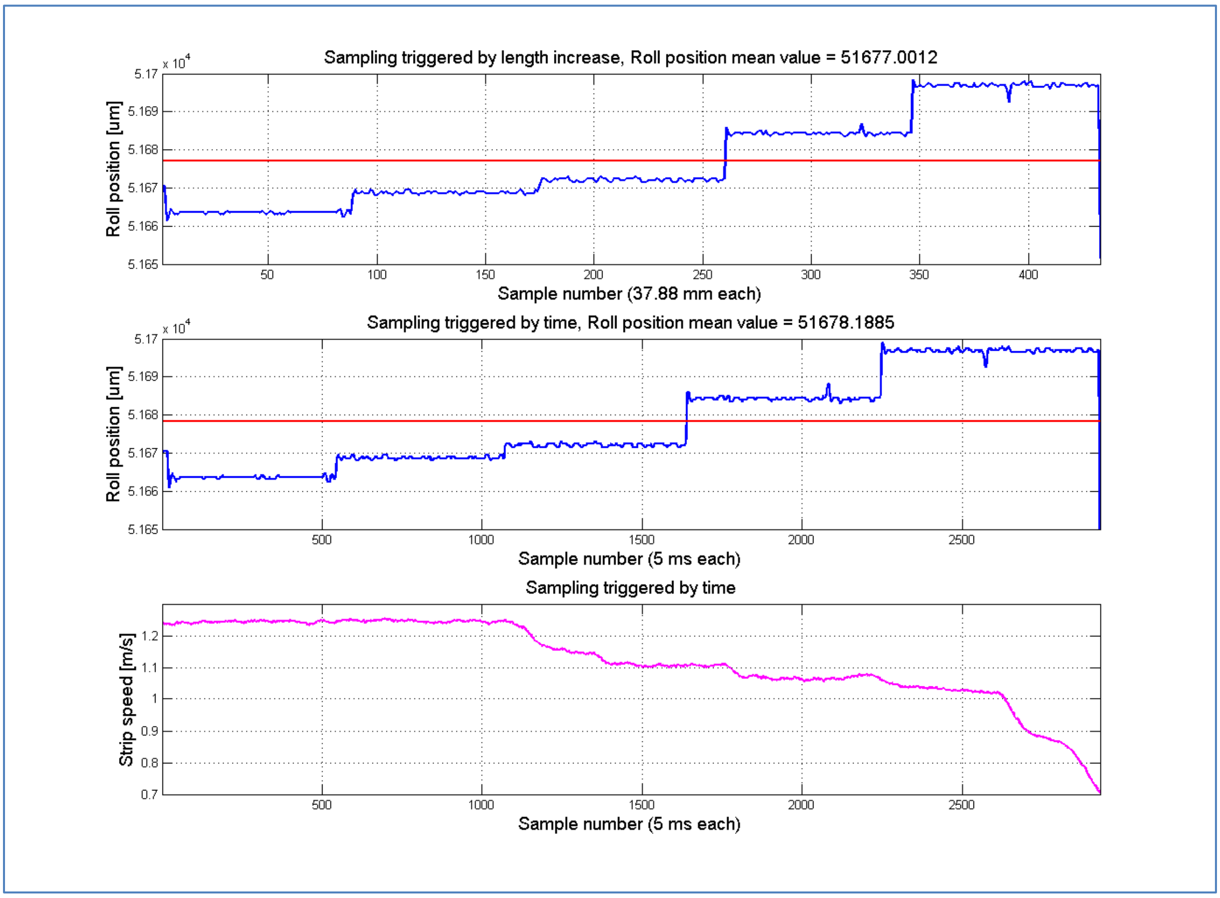


Figure 6 Comparison of recordings with samples triggered by length increments and by time ticks respectively.

In the upper plot, there is the recording with samples triggered by increase of strip length, each 37.88 mm a sample of roll position signal value is stored. In the middle plot, the same signal is recorded with sample triggering by time ticks, each 5 milliseconds a sample of signal value is stored. In the lower plot, strip speed signal recording can be seen. To demonstrate the influence of sampling strategy on statistical coefficient calculation, a time period was chosen when the strip speed is changing substantially. In time periods with a constant strip speed, the influence of sampling strategy is minimal.

In the first half of the recording, the strip speed is higher than in the second half and thus the recording with sampling triggered by length increase has more samples in the first half. More samples mean higher weight in the mean value calculation and thus the mean value of roll position is lower than in the case of the recording with sampling triggered by time. See the red lines and titles of the upper and middle plots.

In paragraphs above, the reasons were shown why the advisory system distinguishes the nature of signals in the phase of data acquisition.

4.1.4 Improvement of Data Quality

As the final results of the advisory system outputs are dependent on the quality of measured signals—inputs of the system, process of check and possible improvement of signal quality became a substantial part of development of the advisory system. Quality improvement consists mainly in filtering and signal reconstruction. Some examples can be found in [29], [30] and in chapter 4.5.1.2.

4.2 Data Processing Based on Bayesian Probability

4.2.1 Bayesian Statistics

As the Bayesian statistics is the key theoretical background of this work, in this chapter, we will explain the basic ideas of this theory, foundations of which were laid by Thomas Bayes, British mathematician of the 18th century. More detailed explanation of this problematic can be found in [31] e.g. This chapter is fully inspired by this article, only the example of the probabilistic system is chosen from a more practical field (an example from traffic control) and more stress is put on the explanation of importance of the prior knowledge which substantially differentiates the Bayesian statistics from the classical one.

4.2.1.1 Theoretical Minimum

Text in this chapter is based on [31] . We will demonstrate the principles of utilization of the Bayesian approach on an example of cars going through a simple crossroad. Coming cars turn left or right randomly. For a possible traffic control system, the information whether the coming car is going to turn left or right will be highly useful.

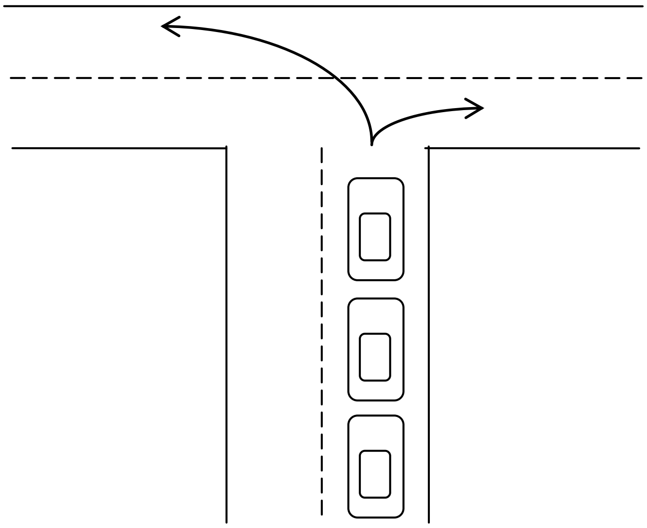


Figure 7 Cars on a simple crossroad as the demonstration of a stochastic process

Remark:
This example was chosen because the traffic problem was one of the fields where the theory was verified in the frame of the research and development projects mentioned in chapter 1.

According to [31] we will describe the process as follows:

The turns of particular cars are registered as values of a stochastic variable. The values form a sequence

$y(T) = [y_1;\ y_1 \dots\ y_T\ ]$ *(1)*

$y_t \in \{0; 1\}$

where y_t represents the turn of t-th car. Value of 0 represents the turn to the left and value of 1 the turn to the right. We understand the behaviour of particular cars as independent of each other.

According to [31] we will describe the process by a model that will help us to explore the behaviour of process. Parametric model describing the process in one time instance t (for t-th car) is as follows:

$f(y_t \mid \Theta) = \Theta^{y_t}(1-\Theta)^{1-y_t}$	Where	*(2)*
$y_t \in \{0; 1\}$	behaviour of t-th car, 0-turns left, 1-turns right	
$\Theta \in \langle 0; 1 \rangle$	probability that cars turn right	
$f(y_t \mid \Theta)$	probability density function (pdf) of occurrence of y_t event conditioned by unknown parameter Θ	

When a sequence of T cars is passing through the crossroad and some cars turn left and some cars turn right, we are interested in probability that a number of cars turn right and the remaining turn left. An example of the sequence of 10 cars can look like this:

$$y(10) = [1; 0; 1; 1; 1; 0; 1; 0; 1; 1;] \tag{3}$$

According to [31] the model (1) can be rewritten for a sequence of Tcars (under condition of independence of particular cars):

$$f(y(T) \mid \Theta) = \prod_{t=1}^{T} f(y_t \mid \Theta) = \prod_{t=1}^{T} \Theta^{y_t}(1-\Theta)^{1-y_t} \tag{4}$$

If we denote $v_{1;T}$ the number of cars in the sequence of Tcars that turned right:

$$v_{1;T} = \sum_{t=1}^{T} y_t \tag{5}$$

and $v_{0;T}$ the number of cars in the sequence of Tcars that turned left:

$$v_{0;T} = \sum_{t=1}^{T} (1 - y_t) \tag{6}$$

we can write the model for the sequence of Tcars in the following form:

$$f(y(T) \mid \Theta) = \Theta^{v_{1;T}}(1-\Theta)^{v_{0;T}} \tag{7}$$

For the purposes of the advisory system, it is useful to exploit this model for two possible tasks:

- to estimate unknown parameter Θ with the use of historical data and
- to predict future data with the use of historical data.

Bayes' theorem explains the relation between a conditioned probability of occurrence of an event and the reverse conditioned probability. With the use of it we can write according to [31]:

$$f(\Theta|y(T)) = \frac{f(y(T)|\Theta)f(\Theta)}{f(y(T))} \qquad \text{Where} \qquad (8)$$

$f(\Theta) = f(\Theta|y(0))$ prior probability density function expressing the expected value of parameter Θ at the start of the estimation, the expectation is based on the so far known data $y(0)$

$f(\Theta|y(T))$ posterior probability density function expressing the expected value of Θ parameter at the time instant when the T-th car went through the crossroad, it is function of Θ and $y(T)$ is taken as constant

$f(y(T))$ is taken as normalization constant because $f(\Theta|y(T))$ is a function of Θ and $y(T)$ is taken as constant, can be omitted now and the posterior probability density function (pdf) can be normalized if necessary (integral of pdf must be equal to one)

After the use of *(7)* for replacement of $f(y(T)|\Theta)$ and for expression of $f(\Theta|y(0))$ and after omission of $f(y(T))$ described in detail in [31], we can get the final form of expression for the posterior probability density function expressing the expected value of Θ parameter:

$$f(\Theta|y(T)) = \Theta^{(n_{1;0}+V_{1;T})}(1-\Theta)^{(n_{0;0}+V_{0;T})} \qquad \text{Where} \qquad (9)$$

$v_{1;T}$ see *(5)*

$v_{0;T}$ see *(6)*

The constants $n_{1;0}$ and $n_{0;0}$ express the prior information.

There is the most important point of explanation of Bayes statistics here—prior information. This new notion will be discussed in the next chapter.

4.2.1.2 Prior Information as a Notion of Bayesian Statistics

Classical statistics does not know this notion. In classical statistics, the results are influenced only by the events that happened as late as after the start of observation of the stochastic process. On the contrary, in Bayesian statistics, results of an experiment can be influenced by the prior information even before the experiment begins.

The sources of the prior information can be according to [31]:

- results of the former observations of the stochastic process or
- expert knowledge.

4.2.1.2.1 Prior Information Based on Former Observations

In our case with cars and crossroad the results of former observations can be used as a starting condition for the estimation of the Θ parameter. With the setting of the $n_{1;0}$ and $n_{0;0}$ variables to constant values, we can influence the development of the estimated value of the Θ parameter during the estimation phase. If we know from former observations that the number of cars turning left is almost the same as the number of cars turning right, we can set the values of $n_{1;0}$ and $n_{0;0}$ equal to one. Then, after the experiments starts, after the first car passed through the crossroad and turned right, we get the equation *(9)* in the following form:

$$f(\Theta|y(1)) = \Theta^{(1+1)}(1-\Theta)^{(1+0)}$$

Now, we can calculate the values of the probability density function $f(\Theta|y(1))$ for different values of the Θ parameter. We know that value of the Θ parameter must be between 0 and 1, so we divide the $\langle 0; 1\rangle$ interval into let us say 100 subintervals and for each subinterval $\langle 0.00;0.01)$, $\langle 0.01;0.02), \dots, \langle 0.99; 1.00\rangle$ we calculate the value of $f(\Theta|y(1))$ probability density function. The value of the $f(\Theta|y(1))$ pdf for a particular interval has a meaning of likelihood (in the stage when since start of estimation the first car went through the crossroad) that the estimated value of Θ parameter will fall into this interval.

In the second step, after the second (from the start of the experiment) car went through the crossroad and turned left we get the equation *(9)* in the following form:

$$f(\Theta|y(2)) = \Theta^{(1+1)}(1-\Theta)^{(1+1)}$$

We can calculate the values of the probability density function $f(\Theta|y(2))$ for different values of the Θ parameter again. And so on.

Remark:
Let us note that the calculated values of the pdf are not normalized. Normalization should be done by dividing each value by the sum of all pdf values. After normalization the sum of all values must be equal to one (the integral over the entire interval $\langle 0; 1\rangle$ must be equal to one).

The development of the $f(\Theta|y(T))$ pdf values, we will discuss later in chapter 4.2.1.3.

4.2.1.2.2 Prior Information Based on Expert Knowledge

Instead of the prior knowledge based on former observations, expert knowledge can be used as prior information. In our case we can imagine e.g. we know that the left road leads to a waste dump while the right road runs to a shopping centre. In that situation, it is reasonable to presume that much more cars will turn right than to left. In this case we would set the values of $n_{1;0}$ and $n_{0;0}$ .as follows, e.g.:

$n_{1;0} = 4$

$n_{0;0}$ = 1

It is the unique property of the Bayesian statistics in comparison to the classical one the possibility to apply an expert knowledge with the aim to improve the results of an experiment. In the classical statistics, we would have to wait for a much longer series of events before the process is able to show its real nature in acquired data.

4.2.1.2.3 Weight of Prior Information

Not only the relation between the $n_{1;0}$ and $n_{0;0}$ values is important but Bayesian statistics enables also to assign a specific weight or strength to prior information.

In case of prior information based on former observations, the weight of prior information is apparently given by the number of events observed. On the other hand, in case of expert knowledge, the weight corresponds to that how sure we are. This is a problem because it is a very subjective matter to express the level of certainty exactly.

In practice, the weight of prior information is given by the values of $n_{1;0}$ and $n_{0;0}$. We can demonstrate it on the case of cars passing through a crossroad. If we want to express that presence of waste dump and shopping centre in directions to left and to right respectively and if we set

$n_{1;0} = 4$ and

$n_{0;0}$ = 1

the prior information is not very strong. This prior information can be overcome by a relatively small number of cars passing through the crossroad.

But if we set

$n_{1;0} = 400$ and

$n_{0;0}$ = 100

the prior information is much stronger and if it were set improperly, hundreds of cars would have to went through the crossroad to overcome the prior information.

Influence of prior information on the results of an experiment we will discuss in the next chapter 4.2.1.3 in detail.

4.2.1.3 Demonstration of Influence of Prior Information

With the help of a simple MATLAB function, we will demonstrate the influence of prior information on the construction of the posterior probability density function expressing the expected value of Θ parameter *(9)*. The MATLAB function is inspired by the script published in [31].

The principle of the demonstration is as follows:

During this demonstration we use not real but simulated $y(T)$ data. The simulation of $y(T)$ data is based on a selected constant value of Θ parameter. Then we calculate values of the posterior pdf expressing the expected value of Θ parameter *(9)*. As the value of Θ parameter is known in this case, we know what the results of estimation should look like. We know what value should be the result of estimation. Before the start of calculation of pdf values, we repeatedly assign a different prior information to see its influence on the results.

We call this function repeatedly with different parameters and plot results to demonstrate the influence of different prior information in a MATLAB script. All experiments use the same set of parameters except for n0_0 and n1_0 that represent the prior information.

Θ parameter is set to 0.7 which characterizes the process in that way that most cars turn right (7 of 10 in average).

$\langle 0; 1\rangle$ interval of Θ parameter is divided into 100.

Number of simulation steps (estimation iterations) is set to 150.

The results are described in next chapters.

4.2.1.3.1 Incorrect Prior information

In this chapter, we study the influence of incorrect prior information on the simulation results. Incorrect prior information means in practice that e.g. the observations of the process before the experiment were interpreted wrongly or that the expert knowledge is bad.

4.2.1.3.1.1 Low Weight

In the first experiment, we use prior information with low weight. We set

$n_{0;0} = 7$ (n0_0 identifier in MATLAB) and

$n_{1;0}$ = 3 (n1_0 identifier in MATLAB)

Low weight is given by low values of n0_0 and n1_0 parameters in comparison to number of simulation steps. Incorrectness is given by the fact that we expect the estimated value of Θ parameter equal to 0.7 but prior information corresponds to a value from the first half of $\langle 0; 1\rangle$ interval. Exactly, it is $\frac{n_{1;0}}{n_{0;0} + n_{1;0}} = 0.3$. Results of experiment are in Figure 8.

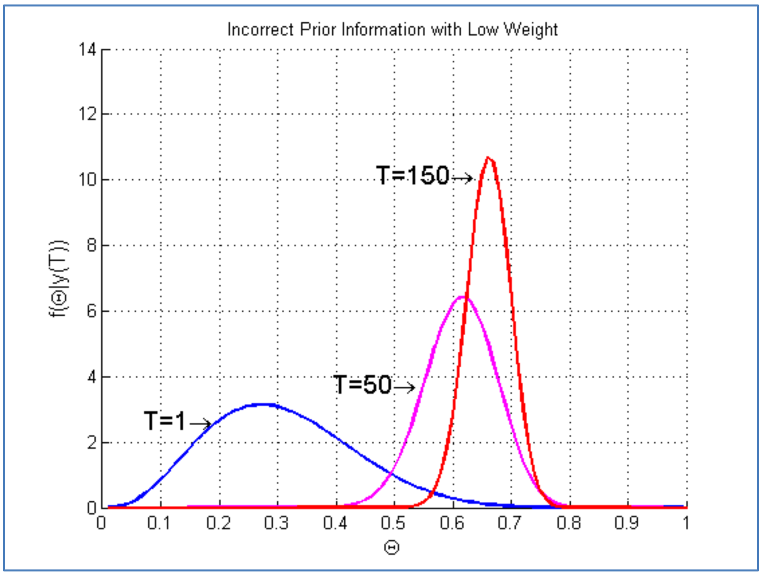


Figure 8 Results of experiment with incorrect prior information with low weight

Three curves represent pdf values in different steps of simulation (estimation). The curves correspond to results after 1, after 50 and after 150 steps respectively.

Blue curve represents the stage after one step of simulation. One randomly generated value $y(T)$ where $T = 1$ cannot overcome incorrect prior information and thus the pdf denotes that Θ parameter value is kept near to 0.3. Uncertainty is relatively high as the curve is wide and low.

Magenta curve represents the situation after fifty steps of simulation. Fifty randomly generated values $y(T)$ where $T = 50$ apparently easily overcome incorrect prior information with low weight and thus the pdf denotes that Θ parameter value is drawn near to expected 0.7. Uncertainty is lower, the curve is narrower and low.

Red curve represents the end of simulation after 150 steps. 150 randomly generated values $y(T)$ where $T = 150$ enforced real nature of the stochastic process against incorrect prior information with low weight. The pdf shows that the most probable value of Θ parameter value is near to expected 0.7. Uncertainty is relatively low, the curve is narrow and high.

4.2.1.3.1.2 High Weight

In the second experiment, we use prior information with high weight. We set

$n_{0;0} = 70$ (n0_0 identifier in MATLAB) and

$n_{1;0}$ = 30 (n1_0 identifier in MATLAB)

High weight is given by relatively high values of n0_0 and n1_0 parameters in comparison to number of simulation steps. Prior information corresponds to $\frac{n_{1;0}}{n_{0;0} + n_{1;0}} = 0.3$ again. Results of experiment are in Figure 9.

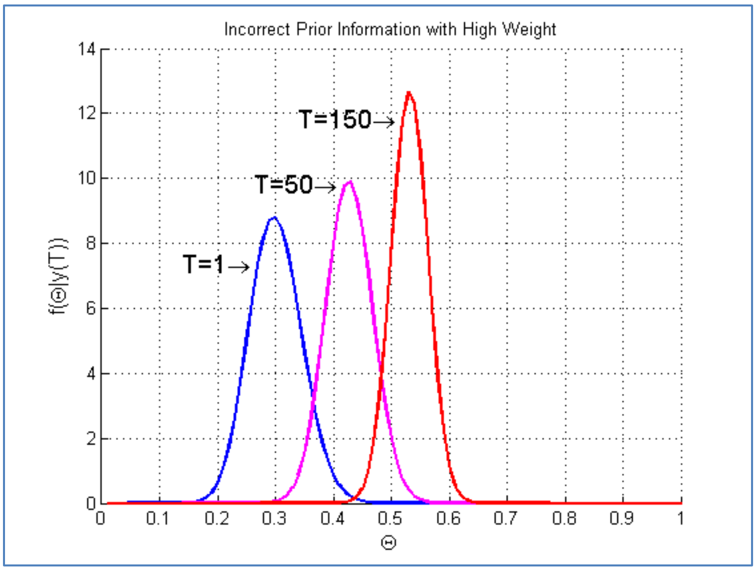


Figure 9 Results of experiment with incorrect prior information of high weight

Blue curve shows that one randomly generated value $y(T)$ where $T = 1$ has no weight in comparison to the strong incorrect prior information and thus the pdf denotes that Θ parameter value is equal to 0.3 which is the value given by prior information.

Magenta curve represents the situation after fifty steps of simulation. Fifty randomly generated values $y(T)$ where $T = 50$ pushed the most probable value of Θ parameter nearer to expected 0.7.

Red curve represents the end of simulation after 150 steps. Not even 150 randomly generated values $y(T)$ where $T = 150$ could fully enforce real nature of the stochastic process against too strong incorrect prior information. The estimated value of Θ parameter approaches value of 0.5 instead of expected 0.7.

4.2.1.3.2 Correct Prior Information

In this chapter, we study the influence of correct prior information on the simulation results. Correct prior information means that this information corresponds with the nature of the explored stochastic process.

In the low weight experiment, we set

$n_{0;0} \; = 4$ (n0_0 identifier in MATLAB) and

$n_{1;0}$ = 8 (n1_0 identifier in MATLAB)

Prior information denotes the value of Θ parameter equal to $\frac{n_{1;0}}{n_{0;0} + n_{1;0}} = 0.\overline{6}$. This value is near the expected one of 0.7. Results of experiment are in Figure 10.

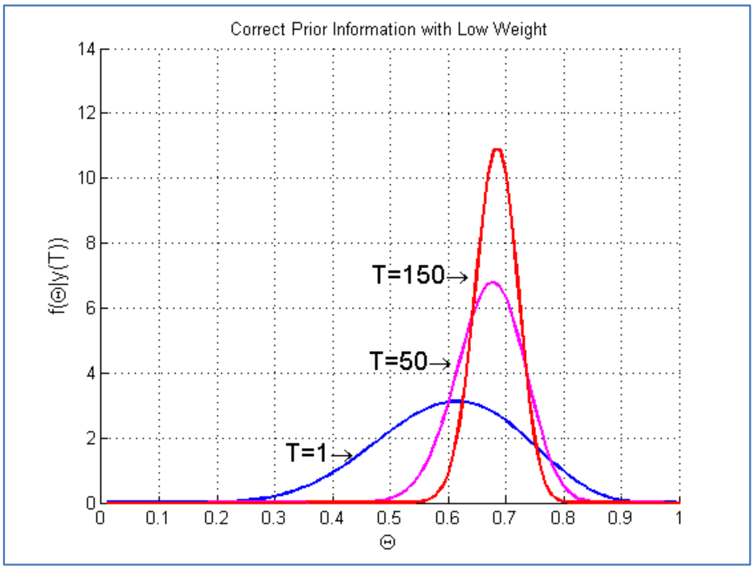


Figure 10 Results of experiment with correct prior information with low weight

In the high weight experiment, we set

$n_{0;0} = 40$ (n0_0 identifier in MATLAB) and

$n_{1;0}$ = 80 (n1_0 identifier in MATLAB)

Prior information denotes the value of Θ parameter equal to $\frac{n_{1;0}}{n_{0;0} + n_{1;0}} = 0.\overline{6}$ again, near to expected 0.7. Results of experiment are in Figure 11.

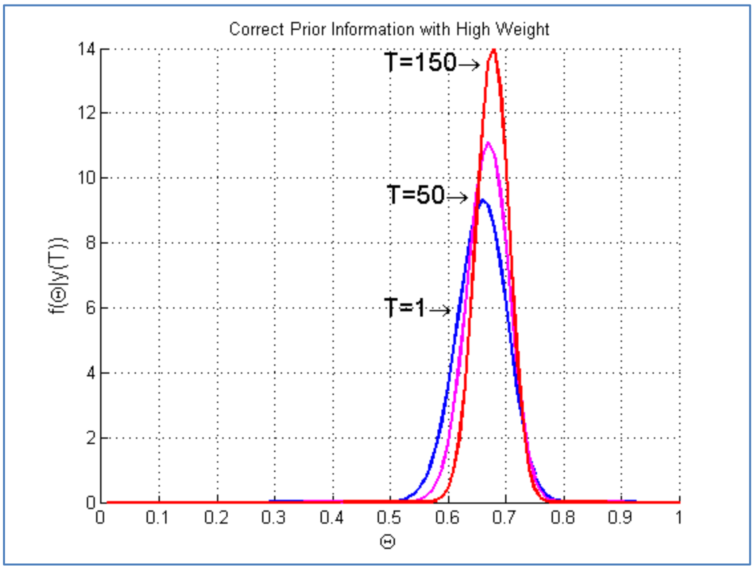


Figure 11 Results of experiment with correct prior information with high weight

In Figure 10, we can see that correct prior information with even a low weight can speed up the movement of the top of pdf curve to the expected value (0.7) during the simulation process.

By comparing the results of both the weak and strong prior information experiments, we can see that the strong prior information has much bigger influence on the simulation process. In the case of the strong prior information, the top of pdf curve is even at the beginning of simulation very close to the expected value of 0.7 and the curve is very slim which means small uncertainty.

4.2.1.4 Conclusions Concerning Prior Information

From the theoretical explanation and from the demonstration experiments described above, we can form some conclusions concerning Bayesian statistics and prior information that will be useful for further considerations. Let us sum up at least some of them here:

- correct prior information can help to get more precise results,
- correct prior information can speed up the way to correct results,
- the stronger the correct prior information is, the sooner we approach the correct results,
- incorrect prior information that is too strong can prevent finding correct results.

In chapters above, main principles of Bayesian statistics were explained and demonstrated on a simple stochastic process with one random variable. The random variable could take on only two values—true / false or turn right / turn left. In practice, the developed advisory system is intended for multivariate problems. Tens of signals acquired from the process are taken as stochastic variables. Moreover, nature of these signals is often not logical but continuous and thus can take on unlimited number of values.

4.2.2 Underlying Theory of Probability Mixtures

Probability mixtures or more precisely mixtures of probability density functions are the key notion of the statistical theory, the developed advisory system is based on. In the next chapter we explain the motivation for using of these mixtures.

4.2.2.1 Information Contained in Historical Data

As mentioned above, information about the investigated process is obtained by acquiring of values of signals connected to the process. Signals are sampled with predefined frequency and stored with a certain history. These data records we will denote as follows (according to [32] or [33] pages 573-4):

$d(t^{\#})$	sequence $(d_1, d_2, \dots, d_{t^{\#}})$ of data records d_t
d_t	data record $(d_{1;t}, d_{2;t}, \dots, d_{n;t})$ of signal / channel values $d_{i;t}$
	where n is number of signals / channels
$d_{i;t}$	value of i-th channel in time instant t

In computer representation, the sequence of data records is a two-dimensional matrix:

$$\begin{bmatrix} d_{1;1} & d_{2;1} & \cdots & d_{n;1} \\ d_{1;2} & d_{2;2} & \cdots & d_{n;2} \\ \vdots & \vdots & \ddots & \vdots \\ d_{1;t^{\#}} & d_{2;t^{\#}} & \cdots & d_{n;t^{\#}} \end{bmatrix}$$

By nearer examination of data acquired from the explored process, we can find out some typical properties of these data describing the natural behaviour of the process. We will demonstrate it on examples of data acquired from real processes.

For practical reasons, we use data records with two channels ($n = 2$) only, which enables easy graphical presentation.

Data records come from a control system of a rolling mill. Two analog signals are acquired with scan period of 5 milliseconds during the process of rolling. The first channel, called MillDriveCurrent in Figure 12, is electric current of the main rolling mill drive in [kA] (sign of MillDriveCurrent changes with direction of rolling). The second channel, called RollingForce in Figure 12, is the force that hydraulic positioning system of working rolls produces to deform the rolled material. Values are in meganewton units. Sequence of data records $d(t^{\#})$ has $t^{\#} \cong 60000$. In the left part of Figure 12, d_t data records are plotted one after another into a plot area. Clusters formed by data points are easily recognizable here.

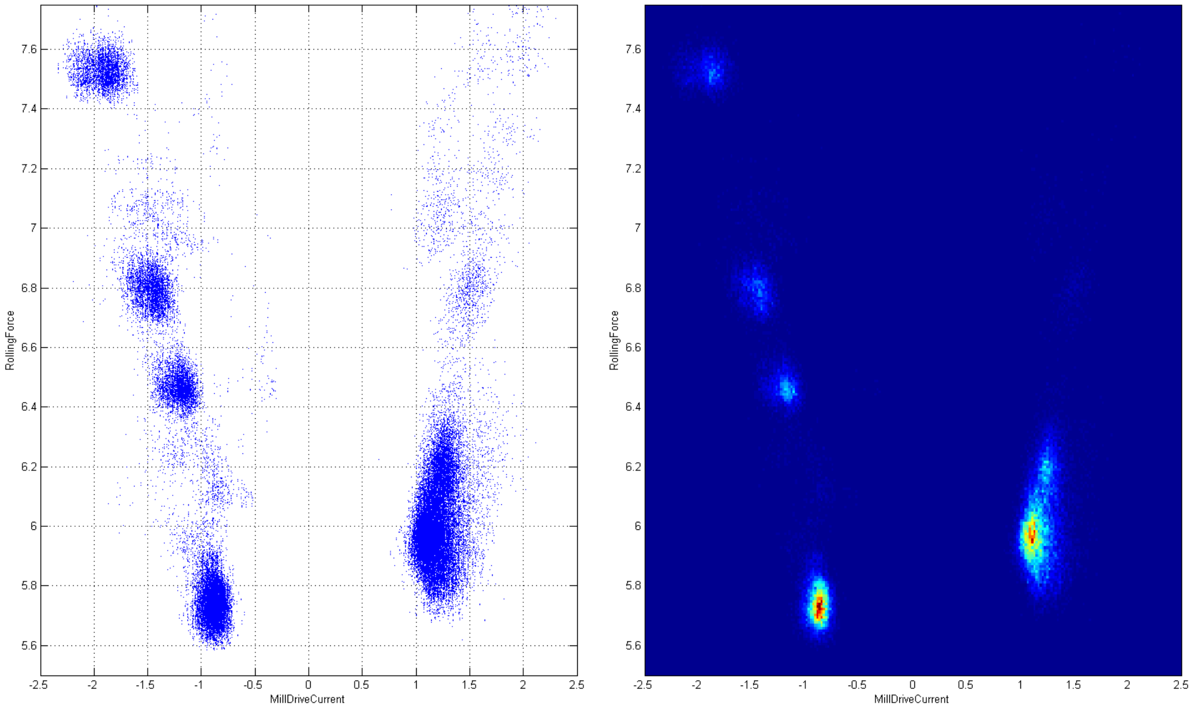


Figure 12 Values of two analog signals, acquired from a rolling mill, form clusters. Data points are plotted as dots (left picture) and in histogram-like form (right picture)

If the number of data points is high as in our case ($t^{\#} \cong 60000$), plotted points are too dense and overlap, and that is why an alternative data presentation is better to be use. Intervals of values of both channels are divided into subintervals and frequencies of data points falling into particular subintervals are calculated. This histogram-like result is displayed in the right part of Figure 12. Colours allow to distinguish areas with high density of data points much better.

Clusters of data points represent areas the actual working point of the explored process was often moving close to. Now, it is possible to explain one of the main principles of the developed advisory system:

1. We choose a criterion that characterises the requested state of the explored process. As examples we can name:
    a. power consumption of a production machine,
    b. quality of production characterized by statistical C_p, C_{pk} coefficients,

   c. energy conversion efficiency in a power plant, etc.
2. From all historical data recordings, we select a subset that contains data acquired at time periods where explored process met the determined criterion.
3. We process the selected data recordings and plot them in a similar way as in Figure 12.
4. Clusters of data points represent areas where working point should reside if we want the process to meet the selected criterion.

4.2.2.2 Motivation for the Use of Probability Mixtures

In previous chapter in Figure 12 we saw that there is useful information contained in the historical data. This information can be easily visible in two-dimensional space but there are two problems related with the information:

- how to describe this information and
- how to calculate with this information even in multi-dimensional data space

so that we could exploit it for the purposes of the advisory system.

We must be able to describe each particular cluster of data points, its shape and distribution of density of occurrences of data points within the data cluster. At the same time, we must be able to describe distribution of data clusters within the whole multi-dimensional data space.

During the ProDaCTool project, the theory of mixtures of probability density functions was selected for representation of data and for calculations for the purposes of the advisory system.

Key principles of the use of the theory of mixtures of probability density functions are in short described further in this chapter.

As mentioned above, the sequence $d(t^{\#}) = (d_1, d_2, \dots, d_{t^{\#}})$ of data records $d_t = (d_{1;t}, d_{2;t}, \dots, d_{n;t})$ of signal / channel values $d_{i;t}$ represents history of discrete (in time) values of continuous variables describing the behaviour of the explored process. In the theory of mixtures of probability density functions, the $d(t^{\#})$ sequence is modelled by the joint probability density function (see [32])

$$f(d(t^{\#})|\Theta) = \prod_{t=1}^{t^{\#}} f(d_t|d(t-1), \Theta) \tag{10}$$

The equation *(10)* says that the probability density function of the whole sequence $d(t^{\#}) = (d_1, d_2, \dots, d_{t^{\#}})$ of data records conditioned by Θ vector of parameters is constructed as product of probability density functions of data records $d_t = (d_{1;t}, d_{2;t}, \dots, d_{n;t})$ in all previous time instances, each conditioned by sequence of data records until $(t-1)$ time instance and by Θ vector of parameters. In other words, the pdf of the whole $d(t^{\#})$ data sequence is the product of pdf's of all previous data sub-sequences. The Θ vector of parameters characterizes the explored process. As we do not know the process, the Θ vector of parameters must be estimated with the use of measured historical data.

Probability density function of a data record in particular time instances can be described as follows (see [32]).

$$f(d_t|d(t-1),\Theta) = \sum_{c=1}^{c^{\#}} a_c\, f(d_t|d(t-1),\Theta_c,c) \tag{11}$$

The equation *(11)* is called parameterized mixture model. The right side of the equation is called mixture of parameterized components—mixture of probability density functions. Coefficient c identifies particular components. Each component has its Θ_c vector of parameters. The a_c coefficients has the meaning of weights of particular components. The a_c coefficients must meet the following conditions

$$a_c \geq 0, c \in (1,\dots,c^{\#}), and \sum_{c=1}^{c^{\#}} a_c = 1 \tag{12}$$

Components $f(d_t|d(t-1),\Theta_c,c)$ on the right side of *(11)* represent distribution of probability in one data cluster and $c^{\#}$ is the number of data clusters. Each component corresponds to a particular system status. In one system status data points are concentrated in one data cluster. Each component represents a model of the system in a particular status.

Because the data is modelled under uncertainty, we cannot expect output of the model in the form of a vector of values but as distribution of probability of appearance of values in the data space (see [34]).

Explanation concerning mixtures of probability density functions introduced in this chapter is very simplified and should be taken as motivation for further study only. Detailed description of the theory can be found in [2] or [35], e.g.

4.2.2.3 Demonstration of Use of Probability Mixtures in 1D a 2D Data Space

For representation of probability density functions mentioned in previous sections, the Gaussian function is usually used. This well known function has several advantageous properties that enable its use in mixtures for approximation of general probability density functions representing distribution of data points in the whole data space. Advantages and some key properties of Gaussian functions are demonstrated in this chapter.

Univariate Gaussian function

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{13}$$

is parameterized by two parameters only. Parameter $\mu \in R$ has the meaning of average value and $\sigma \in R$ parameter is called standard deviation or variance in its σ^2 form.

Gaussian function also meets the following condition for probability density functions

$$\int_{-\infty}^{+\infty} f(x) = 1 \tag{14}$$

As the Gaussian function is parameterized by its mean and variance, the function is often denoted by $N(\mu,\sigma^2)$. Its special case $N(0,1)$ is called standard normal distribution.

For the purposes of the probabilistic advisory system, we need the probability density function to have different shapes and positions in data space. This is enabled by the μ and σ parameters. Following figure demonstrates shaping and positioning of univariate Gaussian functions.

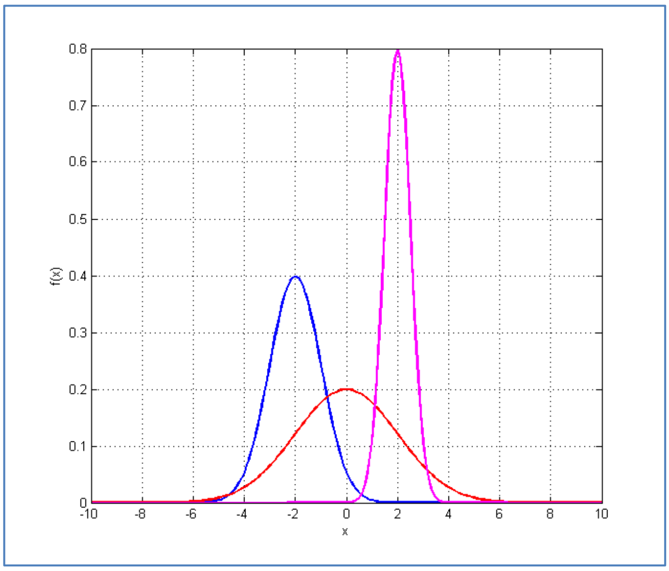


Figure 13 Demonstration of shaping of Gaussian functions by μ and σ parameters. Blue curve has μ=-2 and σ=1, red curve has μ=0 and σ=1, magenta curve has μ=2 and σ=0.5.

For all values of μ and σ parameters, the function meets the *(14)* condition of probability density function.

In the multivariate version of Gaussian function we express that $\boldsymbol{X}$ vector of n random variables has normal distribution with mean vector $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Lambda}$ by the following expression ([36] page 121):

$$\boldsymbol{X} \sim N(\boldsymbol{\mu}, \boldsymbol{\Lambda}) \qquad \textit{(15)}$$

$\boldsymbol{X} = (X_1, X_2, \dots, X_n)'$ vector of n random variables

$\boldsymbol{\mu}$ vector of n means

$\boldsymbol{\Lambda}$ covariance matrix, $n \times n$ positive definite, symmetric matrix

Covariance matrix expresses relations between particular random variables X_i. For elements of covariance matrix, we can write according to [36] page 119:

$$\lambda_{ij} = E\{(X_i - \mu_i)(X_j - \mu_j)\} = Cov(X_i, X_j), i, j = 1,2, \dots, n \quad E \text{ denotes mean} \qquad \textit{(16)}$$

$$Cov(X_i, X_i) = \sigma^2$$

Multivariate version of Gaussian function has the following form ([36] page 125):

$$f_X(\boldsymbol{X}) = \left(\frac{1}{2\pi}\right)^{\frac{n}{2}} \frac{1}{\sqrt{\det \boldsymbol{\Lambda}}} e^{-(\boldsymbol{X}-\boldsymbol{\mu})' \boldsymbol{\Lambda}^{-1} (\boldsymbol{X}-\boldsymbol{\mu})} \quad \text{for } \sqrt{\det \boldsymbol{\Lambda}} > 0 \qquad \textit{(17)}$$

To express the Gaussian function for two random variables X_1, X_2 in another form, we introduce the correlation coefficient ([36] page 126):

$$\rho = \frac{Cov(X_1, X_2)}{\sigma_1 \sigma_2} \qquad \text{correlation coefficient} \qquad (18)$$

With the ρ correlation coefficient we can write for two random variables X_1, X_2

$$f_{X_1,X_2}(x_1, x_2) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}}\ e^{-\frac{1}{2(1-\rho^2)}\left(\left(\frac{x_1-\mu_1}{\sigma_1}\right)^2 - 2\rho\frac{(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2} + \left(\frac{x_2-\mu_2}{\sigma_2}\right)^2\right)} \qquad (19)$$

where $\sigma_1 > 0\ and\ \sigma_2 > 0\ and\ |\rho| < 1$

With this form, we can simply demonstrate shaping and positioning of bivariate Gaussian functions.

First, we demonstrate shaping and positioning of bivariate Gaussian function by $\sigma_1, \sigma_2, \mu_1, \mu_2$ parameters while $\rho = 0$. See the following pictures.

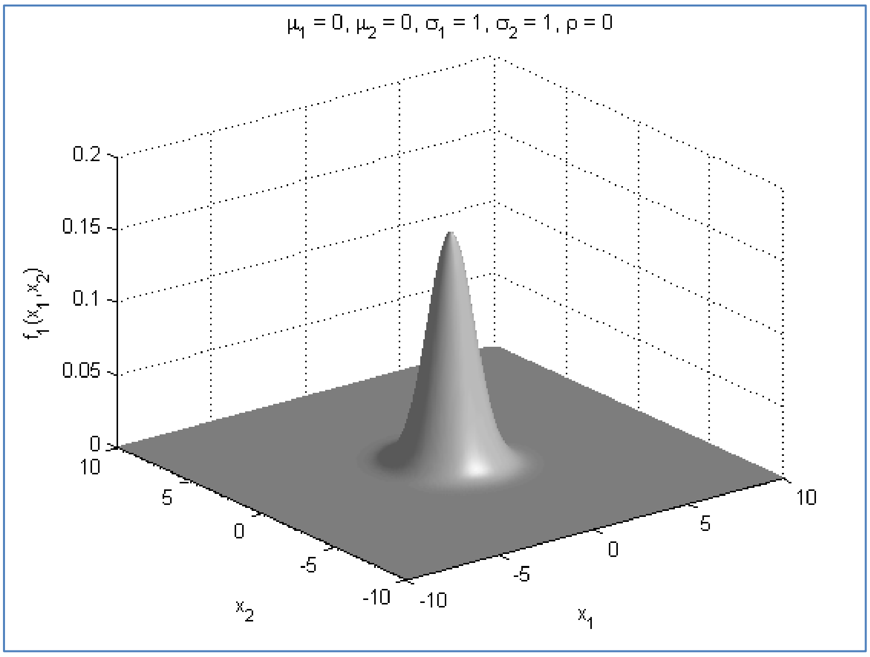


Figure 14 Bivariate Gaussian function with $\sigma_1 = \sigma_2$ positioned at [0,0] data point.

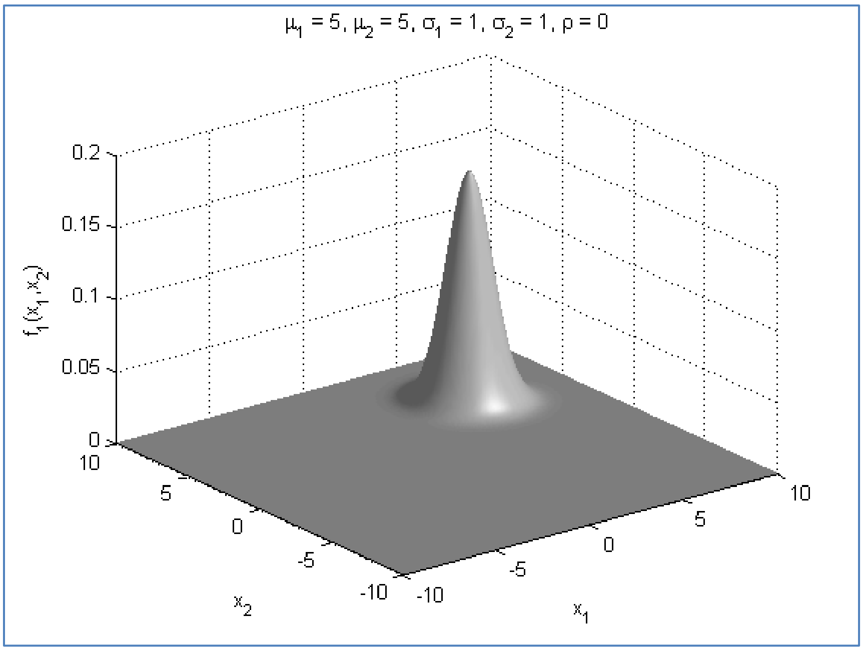


Figure 15 Bivariate Gaussian function with $\sigma_1 = \sigma_2$ positioned by values of μ_1, μ_2 at [5,5] data point.

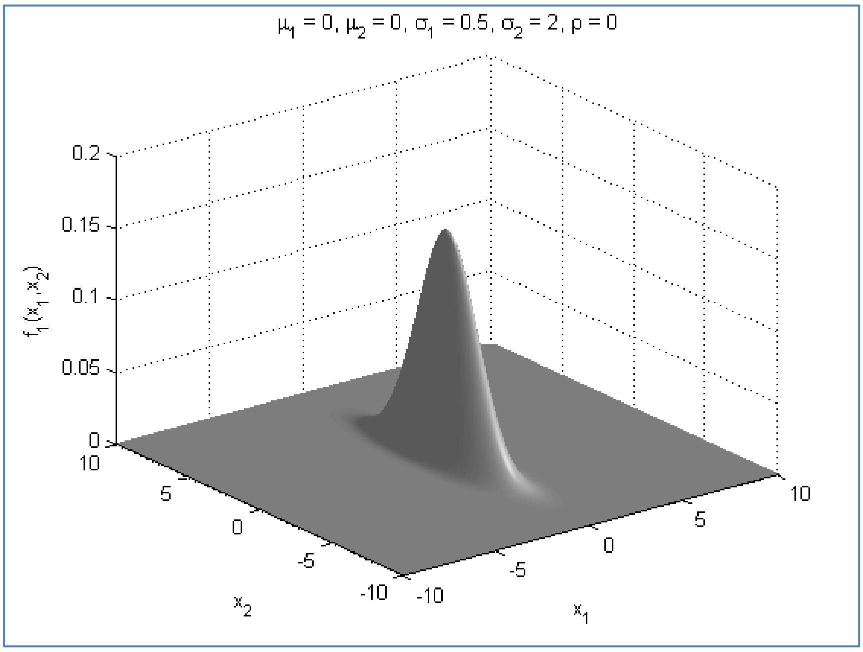


Figure 16 Bivariate Gaussian function with $\sigma_1 < \sigma_2$ positioned at [0,0] data point.

All above displayed functions have $\rho = 0$ and flattening is done by σ_1/σ_2 ratio in x_1 or x_2 axis directions only. Nonzero correlation coefficient ρ enables to rotate the flattened function as demonstrated in the following picture.

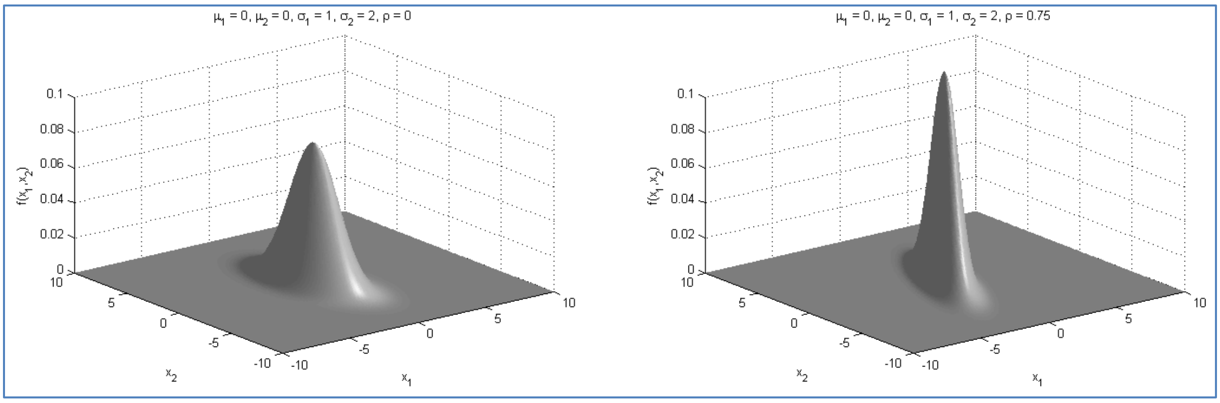


Figure 17 Demonstration of how to rotate a flattened bivariate Gaussian function by nonzero correlation coefficient.

All above stated pictures illustratively show the capability of Gaussian functions to represent clusters of data points (see Figure 12) in one- and two-dimensional data spaces. Multivariate Gaussian functions can apparently be used for representation of data clusters in n-dimensional data space where $n > 2$.

Use of a mixture of two bivariate Gaussian functions is demonstrated in the following picture.

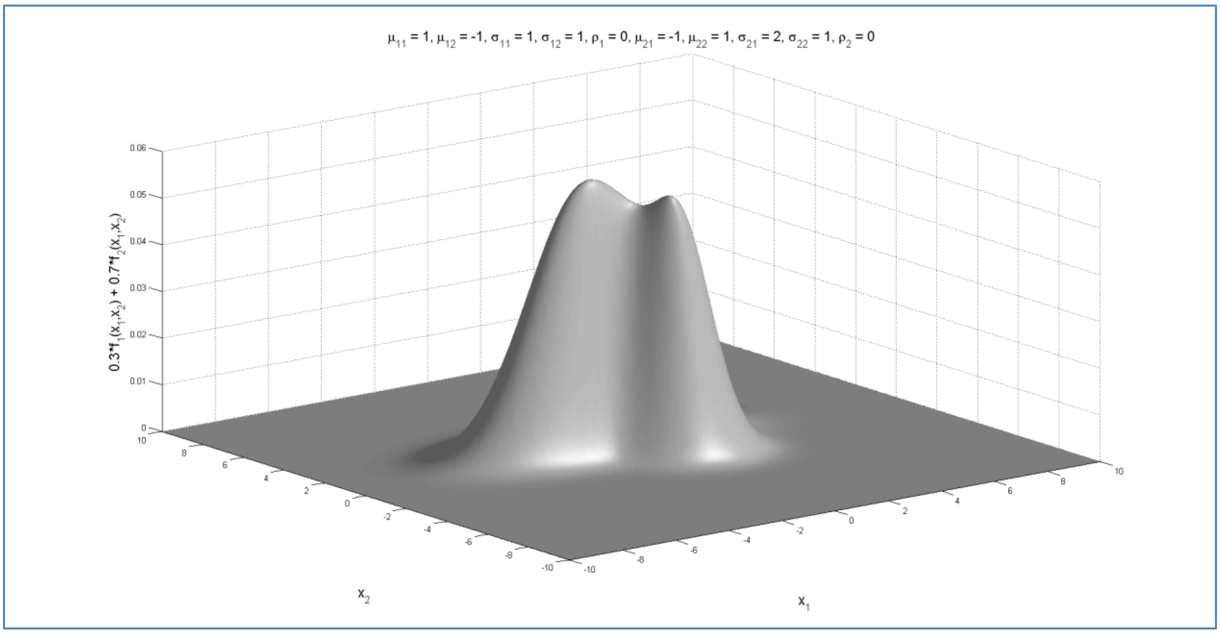


Figure 18 Simple mixture of two bivariate Gaussian functions.

According to *(11)* and *(12)*, probability density functions are combined with their respective weights in the mixture. In Figure 18, weights $a_1 = 0.3$ and $a_2 = 0.7$ are used.

4.2.3 MixTools Function Library as the Key Software Tool for Probability Mixture Handling

There was shown in previous chapters that data containing information about behaviour of a process or system can be represented by weighted combination of probability density functions where particular probability density functions are represented by parameterized Gaussian functions.

The main idea is simple but there arise several problems in practice, e.g. how to find the representation of real data in the form of a probability mixture, how to generate data simulated by a mixture, how to calculate with mixtures, etc. These problems has been solved during several past years by the colleagues from the Department of Adaptive Systems, Institute of Information Theory and Automation of the ASCR. The underlying theory and algorithms were worked out and these results were implemented into the function library called MixTools.

MixTools function library is a wide set of functions coded originally as MATLAB scripts. The development of this library started more than ten years ago and was supported by several research and development projects. During the whole development period, the library was continuously extended by newly achieved knowledge in the form of new or extended library functions. Now, the library has the form of a standard MATLAB toolbox with interactive help and wide set of examples. Nevertheless it is not distributed as a real MATLAB toolbox.

Author of this document participated in the development of the MixTools function library in the stage when it was formed as MATLAB toolbox.

MixTools function library covers a wide range of functions for handling with probability mixtures. MixTools library is the key software tool used during the development of the probabilistic advisory system. A short survey of this library can be found in 6Appendix 3.

4.2.4 Offline Processing of Historical Data and Creation of Historical Mixture

In this chapter, the initial processing of acquired historical data will be described.

As mentioned in previous chapters (the acquisition of signals was described earlier in chapter 4.1.3 in detail), information about the behaviour of observed process is acquired by acquisition of series of values of signals connected to the process. Potential problems consist in that fact that resulting $d(t^{\#})$ sequences of data records

- are stored generally in files of different formats,
- they are continuous in time or separated by time periods where no data are acquired,
- they are located in one database table or in separate tables in separate files,
- samples are triggered by time ticks or by some other events.

There are four main tasks in this phase of data processing:

- unification of historical data,
- selection of criterion that characterizes the desirable state of the process,
- separation of historical data recordings meeting the criterion,
- finding the representation of separated historical data in the form of a mixture of probability density functions, called *historical* mixture.

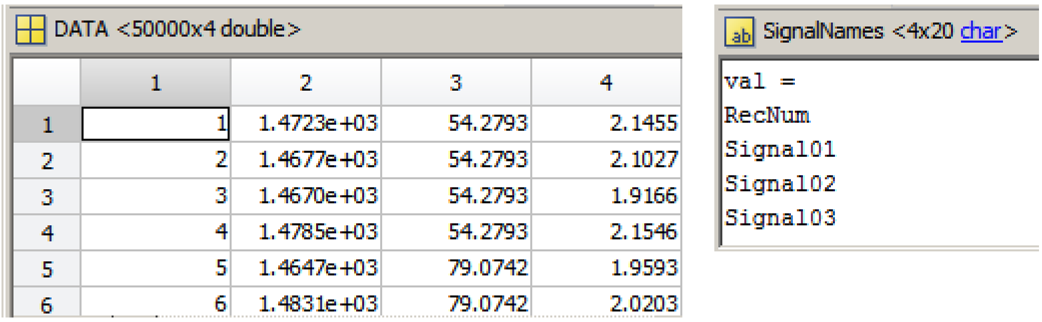
4.2.4.1 Unification of Historical Data

As mentioned above, data recordings may be miscellaneous especially if data were not acquired for the purposes of the advisory system. In some cases, it is not possible to install new purpose-built data acquisition system and data recordings provided by an existing system must be used instead.

The main task of this phase of data processing is to unify all possible sources of data and prepare a unified form of data that will server as input for the next phase of data processing. A MATLAB data structure stored in .MAT file was selected during the development within the framework of the ProDaCTool project and it is still used until now. From the wide range of possible sources of historical data, the Microsoft Access database format in files with .MDB extension is, as the most frequently used source, fully covered by software tools ensuring the conversion to the selected unified form.

Format of MATLAB data structure stored in .MAT file is as follows:

- Sequence $d(t^{\#}) = (d_1, d_2, \dots, d_{t^{\#}})$ of data records $d_t = (d_{1;t}, d_{2;t}, \dots, d_{n;t})$ of signal / channel values $d_{i;t}$ is stored in a two-dimensional matrix. Each column corresponds to a channel. Number of rows corresponds to the number of samples.
- Names of columns of the matrix with data samples are stored in a matrix where each row corresponds to a name of a column and the maximum length of column name is 20 characters.



DATA <50000x4 double>

	1	2	3	4
1	1	1.4723e+03	54.2793	2.1455
2	2	1.4677e+03	54.2793	2.1027
3	3	1.4670e+03	54.2793	1.9166
4	4	1.4785e+03	54.2793	2.1546
5	5	1.4647e+03	79.0742	1.9593
6	6	1.4831e+03	79.0742	2.0203

SignalNames <4x20 char>

```
val =
RecNum
Signal01
Signal02
Signal03
```

Figure 19 Example of the MATLAB data structure used to store $d(t^{\#})$

This approach has one disadvantage. In case of a big number of samples, the `DATA` matrix exceeds the maximum variable size allowed in MATLAB if the .MAT file is loaded into MATLAB workspace. To solve this problem, all MixTools estimation functions accept the `ndat` argument (number of data samples) in the following form as well. (Estimation functions have the `DATA` matrix as input and produce the representation of `DATA` in the form of a mixture which is very compressed information and thus requires only a small memory space.)

```
Ndat={'RecordingsFileName',mdat}
```

`RecordingsFileName` is the name of file containing the sequence of data samples. Samples are written as a table in binary double format and `mdat` is the byte-size of a sample. This enables the so-called *buffered estimation*. This feature is available in functions written in C language (in MEX modules) only. MEX modules enable allocation of a huge `DATA` matrix and the matrix is then loaded from file.

Buffered estimation is very useful in the phase of transformation of historical data to the mixture representation because the number of records must be high, so that the data could contain as much information as possible and thus cover all possible states of the investigated process.

4.2.4.2 Selection of Criterion of Desired State of Process

In this chapter, we will explain how to select the criterion that will enable to separate sequences of data samples that represent required status of the process.

The aim of the advisory system is to help the operator to produce more efficiently, with higher quality, with less power consumption etc. The criteria should meet this requests.

The simplest strategy is to choose a signal / channel and to set a range of desired values of this signal. The condition for selection of recordings that meet the criterion is as follows: Select all samples where criterion signal value is between lower and upper range boundary.

We will explain disadvantage of this simple criterion on an examples. In the following figure, the criterion is applied to an sample signal. Lower and upper range boundaries are set to `-10` and `+10`.

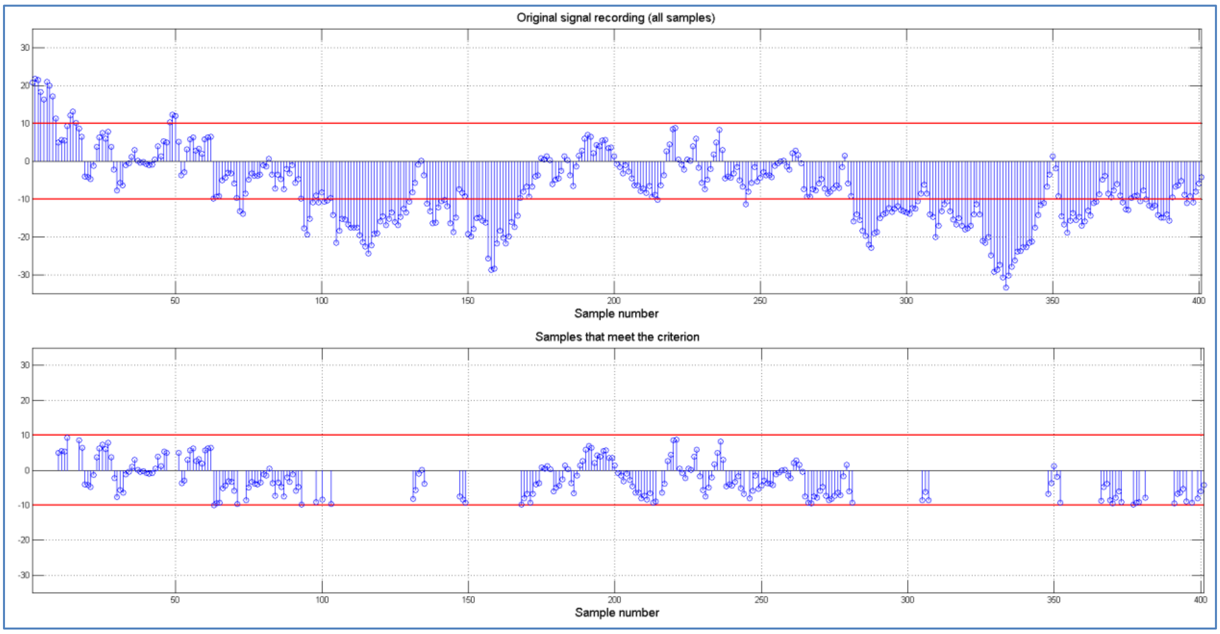


Figure 20 Original sample signal recording (upper plot) and selected samples meeting the criterion that signal value must be between -10 and +10 boundaries (lower plot).

In the lower plot of the Figure 20, we can see that the recording can be significantly fragmented by application of the criterion. By the fragmentation, the time dependence of subsequent samples is lost and samples are not equidistant any more. The narrower the criterion range is the worse the fragmentation is. On the contrary, a too wide range makes the criterion weaker.

The problem how to separate suitable recordings from all acquired data showed to be quite complex during the work on the ProDaCTool project and a methodology was not fully developed yet, but the following strategy showed to be much better than the one mentioned above. One feature of this strategy is that acquired data are partitioned into such sequences of samples that they represent the whole compact production periods which can be qualified good or bad as a whole. This approach takes into account that one production period consists of a set of operation modes that depend one on the others.

Another feature of this strategy is the use of statistical coefficients for the qualification of the production period. This approach enables to qualify the whole production period, in spite of the fact that particular operation modes that create the production period can show highly different relation to qualification criterion. Data recordings from the time when system operates in modes with poor qualification cannot be omitted because these modes are integral parts of the whole production period. (Car cannot reach a constant travel speed without an acceleration phase.)

We can name the following examples as production periods consisting of several production modes:

1. In a power plant, an example of one production period is a start-up after a planned shutdown. Or the switching between power production and power consumption in a pumped storage plant.
2. In medicine, one production period (with awareness that "production" is not very suitable adjective in this branch) can be one sequence of chemotherapy.
3. In steel industry, one pass of rolling of steel strip can be named as example of production sequence. We will describe this example in more details in the next chapter.

If the data acquisition system produces long-time recordings, whole shifts e.g., it may be hard to find the sought production period sample sequences in the whole data repository with a huge amount of data. That is why, if the data acquisition system is developed for the purpose of advisory system, it is convenient to separate particular production periods online during the phase of data acquisition.

4.2.4.3 Separation of Recordings Meeting the Given Criterion

As mentioned above, no consistent methodology for separation of recordings meeting the criterion was developed yet. The criterion has to be formulated from case to case especially if investigated processes differ so significantly as in the examples in previous chapter. That is why we will demonstrate this phase of data processing on the third example from the previous chapter.

Production of metal strip on a reversing rolling mill consists usually of several production periods. In this case these periods are called passes. In each pass, the strip is unwound on the input side of the rolling mill, passes through the rolling gap, where the thickness is reduced, and is wound up on the output side. If the whole strip passes through the rolling gap in one direction, direction is reversed. Number of passes is between 1 and 15 usually. Each pass is characterized by special operating conditions, by special settings of process parameters. Especially the first and the last passes have a specific position among other ones and influence the final production quality substantially.

One pass is characterized by a set of technological parameter settings. A common minimal subset of these parameters is listed in the following table.

Parameter name	Description
`ThicknessReduction`	Relation between input and output strip thicknesses.
`InputTension`	Tension exerted in strip by de-coiler on the input side.
`OutputTension`	Tension exerted in strip by coiler on the output side.
`MillSpeed`	Peripheral speed of working rolls.
`RollTilting`	Tilting of working rolls that influences the cross profile of the strip.
`RollBending`	Bending of working rolls that influences the cross profile of the strip.
`RollCooling`	Cooling of rolls that influences the cross profile and surface quality of the strip.

Table 2 A minimal subset of technological parameters influencing steel strip production.

Setting of these parameters during one production period (pass), influences the resulting quality of produces steel strip. Resulting quality is characterized by the quality attributes listed in the following table.

Quality attribute	Description
Thickness	The thickness of strip has to be of the required thickness with an allowed difference given by positive and negative tolerances.
Cross profile	During the rolling the cross profile of strip becomes a required specific shape. The required shape is dependent mainly on the purpose the strip is used for and on material type. It is reviewed to what extend the cross profile of produced strip meets the parameters of requested profile.
Mechanical properties	Material changes during the forming its mechanical properties. The way of forming must follow predefined sequence of operations to reach required target mechanical properties.

Table 3 Attributes characterizing outgoing quality of produced strip.

It is a complex problem to find a criterion that would cover all quality attributes. That is why, for the purpose of explanation of principles, we will simplify the criterion as much as possible.

We measure the final quality of produced strip by the quality of strip thickness only and in the last pass only. For the explanation, strip thickness is taken as discrete random variable and we use symbols listed in the following table.

Symbol	Meaning
$H_{2i}, i = 1 \dots n$	Discrete values of random variable strip thickness in one pass.
H_2	Mean value of H_{2i}. in one pass.
H_{2nom}	Nominal output thickness of strip. Required thickness in a particular pass.
$h_{2i}, i = 1 \dots n$	$H_{2i} - H_{2nom}$
h_2	Mean value of thickness deviation. Equals to $H_2 - H_{2nom}$.
Tol_{pos}	Positive tolerance.
Tol_{neg}	Negative tolerance

Table 4 Symbols used for description of output thickness quality.

The ideal thickness would meet the criterion $H_{2i} = H_{2nom}$ for all $i = 1 \dots n$ but it is impossible in practice. That is why positive and negative tolerances are introduced. Then the weaker condition for acceptable H_{2i} values is $H_{2i} \in \langle H_{2nom} + Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$. With this criterion, we are at the point described in the chapter 4.2.4.2, where it was shown that selection according to this criterion is not a good choice. We use statistical coefficients instead, that enable to evaluate the production period as a whole.

Known statistical coefficients C_p and C_{pk} showed to be the right choice. C_p is called capability index and C_{pk} is called centring capability index.

$$C_p = \frac{Tol_{pos} - Tol_{neg}}{6\sigma}$$

$$C_{pk} = \frac{min(h_2 - Tol_{neg}, h_2 + Tol_{pos})}{3\sigma}$$

where σ is standard deviation

$$\sigma = \sqrt{((h_{21} - h_2)^2 + \cdots + (h_{2n} - h_2)^2)/n}$$

and h_2 is mean value of $h_{2i}, i = 1 \dots n$

$$h_2 = \frac{1}{n}\sum_{i=1}^{n} h_{2i}$$

Meaning of these two coefficients is to be seen in histogram representation of h_{2i}.

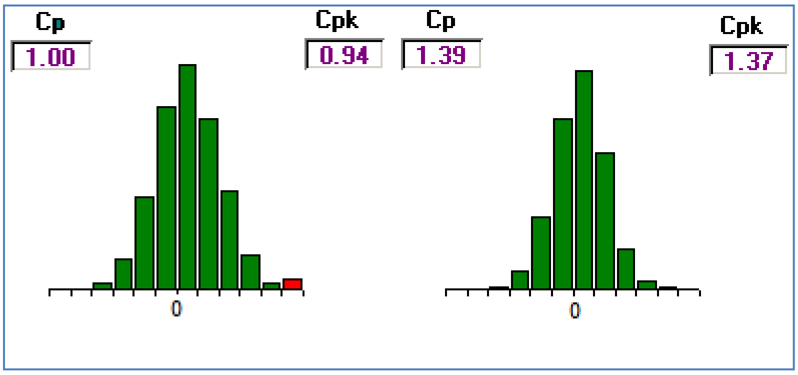


Figure 21 Relation between histogram and C_p, C_{pk} coefficients.

In Figure 21, the bars in most left and right positions of x-axis (red coloured if present) represent all H_{2i} values that fall out of $\langle H_{2nom} + \ Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$ interval.

Capability index C_p expresses how narrow the histogram is and centring capability index C_{pk} tells how much the bars of histogram are centred on x-axis. Values of C_p lower than 1.00 signalize that histogram is too wide and that exist H_{2i} values out of $\langle H_{2nom} + \ Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$ interval. Values $C_p \geq 1.00$ tells that histogram is narrow enough that all H_{2i} values would fall into $\langle H_{2nom} + \ Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$ interval if histogram were centred.

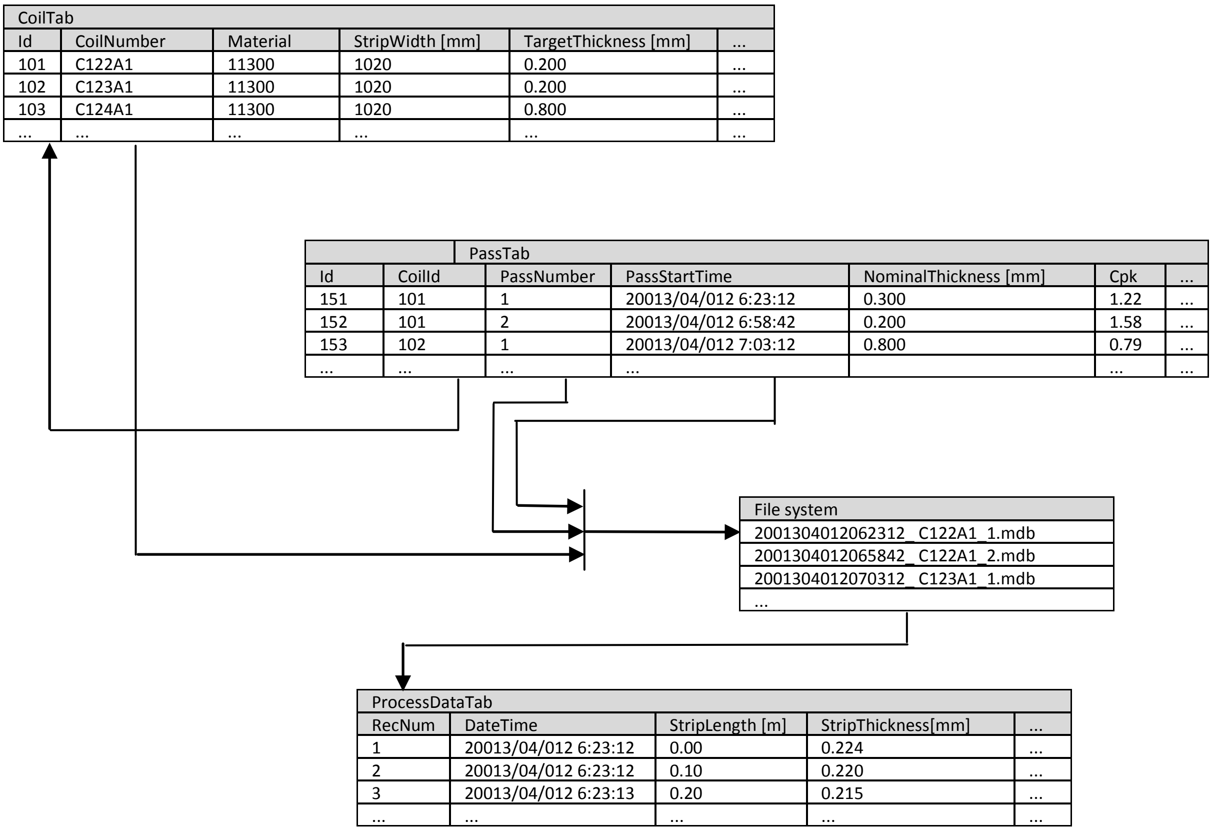
Values of $C_{pk} \ \geq 1.00$ signalize that histogram is narrow and centred enough that all H_{2i} values fall into $\langle H_{2nom} + \ Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$ interval.

In Figure 21, the left histogram is narrow enough ($C_p = 1.00$) but $C_{pk} < 1.00$ indicates that histogram is not centred and that is why we must expect some H_{2i} beyond $\langle H_{2nom} + Tol_{neg}; H_{2nom} + Tol_{pos}\rangle$ interval boundaries. In the right histogram in Figure 21, there can be seen that $C_{pk} > 1.00$ is sufficient condition for all H_{2i} values being in allowed interval.

Based on this theoretical assumptions, C_{pk} is chosen as criterion for evaluation of data recordings representing particular production periods, passes. Based on this C_{pk} value, we can select recordings of production periods representing results of production, that are of desired quality.

As mentioned in previous chapter, if the data acquisition system produces long-time recordings not corresponding to desired production periods, it is necessary to divide these recordings into parts that represent production periods first. In other words it is necessary to reconstruct what exactly was produced at each recording time. Then, additional attributes must be assigned to the recordings. Attributes of that king that enable division of recordings to corresponding production periods. This is generally a complex problem, that is why we pretend that data acquisition system is constructed for the purpose of the advisory system and acquires data in a form suitable for application of C_{pk} criterion.

For this explanation we pretend the data acquisition system described in Chapter 4.1.3. Resulting structure of acquired data consists of a database tables comprising parameters of produced strips and parameters of particular production periods (passes). Detailed recordings of particular passes are stored in separate files containing database tables with values of all acquired data channels. Structure of acquired data is described in Figure 22 in detail.



CoilTab					
Id	CoilNumber	Material	StripWidth [mm]	TargetThickness [mm]	...
101	C122A1	11300	1020	0.200	...
102	C123A1	11300	1020	0.200	...
103	C124A1	11300	1020	0.800	...
...	...	...	...	...	...

PassTab						
Id	CoilId	PassNumber	PassStartTime	NominalThickness [mm]	Cpk	...
151	101	1	20013/04/012 6:23:12	0.300	1.22	...
152	101	2	20013/04/012 6:58:42	0.200	1.58	...
153	102	1	20013/04/012 7:03:12	0.800	0.79	...
...	...	...	...		...	...

File system
2001304012062312_ C122A1_1.mdb
2001304012065842_ C122A1_2.mdb
2001304012070312_ C123A1_1.mdb
...

ProcessDataTab				
RecNum	DateTime	StripLength [m]	StripThickness[mm]	...
1	20013/04/012 6:23:12	0.00	0.224	...
2	20013/04/012 6:23:12	0.10	0.220	...
3	20013/04/012 6:23:13	0.20	0.215	...
...	...	...	...	...

Figure 22 Structure of acquired data

In Figure 22, the CoilsTab database table contains parameters of particular coils of strip. A coil is characterised by a set of parameters that identify it and denote its material properties and dimensions. These parameters will be useful for the selection of similar coils later in this chapter. PassTab database table stores parameters that characterize properties of strip at the time of the particular pass, especially statistical coefficients that enable to consider the quality being reached during the production period. Samples of signal values are stored in a database table during one particular pass. The database table is stored in a file, name of the file is constructed from several parameters stored in CoilTab and PassTab respectively.

This data structure enables easy separation of production periods of required quality level. With a simple SQL query, the required data can be selected:

```
PARAMETERS CpkMinimumPar  Double;
SELECT * FROM PassTab
INNER JOIN CoilTab ON CoilTab.Id=PassTab.CoilId
WHERE PassTab.Cpk >= CpkMinimumPar
```

With setting the `CpkMinimumPar`, records that correspond to the production of required quality can be selected. For each selected record, the corresponding database file with

ProcessDataTab, can be found. This way, a set of database files containing required data can be prepared for further processing.

These principles were verified during the ProDaCTool project and following research.

4.2.4.4 Representation of Data by Historical Mixture

In this phase, the advisory system has enough information describing behaviour of the investigated process in time periods when the system meets the selected criterion. The behaviour is described by a number of records with signal values. The number of records may often be, and is recommended to be, enormous. It is hard to work with this huge amount of data. The information contained in data is to be represented in a concentrated form. And now, the representation of statistical data by a mixture of probability density functions described in previous chapters comes into consideration.

Data are transformed into the mixture representation. For this transformation, functions from MixTools function library are used. MixTools and underlying theory are described in chapters above.

The resulting mixture is plotted into Figure 23. As the signal channel samples contained in DATA matrix are same as those plotted in Figure 12, the figures can be visually compared. Signal channels come from data acquisition system of a rolling mill again.

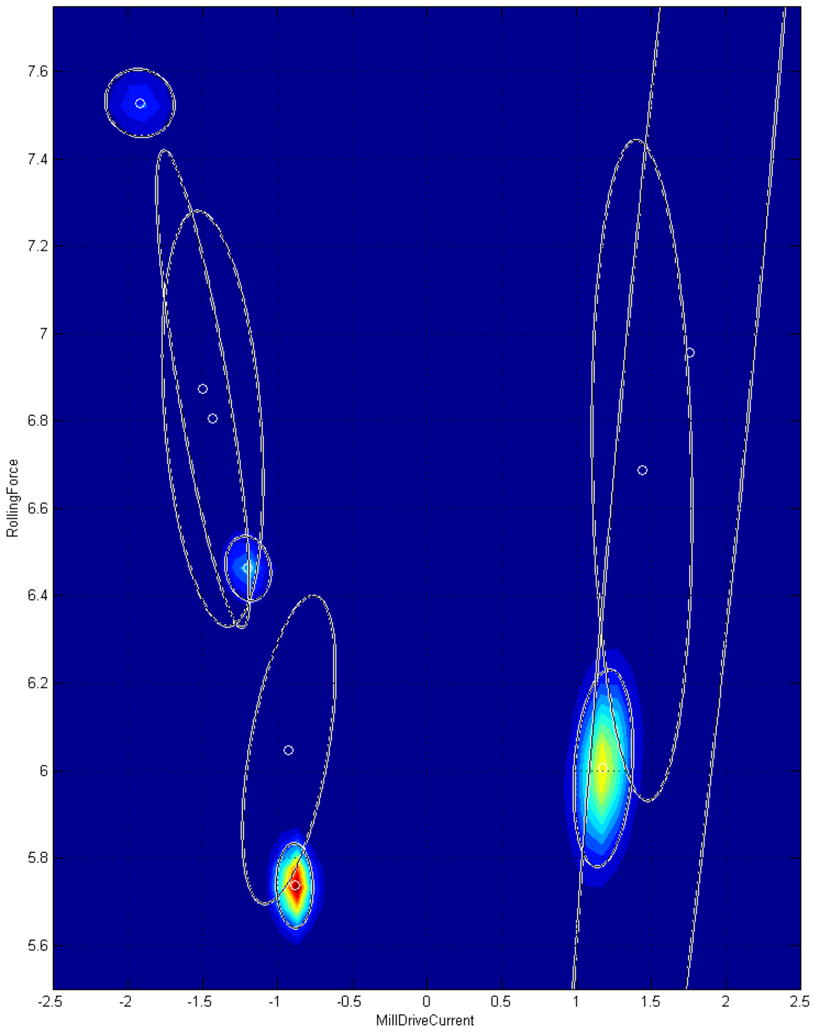


Figure 23 Historical mixture representing data from Figure 12.

The mixture is denoted as historical mixture because it represents the behaviour of system in history. In our case, data points are covered by 9 components of the mixture. Colours show that two of them situated in lower part of the figure has a dominant position. These two components represent regions where most of data points fall into.

Visual representation of the historical mixture enables us to read some useful information from this form of acquired data. Mentioned dominant components are situated in positive and negative parts of MillDriveCurrent-axis respectively. Positive and negative current corresponds to different rolling directions in this case. Rolling in one direction (let us say to left) is characterized by MillDriveCurrent having value around -0.8 and RollingForce around 5.7 while in the opposite rolling direction, MillDriveCurrent is around 1.2 and RollingForce around 6.0. (We omit physical units because we explain the principle only and. Values of MillDriveCurrent change sign with direction of rolling.)

If we disregard influence of other parameters or signal channels and if we simplify the problem very much, we can demonstrate the main idea of the advisory system by deducing the following conclusion:

"If the operator is keeping MillDriveCurrent close to -0.8 and RollingForce close to 5.7 while rolling to left, and MillDriveCurrent close to 1.2 and RollingForce close to 6.0 while rolling to right, the quality of production will be good."

There may arise a question why to use the mixture representation of data if the same conclusion may be deduced from other representations of data, e.g. in Figure 12. The answer is that the main reasons are as follows:

- Mixture representation comprises huge number of data records to a relatively small set of parameters that is much easier to operate with.
- There exist mathematical functions for handling with mixtures.
- Mixtures are suitable for n-dimensional data space and not limited to $n = 2$ or $n = 3$.

The existence of historical mixture as the result of initial data processing functions is the base for proper functionality of the whole advisory system.

4.2.5 Actual Production Mode and Creation of Target Mixture

In previous chapter, the offline phase of data processing was described while online phase of data processing begins in this chapter. Now, advisory system disposes of information describing behaviour of the investigated system in history—historical mixture. The history comprises lots of operation modes of the system. If the operator wants to exploit the advisory system, he has to express his intention to use the system in a particular mode. In case of power station, operator wants to operate the power station at full power, e.g. In case of traffic control, the operator wants to operate the traffic lights under condition that one of four roads of a crossroad is under reconstruction and closed, e.g. Operator of a rolling mill has to roll, let us say, steel strip from input thickness of 1.00 mm to output thickness of 0.75 mm, width of 620 mm.

Generally said, operator with his requests narrows a wide range of operation modes of the system. In the concept of the advisory system, the intention of operator is expected in the form of a mixture called *target* mixture. Same set of channels is used for the construction of target mixture as for the calculation of historical mixture. During the construction of target mixture, all possible ranges of values in all channels are narrowed. There are two subsets of channels. One subset contains channels that operator knows how to set. With the other subset of channels, operator does not know how to, or does not want to set the values of channels. If operator knows how to set a channel, he has two possibilities:

- Operator sets the channel to a constant value. This way, the n-dimensional data space (n is number of channels) is reduced by one dimension.
- Operator expresses the requested value of the channel by a univariate Gaussian function *(13*). With μ, he expresses the average value and with σ he says how much the value may fluctuate around μ.

Channels set to a constant are usually type of material or strip width e.g. (in case of rolling mill production).

For channels where operator does not set a channel value, two methods were tested during the ProDaCTool project and following research. Both methods are based on calculation of marginal pdf in each concerned channel of historical mixture. Marginal pdf $f_{MC_1}(c_1)$ for two channels (random variables) C_1, C_2 is defined as follows:

$$f_{MC_1}(c_1) = \int\limits_{C_2^*} f_{C_1C_2}(c_1,c_2)\,dc_2$$

where $f_{C_1C_2}(c_1,c_2)$ is joint pdf of two random variables. In other words, the marginalization applied on historical mixture means that for all values of one channel, pdf values are summed up for all possible values of the other channels.

Demonstration of marginal pdf is shown in the following figure.

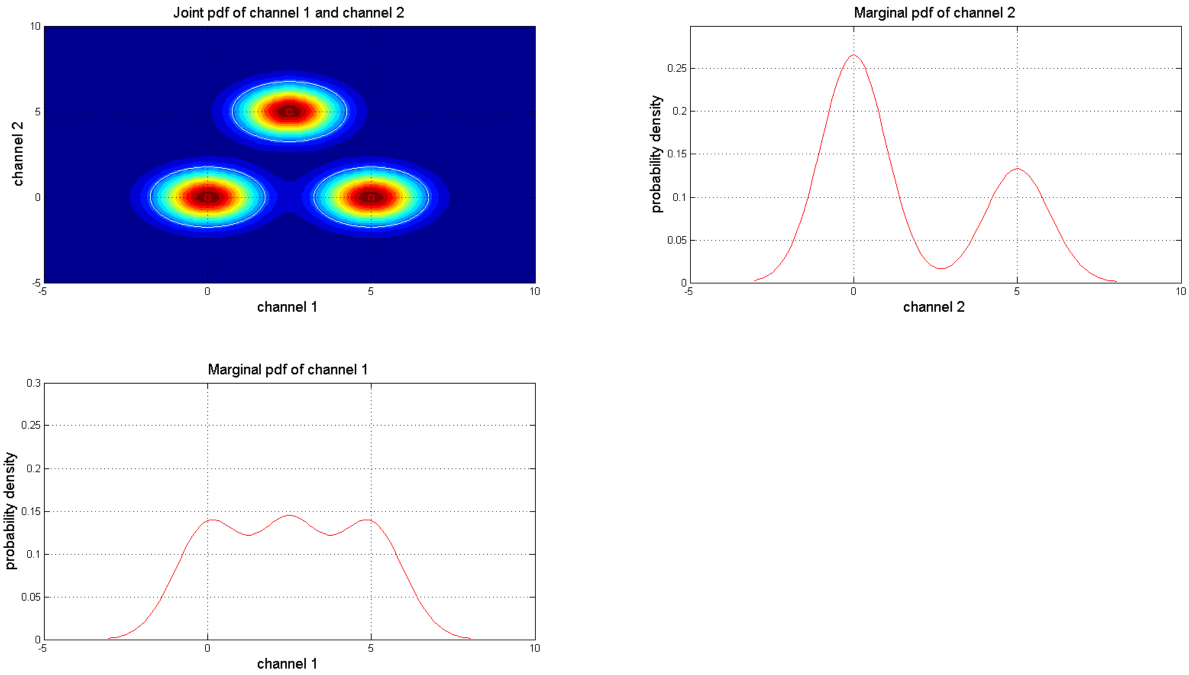


Figure 24 Demonstration of marginal pdf

In the top left subplot, there is a sample joint pdf of two channels (random variables) represented in the form of mixture pdf consisting of three components. In the bottom subplot, there is marginal pdf of channel 1. It can be imagined as bottom up view of top left subplot. Right left view of top left subplot corresponds to marginal pdf of channel 2 that is plotted in top right subplot. Marginal pdf is not a simple projection of two-dimensional joint pdf in one axis direction. The influence of integral is to be seen well in the top right subplot where one component behind another in top left subplot result in a higher "hill" in the marginal pdf.

With the knowledge of marginal pdf, we can come back to methods mentioned above, that help to determine possible values of channels where operator does not set a range of channel values himself. In the first step, marginal pdf is calculated for each of those channels. Then the methods differ:

- In the first method, target pdf is chosen as the component "nearest" to the historical pdf with maximum density.
- In the second method, target pdf is chosen as the component replacing the whole cluster of pdfs with high density.

Both methods are demonstrated in the following figure.

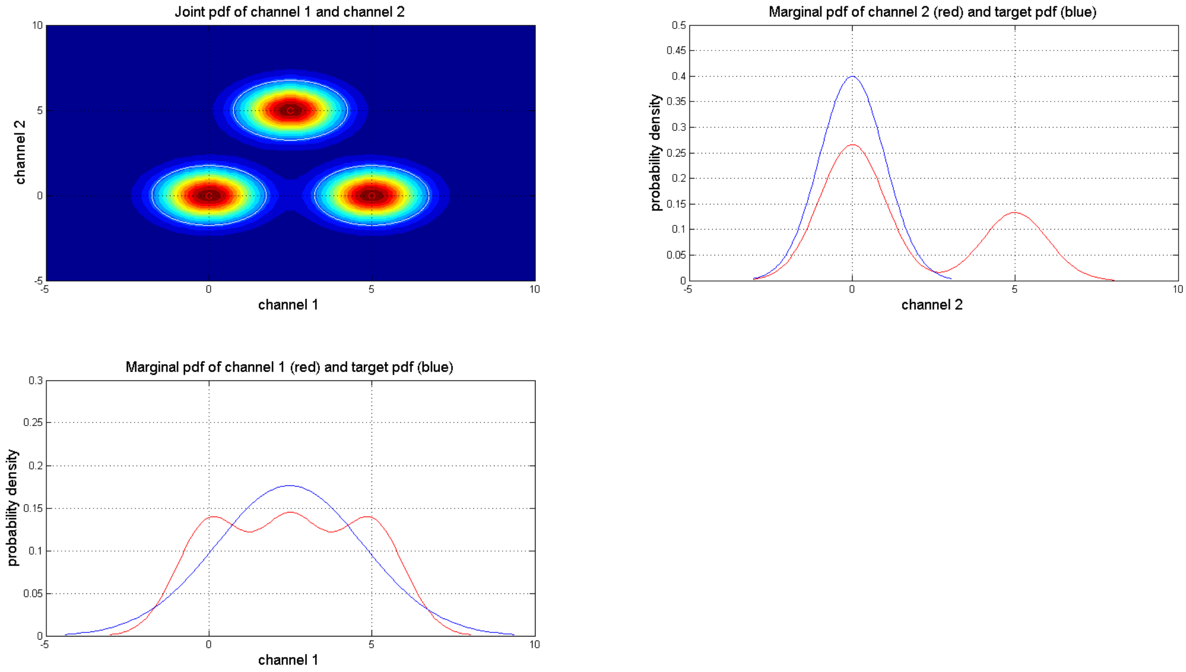


Figure 25 Top right subplot demonstrates method 1 for replacing of marginal pdf of channel 2 with one component in the position with the highest probability density. Bottom left subplot demonstrates method 2 for replacing of a cluster of marginal pdf components of channel 1 with one component.

In the process of creation of target mixture, each channel is represented by a constant or by a univariate Gaussian function. As a result of this, target mixture is a one-component mixture. This one-component condition is important for further data processing, as it is explained in the next chapter.

4.2.6 Final Data Processing and Generation of Advices

At this stage of data processing, we have historical and target mixtures available. Historical mixture contains the information where the working point should reside in order to meet selected criterion (requested production quality, e.g.). Target mixture is a one-component mixture and represents the ideal area in data space, where the working point should reside, as the result of actual operator's requests. As the target mixture does not respect the historical data, the target mixture component does usually overlap none of historical mixture components. In other words, target mixture can tend to position the working point to an area outside areas recommended by historical mixture.

This problem solves the advisory mixture. During the generation of advisory mixture, the historical and target mixtures and actual working point are confronted. The advisory mixture is a one-component mixture again. The component is chosen as a component of historical mixture, that is the "nearest" one to the target mixture component while respecting the actual working point. The notion "nearest" is meant in the Kullback-Leibler divergence sense (see [2] page 28).

The resulting one-component advisory mixture represents the area in data space, where the working point should reside according to operator's request given by target mixture while respecting the position of actual working point.

4.3 Presentation of Results to the Operator

Next step is to present the results to the operator and to instruct him to move the actual working point to the area in data space that is recommended by the advisory mixture.

There was shown during the tests that the generation of advices and proper visualization of information for the operator is the key part of the whole advisory system. If this is not presented in a comprehensible form, the operator is confused and loses his confidence in the whole system.

There are two problems with the presentation of results to the operator:

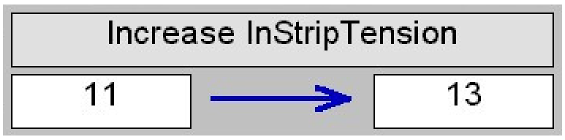
- how to find proper relation between simplicity and comprehensiveness,
- how to solve the contradiction between multidimensional nature of output information of the advisory system and 2D-screen.

The experience with operators in many industrial applications shows that operators are usually not willing to follow too complex information at first. A subjective reason is the natural conservativeness and distaste for anything new. Another, objective reason is that an operator can follow only a limited amount of information. As late as after some period of familiarization with the new interface, the operator starts believing the information presented and is interested in more details.

By reason of this, the operator interface should contain the information in a very simple form together with the ability to show more details.

The resulting layout of the screen is not fully a matter of a scientific approach but it is a result of a dialog with operators usually because their subjective meaning has to be taken into account which is often supported by factory managers too.

An example of a simple presentation of the advisory system output is shown in Figure 26.



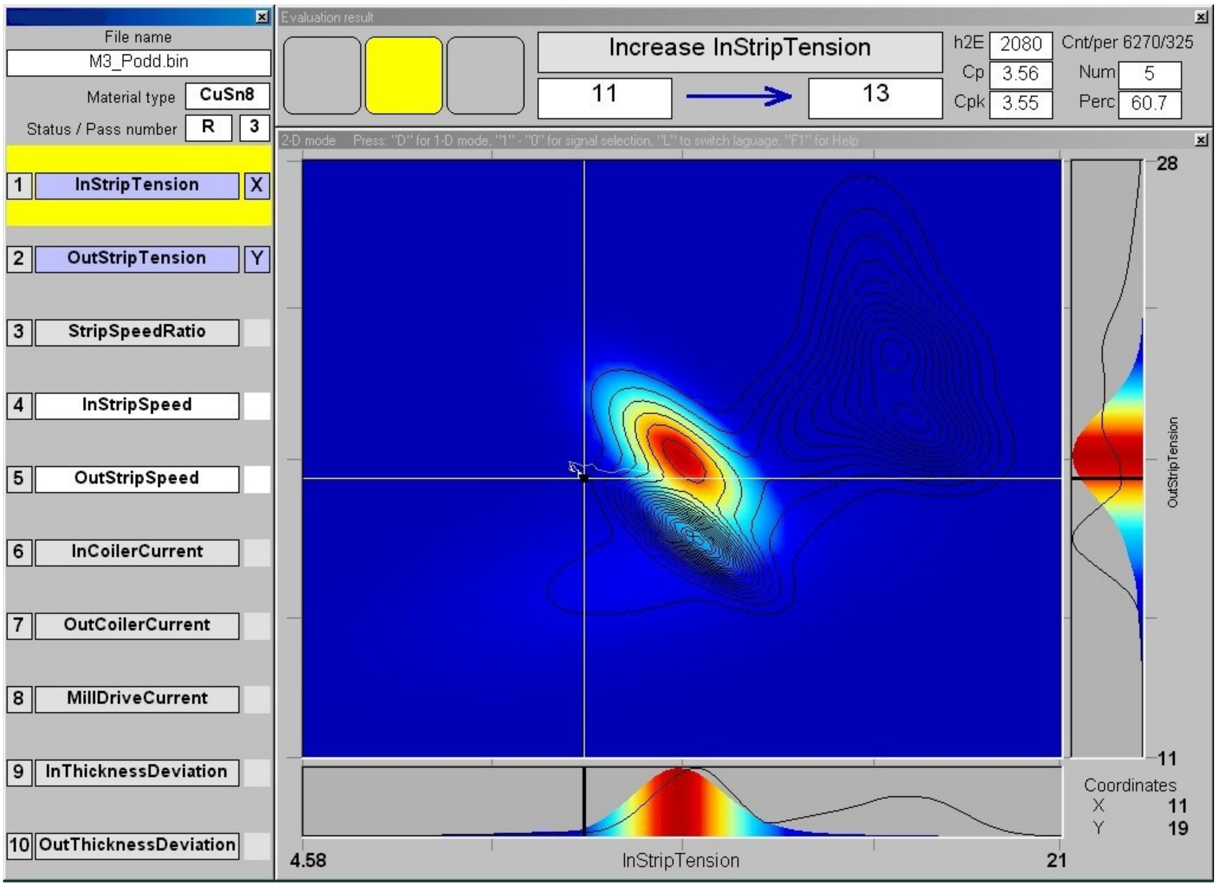
Increase InStripTension

11 → 13

Figure 26 An example of a simple presentation of the advisory system output.

It is very simple but the operator must have the possibility to see the reason for this so that he can believe the message. As a result of this, instead of adding the simple information frame to an existing standard visualization screen of the control system, a dedicated screen with enough space have to be introduced.

An example of a screen with advisory system output in detailed form is presented in Figure 27.



File name: M3_Podd.bin

Material type: CuSn8

Status / Pass number: R 3

Evaluation result

Increase InStripTension

11 → 13

h2E 2080

Cp 3.56

Cpk 3.55

Cnt/per 6270/325

Num 5

Perc 60.7

2-D mode Press: "D" for 1-D mode, "1" - "0" for signal selection, "L" to switch laguage, "F1" for Help

Coordinates
X 11
Y 19

Figure 27 An example of a screen with advisory system output in detailed form.

The simple "first look" information is located in the top of screen. The traffic lights information indicates with green colour "everything ok", with yellow colour "small correction necessary" and red colour means "something is wrong, big correction necessary". The message-like information instructs the operator what to do together with recommended new value of the particular signal (increase from 11 to 13 kN of input strip tension in our case).

The multidimensional nature of the information the advisory system is working with means that it is necessary to cope with several main signals in parallel. The signals that mainly influence the process behaviour are listed in the left column in the screen. As we cannot display the situation around the actual working point in the whole multidimensional data space, it is necessary to select two most important signals only. What does it mean "to select" and "most important"?

The selection of two signals means that these two signals are assigned to the X and Y axes of the 2D-chart in the middle of screen. The chart represents the probability density function in two dimensions only then, while the not selected signals are taken for constants with the values given by the actual working point. In other words, the chart is created as a 2D-cut of the multidimensional probability density function in the position given by actual working point.

The "most important" signals means (in this sense) the signals, the change of which causes the biggest increase of the probability density. For this purpose, the marginal pdf (see chapter 4.2.5) is calculated for each signal. If the changes of values of a signal in the range around the actual working point cause big changes in the marginal pdf of the signal, then the signal is important. In this respect, an important and an unimportant signals are presented in Figure 28 Selection of important (channel2) and unimportant (channel1) signal for the presentation to operator. The X-axis range limited by blue lines represents surroundings of actual working point.

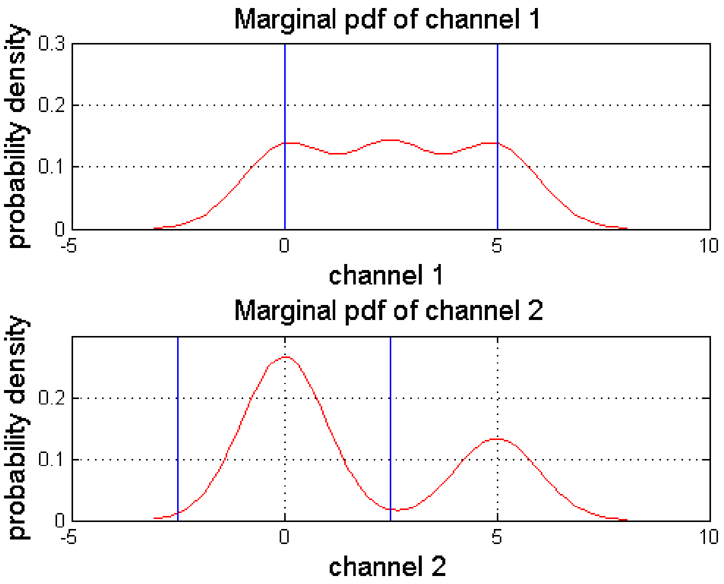


Figure 28 Selection of important (channel2) and unimportant (channel1) signal for the presentation to operator. The X-axis range limited by blue lines represents surroundings of actual working point.

If the blue lines denote X-axis range as a surrounding of actual working point, it is obvious that changes in setting of channel1 do not cause big changes in probability density. So the channel1 is not important for the presentation to the operator on the screen.

Another condition for the selection of a signal to be displayed is that its actual value does not meet the recommendation of the advisory mixture. In other words, if the signal is important and its value given by actual working point is near the value recommended by advisory mixture, then the signal is not selected in visualization. The signal is already set to requested value and that is why it is not interesting any more.

The list of involved signals is displayed on the left side of the screen. Two most important signals that do not meet the recommendation of the advisory mixture are highlighted.

There are two probability density functions displayed in the central 2D-chart. The pdf represented by the one-component advisory mixture is shown as coloured and represents the region where the actual working point should be moved to. The other pdf is the historical mixture and is shown with the help of contours. The advisory mixture overlaps the component of the historical mixture that is the nearest (in Kullback-Leibler divergence sense) to the actual working point. The reason for showing the historical mixture is that operator have an information about regions with low or zero probability density. He should avoid this region if he is moving the working point to the area given by advisory mixture (see chapter 4.3.1 for details).

Information similar to the described 2D-chart is displayed in two 1D-charts near the X and Y axes too (Figure 27). The advisory mixture is coloured again while the historical mixture is replaced by marginal pdf (black curve) derived from the historical mixture.

4.3.1 Movement of the Actual Working Point

Let us note that the simplest way to the region with high probability density is not always the best one, in general. In other words, if operator wants to move the actual working point to the recommended area, it need not be necessarily the same, whether he changes parameter1 before parameter2 or on the contrary. Operator have to keep the working point always in regions with higher density and avoid regions with zero density. Regions with zero density may hide improper working point settings that can cause an instability of the process or even a damage of production. The information about the improper combination of settings is not included in the historical mixture and thus not presented to the operator. The historical mixture is calculated from historical data that undergo a selection (see chapter 4.2.2.1). Data meeting the selection criterion are used, and the criterion is quality production only. As a result of this, the historical mixture does not contain information on improper settings possibly leading to low-quality production. And that is why the operator should keep the working point always in regions with non-zero density. Demonstration of this is in Figure 29.

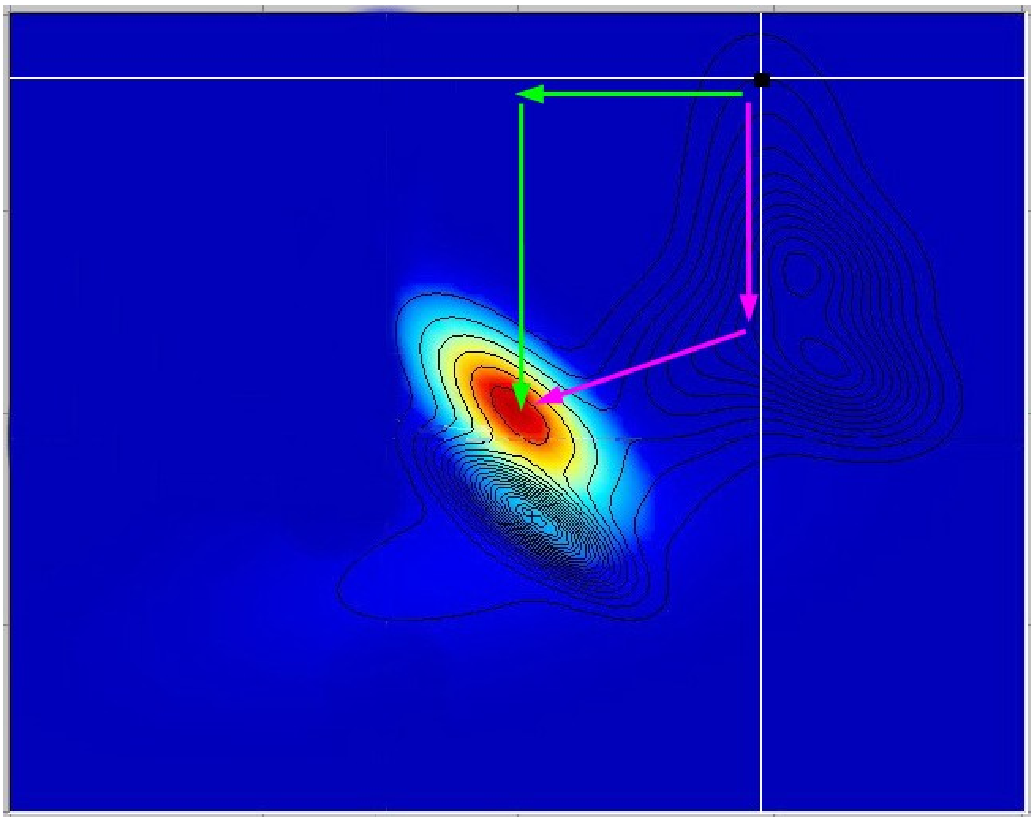
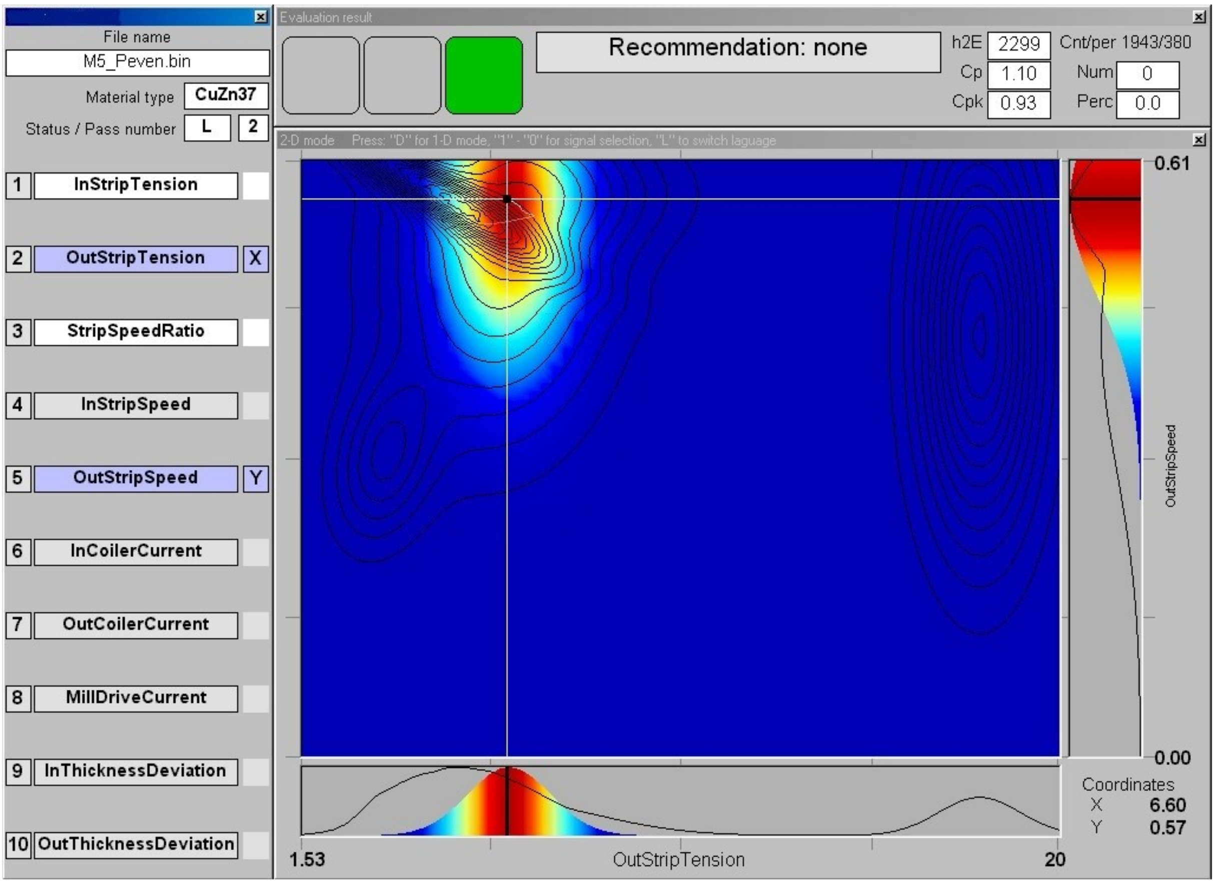


Figure 29 An example of movement of working point to a region with high probability density. Magenta trajectory avoids areas with low or zero density while the green one does not.

If the operator moves the working point while following the magenta trajectory, he avoids areas with low or zero density and the transition is safe. On the contrary, movement along the green trajectory is potentially dangerous because it may cross an area with inacceptable combination of settings. In our demonstration with metal strip rolling, the expert knowledge supports the idea of improper combination of settings because it is known to rolling mill operators that the ratio of input strip tension to output strip tension should be kept in a limited range. In our case, the green trajectory causes the situation where input strip tension (X-axis) is too low in relation to the output strip tension (Y-axis) in the middle of the green trajectory. This combination causes a strip break usually, which represents a financial loss and even a hazardous situation to operators sometimes.

The aim of the advisory system is to keep actual working point in the position meeting the recommendations of the advisory mixture (see Figure 30). There are no recommendations for the operator, he ought to keep the process in this state.



File name: M5_Peven.bin

Material type: CuZn37

Status / Pass number: L 2

Recommendation: none

h2E: 2299

Cp: 1.10

Cpk: 0.93

Cnt/per 1943/380

Num: 0

Perc: 0.0

2-D mode   Press: "D" for 1-D mode, "1" - "0" for signal selection, "L" to switch laguage

Coordinates

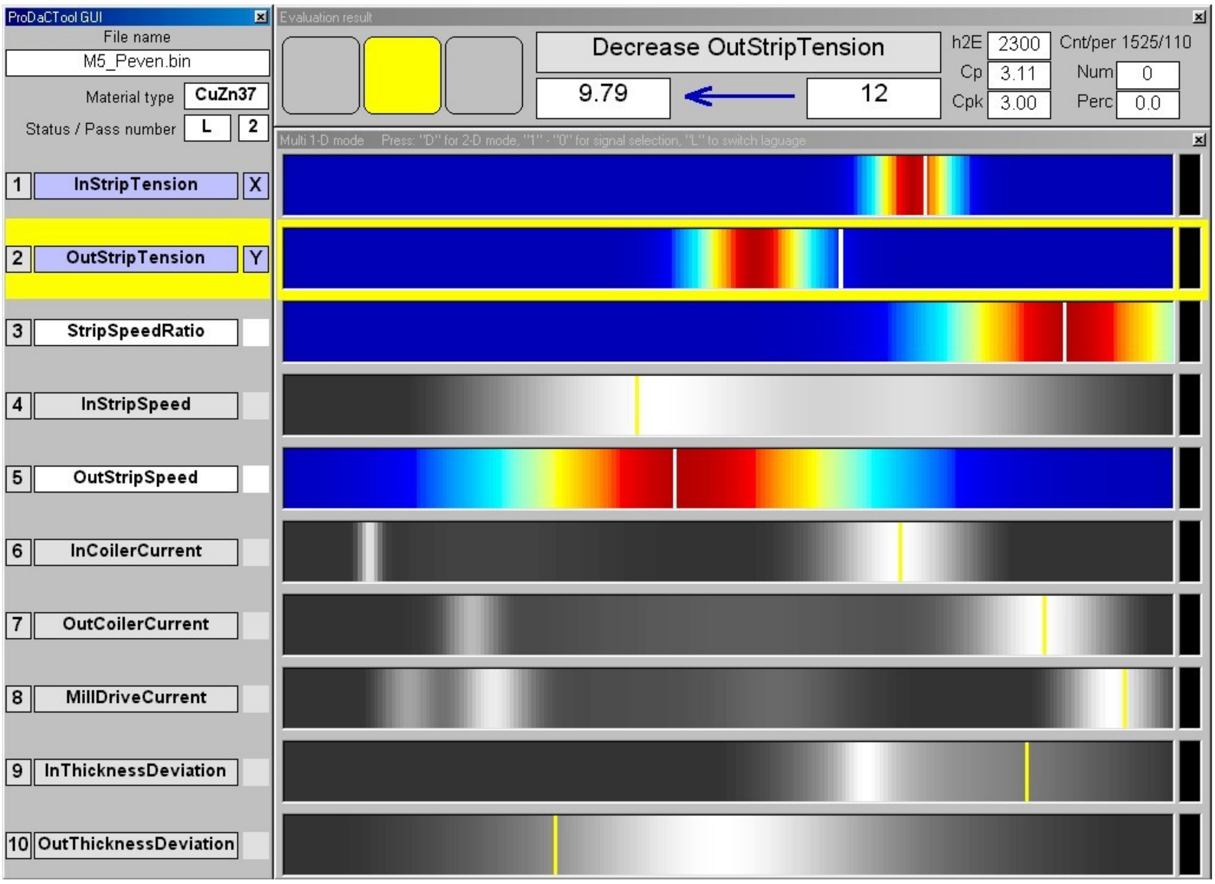
X 6.60

Y 0.57

Figure 30 An example of the advisory system screen in situation where actual working point meets the recommendations of the advisory mixture.

4.3.2 An Alternative Visualization Mode

Another possibility how to cope with the multidimensional advisory system output in the 2D-screen is demonstrated in Figure 31.



File name M5_Peven.bin

Material type CuZn37

Status / Pass number L 2

Decrease OutStripTension

9.79 ← 12

h2E 2300

Cp 3.11

Cpk 3.00

Cnt/per 1525/110

Num 0

Perc 0.0

Multi 1-D mode Press: "D" for 2-D mode, "1" - "0" for signal selection, "L" to switch laguage

Figure 31 An example of the advisory system screen in the mode where more than two signals situation where actual working point meets the recommendations of the advisory mixture.

In this visualization mode, each involved signal has its own 1D-chart. X-axis of this chart has now scale displayed for simplicity but the range of the axis corresponds to the range between minimum and maximum values given by the historical data. Charts of signals that should be changed are coloured. Chart is gray-scaled if the corresponding signal is set correctly (signals indexed as 4, 6, 7 and 8) or if the signal is of small importance.

It is up to the operator which visualization mode he chooses. He can also switch between these two modes easily, according to the current situation.

4.4 Performance Issues

In the prototype of the advisory system, the data acquisition and all parts of data processing (calculations of historical, advisory and target mixtures) were executed in one computer only. As performance problems arose even in the pilot application with a limited number of input signals, it was necessary to prepare a solution with an enhanced performance.

A list of basic features / limitations of the final solution has been created:

- usability in industrial environment,
- reasonable hardware price,
- availability of the hardware spare parts after five to ten years,
- programming in a standard development environment.

4.4.1 Hardware with Enhanced Computing Power

An enhancement of computing power by replacement of a single node hardware was taken into account first.

4.4.1.1 Standard CPU

The easiest way to performance enhancement is obviously the use of more powerful CPU of a standard type, a CPU with higher clock frequency or with higher number of cores. The problem is that even in industrial applications the standard CPUs with highest frequencies and with many cores are used as a standard already. It is not easily possible to buy another CPU with much higher performance.

4.4.1.2 Proprietary Hardware

Another way to better computing performance could be a special hardware in the form of an ASIC (Application Specific Integrated Circuit) or FPGA (Field Programmable Gate Array), e.g.

But there are several issues speaking against this approach:

- Several applications a year come into account and small series of specialized hardware are very cost-ineffective.
- Algorithms have to be divided into some parts suitable for application in the special hardware, while the rest runs on standard CPU.
- Frequent changes of algorithms are not easily applicable.

4.4.1.3 General-purpose Computing on Graphics Processing Units

General-purpose computing on graphics processing units (GPGPU) is widely used for calculation-intensive applications lately. In [37], e.g., a data mining application is described. The application concerns large data sets and a clustering algorithm which is related to our data processing. The article deals with typical consequences of the use of GPU for this type of application. Findings are summed up in the following list:

- The GPU code was developed in CUDA (Compute Unified Device Architecture), NVidia's C extension to support general GPU computing. CUDA enables development in C/C++ programming language, among others.
- The effectiveness of the GPU is best if all data fit into local memory on GPU board.
- If the data set does not fit into local memory the calculation runs in several cycles as follows:
    - Memory on GPU board is allocated.
    - Part of data set is transferred from global memory to GPU local memory.
    - Calculation on GPU is started.
    - Results are transferred from GPU local memory to global memory.
- Movement of data between global and GPU local memory can pose a substantial delay.
- If the whole data set fits into GPU local memory, the calculation of mentioned type of algorithm can be in order of hundred times faster than with one-core CPU.
- Even if the data set does not fit into GPU local memory, the acceleration is significant too. Ten times faster in order, in comparison to one-core CPU.

This approach can be also interesting because the data processing algorithms for the advisory system are developed in MATLAB originally, and the GPGPU is supported in MATLAB. There exists a MATLAB Parallel computing toolbox that can speed up some algorithms by the use of GPU. The algorithm have to meet two requirements, otherwise the GPU acceleration cannot be successful:

- The CPU time spent for the transfer of data to and from the GPU local memory have to be much shorter than CPU time spent for algorithm calculation.
- The algorithm have to be massively parallel, which means that the algorithm can be broken into a big number of units that can be executed in parallel.

4.4.2 MATLAB Environment and Data Processing Algorithms

As mentioned above, most of the algorithms used in the advisory system were developed in MATLAB environment and integrated into a MATLAB toolbox called Mixtools. The algorithms were written in MATLAB scripting language, which enables fast development and easy debugging. This rapid development advantage causes on the other hand long execution times of the developed algorithms. This was verified by initial tests. That is why the calculation-intensive parts of the Mixtools toolbox were rewritten from MATLAB scripting language to C-language, original M-modules were replaced by MEX-modules. This brings substantial acceleration of the algorithms. The relation of M-module time to MEX-module time was measured with an average result of 50 to 1.

4.4.3 Distribution of the Advisory System into a Network of Cooperating Nodes

Another possibility how to speed up the data processing in the advisory system is the distribution into a network of cooperating nodes. In this respect, the key request was to use a simple and already verified solution of distribution suitable for industrial application. That is why instead of investigation of several possibilities of parallelism such as clusters, grids or clouds, the distribution into a few nodes connected via a LAN was selected, with the structure corresponding to the logical structure of the advisory system.

So separate nodes can be created for particular functions such as data acquisition, data preprocessing, calculation of particular mixtures, etc. An example of possible configuration is shown in Figure 32.

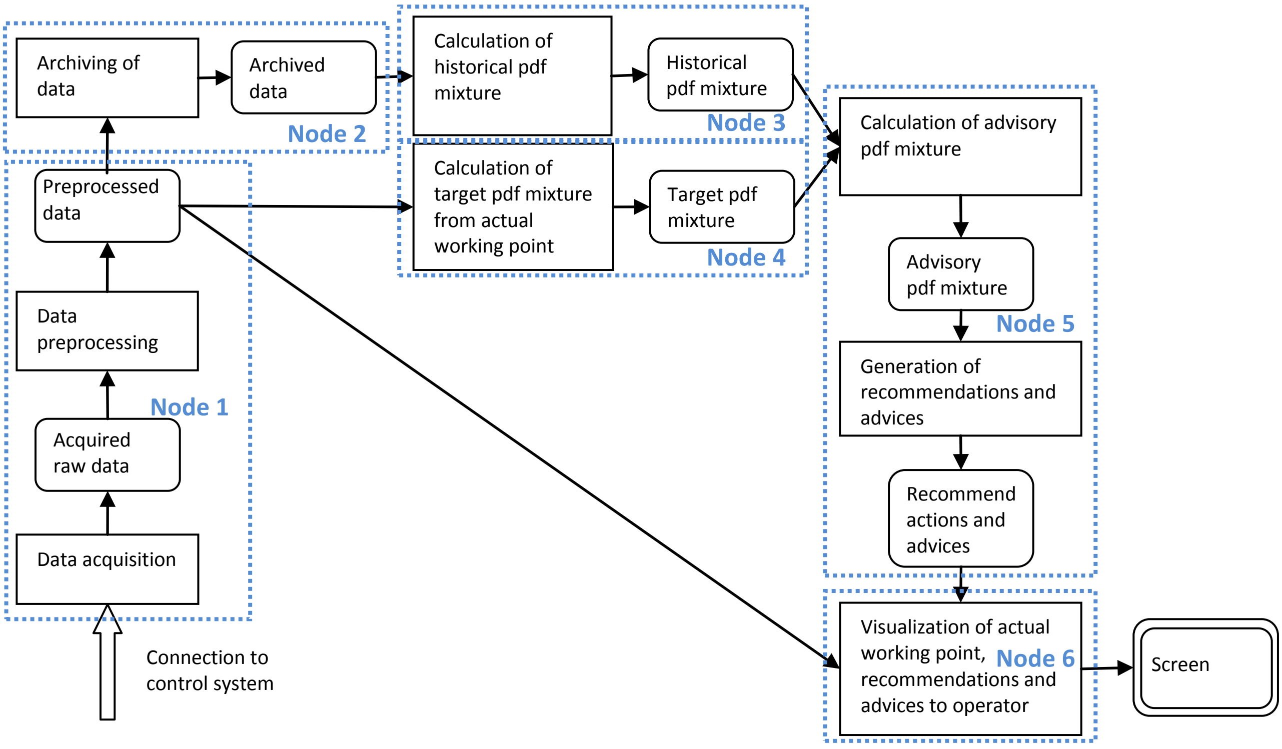

Archiving of data
Archived data
Node 2
Calculation of historical pdf mixture
Historical pdf mixture
Node 3
Calculation of target pdf mixture from actual working point
Target pdf mixture
Node 4
Preprocessed data
Data preprocessing
Node 1
Acquired raw data
Data acquisition
Connection to control system
Calculation of advisory pdf mixture
Advisory pdf mixture
Node 5
Generation of recommendations and advices
Recommend actions and advices
Visualization of actual working point, recommendations and advices to operator
Node 6
Screen

Figure 32 An example of distribution of particular functions of the advisory system among separate nodes.

The above described RDb technology (see chapter 4.1.3.2) can be used for data exchange and synchronisation between the nodes via an dedicated LAN. Big advantage is the simplicity and thus the high speed of communication data exchange in the RDb environment. The effective communication speed was measured under conditions and with results stated in Table 5.

Nodes	Two IPCs with Intel i5 CPUs
LAN	Ethernet 100Mb (typically used on factory floor)
Exchanged data	Group of 200 float signals addressed by RDb names
Time	Less than 1 millisecond per cycle

Table 5 Typical communication parameters between nodes of the advisory system.

Output data of particular nodes are stored in their local RDb data structures and thus put at disposal of all cooperating nodes.

The parallelism is realized by two ways in the structure in Figure 32:

- Two and more nodes can process data in parallel. Node 3 and Node 4 can calculate historical and target mixtures simultaneously, e.g.
- One set of data is processed while the next one is prepared in parallel. The buffering of data in signal history buffers of particular RDb signals is used. Node 1 acquires and preprocesses new data while Node 2 archives older data already stored in history buffers and sets them available to Node 3 for actualization of historical mixture, e.g.

4.4.4 Currently Used Strategy for Performance Enhancement

For the performance enhancement, a combination of above mentioned approaches was selected:

- Distribution into a network of cooperating nodes is used.
- Particular nodes are standard IPCs with standard CPUs.
- RDb technology is used for data storage and exchange and for inter-process synchronization via LAN.
- Computational-intensive parts of data processing algorithms are executed in the form of MATLAB MEX-modules.

This configuration is sufficient for possible current applications.

If a higher computational performance is necessary in the future, general purpose computing on GPUs under the MATLAB Parallel computing toolbox will be involved in the nodes with a higher demand on performance and with algorithms suitable for this type of acceleration.

4.5 Advanced Functions of the Advisory system

After the successful realization of the key functions of the advisory system, some advanced functions have been added recently. This extension concerns mainly the quality of signals and advanced diagnostics.

4.5.1 Quality of Signals

Because of the probabilistic nature of the advisory system, low-rate disturbances of input signals cannot influence the overall quality of output information substantially. Nevertheless, same as in other technical systems, the better the quality of input information is the better quality of output information can obviously be expected. That is why close attention was paid to input signals in our case too.

4.5.1.1 ProDisMon Project and Signal Health

Less than two years ago, a research project called ProDisMon (Probabilistic distributed industrial system monitor) was finished (see Table 1.) The project was concentrated on the condition monitoring problem how to evaluate an overall system health, with the aim to inform operators or maintenance staff. A short characterization of this project follows:

- The health of system is evaluated in hierarchical structure from the lowest level of signals, across blocks and subsystems to the upper most hierarchical level (see [38]).
- Properties of each entity in the system (signal, sensor, actuator, SW module, network component, communication node, ...) are extended by health-values from [0;1] interval.
- As the standard true/false logic is not sufficient for the hierarchical, bottom-up evaluation of the health of the whole system, following approaches are used too:
    - probabilistic logic using for true/false condition evaluation values from [0;1] interval,
    - subjective logic operating besides a type of probabilistic logic with the *uncertainty* notion in addition (see [39]).

A detailed description of the project is beyond the scope of this document, some details can be found in, [38] and[40], e.g.

Some outputs of the ProDisMon project are very contributive for the advisory system too. Especially from the point of view of the quality of signals. After the implementation of the system health evaluation into a control system, the advisory system can benefit from the health information newly added to particular signals. The concept of the signal heath exploitation is as follows:

- The condition monitoring extension of the control system adds health information to each particular signal and stores it in the RDb memory resident database of the node acquiring or preprocessing signals. To each RDb signal "`Signal`*`0123`*", e.g. its health value "`Signal`*`0123`*`_Health`" is added.
- Archival node stores the signal health value together with signal value.
- If data for (re)calculation of the historical mixture are selected according to a given criterion (see chapter 4.2.4.2), the selection condition is simply widen with following limitations: `...AND Signal`*`XXXX`*`_Health > MIN_SIGNAL_HEALTH` for each involved signal.

This can help to "sharpen" the historical mixture, i.e. the recordings with big noise, outliers, faulty sensors, etc. are eliminated from the calculation of the historical mixture and thus the information represented by the historical mixture is more precise.

4.5.1.2 Signal Quality Enhancement and Angular Speed Measurement

In the previous chapter, the methodology is described that enhances the quality of the advisory system outputs by eliminating low-quality input signals. This is very useful in our case but there are situation where this approach cannot be used. If the disturbances are not temporary only or if the low quality comes from the nature of the signal, the signal cannot be simply eliminated without any substitution. In these cases, it is necessary to try to enhance the quality instead.

Signal filtration is usually used for the quality enhancement of signals in various industrial systems. There exist lots of filtration methods that has been developed and verified in last decades. Many of them are used in systems discussed in this document too. But detailed description is beyond the scope of this document.

In some special cases, standard filtration methods do not bring sufficient results. One of these problematic situations was solved during the development of the advisory system.

In many industrial applications, a sensor called incremental rotary encoder (IRE) is used for the measurement of angular speed of a rotating device (see Figure 33).

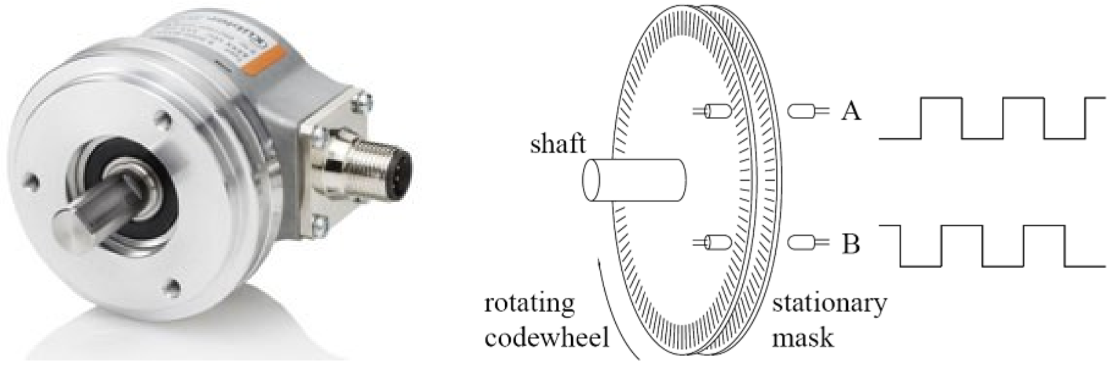


Figure 33 Incremental rotary encoder - picture of the sensor (left) and internal principle (right).

Inside the IRE sensors rotate two code wheels with graduations. The graduations interrupt the light beams between light sources and opposite photodiodes. The photodiodes generate pulses with the width proportional to the angular speed of the rotating shaft. Pulses of A photodiode are a quarter of period shifted against the B pulses (see Figure 33 on the left).

The principle of the angular speed measurement is as follows (see Figure 34):

- Measurement electronic (counter/timer board in most cases) generates internal pulses of high frequency.
- Counting of these fast pulses is triggered by A or B pulses generated by IRE.
- With change of angular speed, the number of fast pulses counted changes.

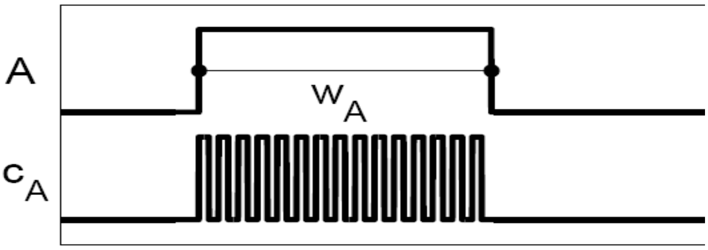


Figure 34 Incremental rotary encoder - width W_A of A-puls proportional to angular speed is measured by the number of fast pulses c_A counted.

Recordings of angular speed measured by a typical IRE show that the measured speed suffers from disturbances (see Figure 35).

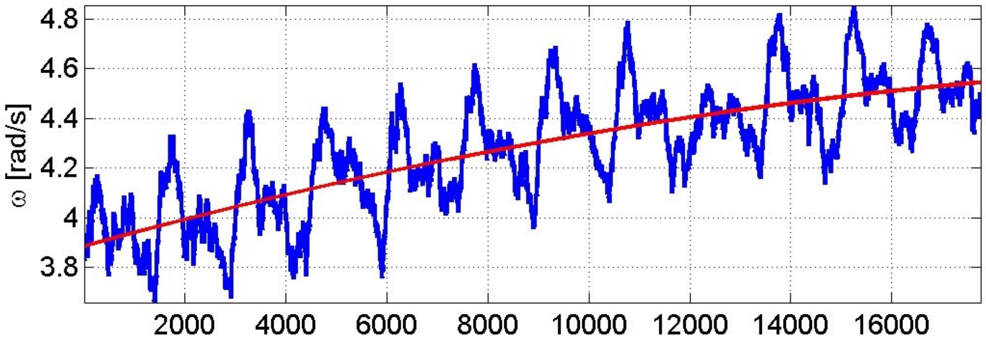


Figure 35 Incremental rotary encoder - Disturbances of measured angular speed (blue line) and real speed (red line). X-axis represents index of sample.

The investigation of disturbances shows that they come from several sources such as imperfection of bearings, eccentricity of the coupling between IRE and the rotating device and others. It is difficult to distinguish the influence of particular sources. Experiments showed that one of the most important sources is the imperfection of the IRE itself. The width of the graduations on the code wheel is not same for each grading line around the periphery. There are typically hundreds of grading lines on the code wheel, with a typical width of 10 microns. This causes that widths of A or B pulses differ even if the angular speed is constant.

First attempts to cope with the disturbances were done with different types of filtration algorithms. Filtration has a big advantage in its simplicity and that it need not distinguish between sources of disturbances. Several filtration algorithms were tested with promising results. Outputs of two types of filters are presented in Figure 36.

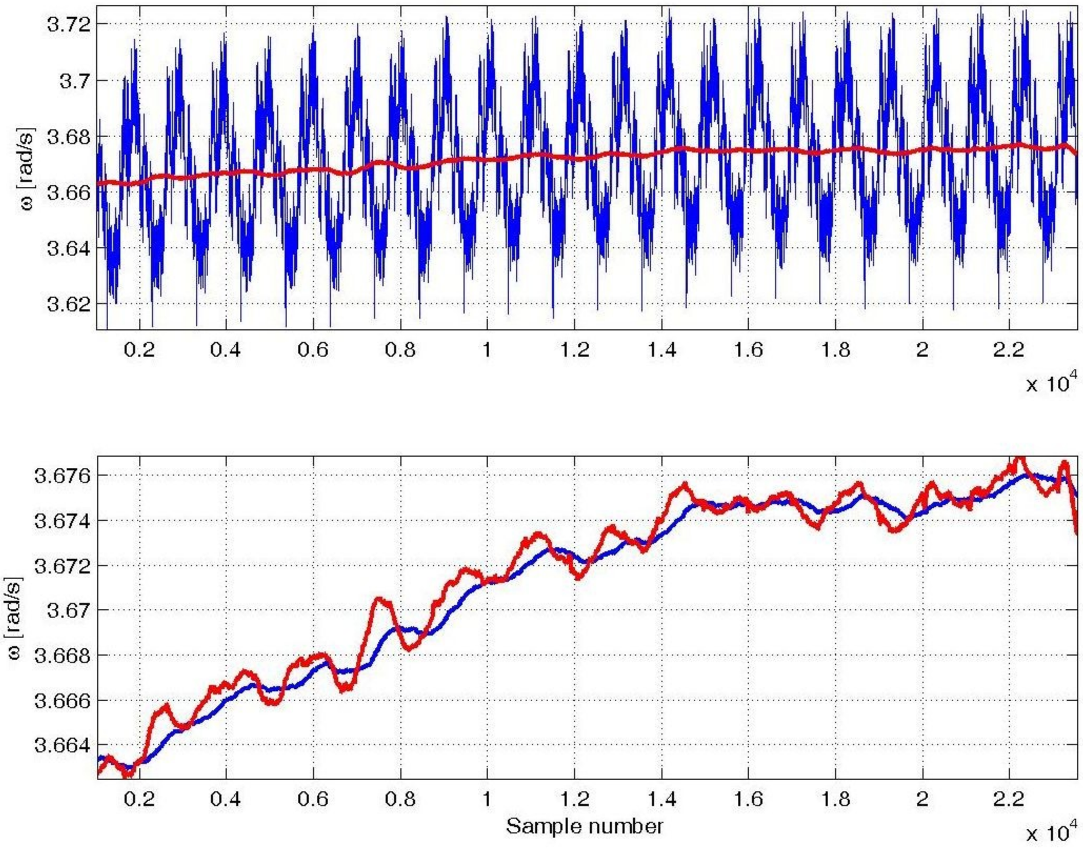


Figure 36 Incremental rotary encoder - filtration methods. Upper plot: Original signal of angular speed (blue line) and filtration result (red line). Lower plot: Outputs of two types of filter, standard moving average (blue line) is more delayed than a special trend preserving filter (red line).

The upper plot shows in blue line the original signal of measured angular speed. The smooth red line represents output of two types of filter, visually overlapping here in this scale. Difference between these two presented filters is visible in detail in the lower plot. Blue line corresponds to a standard moving average filter. Red line is the output of a trend preserving (moving linear fitting) filter. This filter was specially designed with the aim to minimize the time delay and to preserve the dynamics of the original signal.

The filtration approach was published and is described in detail in [30].

As the angular speed signal is not only a key signal of the advisory system but it is primarily used for strip thickness control in rolling mill applications too, the mentioned problem with time delay and preservation of dynamic is of great importance. Therefore an effort was put into a possible correction of the above mentioned imperfection caused by the graduations on the code wheel.

The main idea was that the imperfections can be corrected if they are in principal same in each revolution. It is sufficient to rotate the shaft with constant angular speed and measure the irregularities. But the main problem was how to measure them if they are mixed with other sources of disturbances, including irregularities in the speed of rotation. Tests showed that it is absolutely not easy to rotate the shaft of the IRE sensor at a constant speed with speed deviations at least ten times lower than deviations caused by imperfection of the sensor. In short, after many unsuccessful experiments, the following solution was found:

- Special test bed was created that enables to fix the IRE with shaft in top down position.
- A massive steel flywheel is affixed directly to the IRE shaft.
- The IRE is connected to a device for pulse width measurement.
- The flywheel is set spinning at a reasonable speed (about 3 revolutions per second).
- The measuring device measures width of each pulse during the period of about 10 seconds and archives the measured values.
- Measured values per revolution are indexed from 1 to number of pulses per revolution. Start of revolution is synchronized with the help of the reset signal, where the IRE generates a pulse per revolution.

In this configuration, only two sources of disturbances influence the measured pulse width. The imperfection of the IRE bearings and the sought irregularities of the graduations on the code wheel. It will be shown later that the bearing influence is much smaller and can be omitted.

The measured data are then offline processed with the aim to get correction constant for each pulse indexed from 1 to number of pulses per revolution. The flywheel has (thanks to its high mass) large moment of inertia and smoothes out the mechanical motion of the whole assembly. The deceleration of the angular speed is small enough at the same time. As a result of this, the data can be processed as follows.

In the first step, a short sequence of values representing the width of A pulses is approximated by a polynomial of second order (see Figure 37).

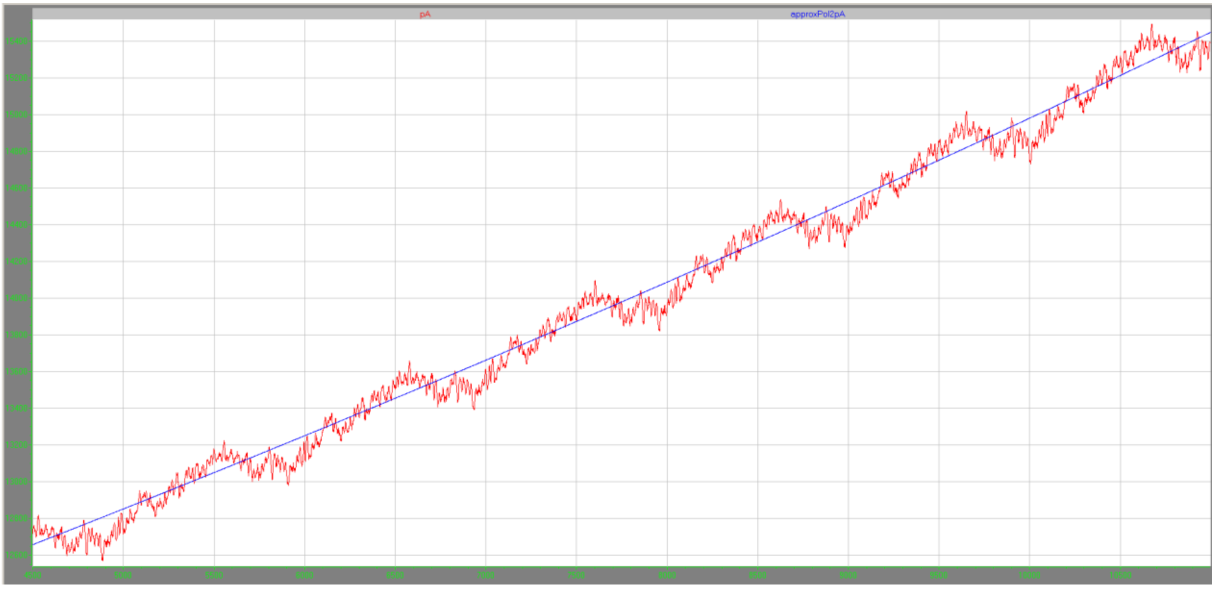


Figure 37 Incremental rotary encoder - recording of pulse width (red line) is approximated by a polynomial of second order (blue line). X- axis represents sample number, Y-axis represents values corresponding to the width of pulse.

The figure shows about 6 revolutions of the IRE shaft. Each revolution generates 1024 pulses. The blue line can be considered an ideal angular speed represented by width of pulses. Deceleration of the flywheel causes the increase of width of pulses in time. Differences between the blue line and the red line correspond to the irregularities of the graduations on the code wheel.

In the second step, the correction constants for each pulse are calculated as the ratio between the ideal (the polynomial of second order) and the measured values of the pulse width. Then, the values of the correction constants are recalculated in respect to the average absolute value of angular speed in the particular revolution. The accurate times of the beginning and the end of the particular revolution stored during the measurement are subtracted with result equal to precise duration of the revolution. Output of this step is an array of correction constants indexed from 1 to number of pulses per revolution.

In the final step, the operation of the second step is repeated several times for different revolutions. The final correction constant is calculated for each pulse index as the average of all revolutions. This gives better results than with correction constants calculated from one revolution only.

The resulting correction constant array is then used by the data acquisition system. For each pulse coming from the IRE, according to its index, the pulse width is corrected by the corresponding correction constant. The resulting corrected pulse widths are shown in Figure 38.

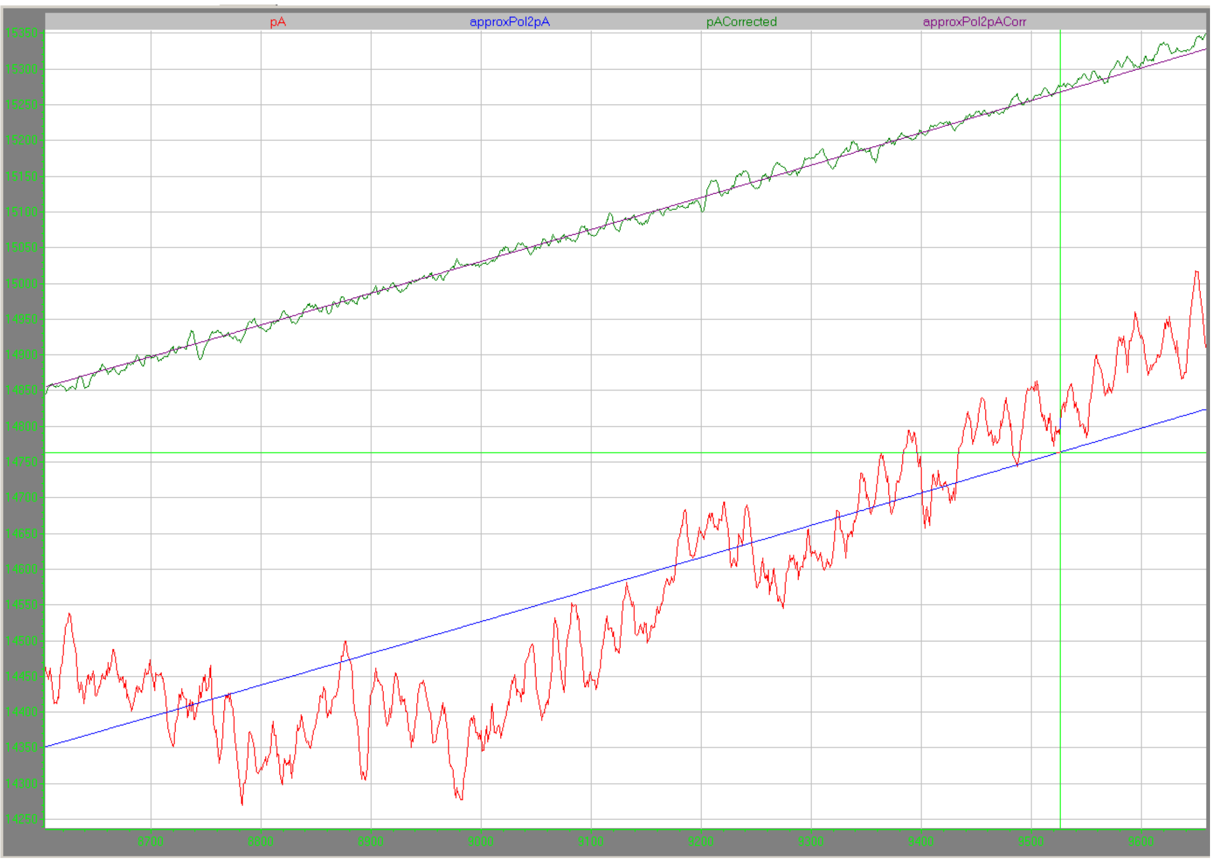


Figure 38 Incremental rotary encoder - recording of one revolution only. Original pulse widths (red line) are approximated by a polynomial of second order (blue line). Pulse widths after recalculation with correction constants are shown in green line. Corrected pulse widths approximated by a polynomial of second order are displayed in black. X- axis represents sample number, Y-axis represents values corresponding to the width of pulse.

It is obvious that the corrected values (green line) have much smaller deviations than the original signal (red line). For the resulting improvement of the signal see Table 6.

Signal	Maximum (in absolute value) deviation from approximated second order polynomial [%]
original	**1.72**
corrected	**0.16**

Table 6 Incremental rotary encoder - comparison of quality of the original and the corrected signals.

The presented improvement is calculated for a particular type of IRE of a manufacturer but experiments with several other IREs of other manufacturers showed similar results.

The above described mechanical stand and the method of IRE improvement was registered as a utility model at the Industrial Property Office of the Czech Republic.

4.5.2 Advanced Diagnostic Functions

Tests and real applications of control and advisory systems showed that besides standard methods for signal quality detection, some advanced approaches must be applied to recognize a malfunction of a signal in special situations. Some of the advanced methods were added to the advisory system and will be described in next chapters.

4.5.2.1 Use of Time-frequency Analysis

In most cases, the low quality of input signal can be recognized or even improved as described above. However in some situations, the functioning of a sensor is degraded to such an extend that the behaviour of sensor output looks very credibly but the measured value does not correspond to the reality. This chapter describes a method how to recognize this situation with the aim to inform the operator. If the production continues in such a situation, resulting production can be of low quality, which results in substantial financial loss. The situation where time-frequency analysis can help to recognize such a problematic case will be described in this chapter. This topic was published and is described in detail in [41], key ideas follow here.

In applications of control and advisory systems in steel strip production, one of the key signals is the strip thickness measured by a contact gauge. The principle of a contact thickness gauge is as follows. The strip runs between two measurement transducers. Transducers are firmly pressed to the upper and lower surfaces of the strip. Each transducer is moveable in the axis perpendicular to the strip surface. The positions of transducers change with the change of strip thickness and are measured and evaluated as a value corresponding to the strip thickness (see Figure 39). The position of strip is kept in the middle of gap between two stable parts of measuring head by four moveable supporting rolls.

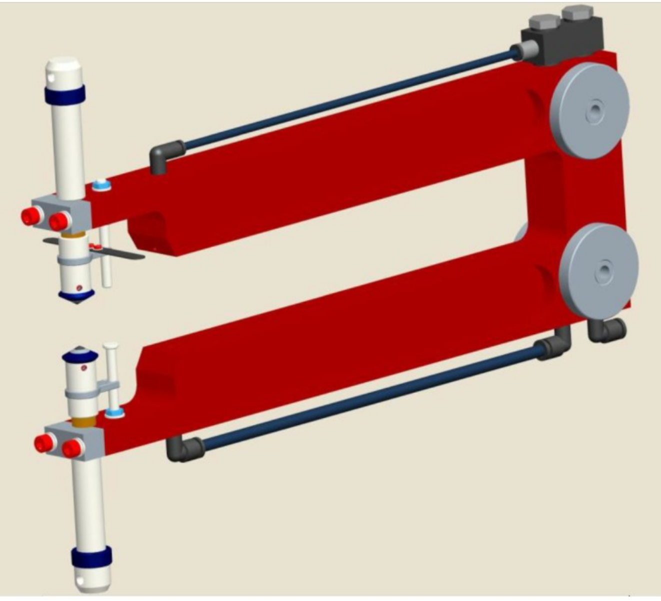


Figure 39 Transducers and measuring head of a contact gauge. (source: www.uvbtechnik.cz)

Typical precision of contact thickness gauge is about 1 µm with measuring range up to 10 mm. Typical speed of strip going through the gauge is up to 10 m/s.

The measured value can be transmitted to the thickness controller via a network as a digital value, but the transmission is usually not fast enough and that is why an analogue signal is used too. In the case of analogue signal, a deviation from thickness set point is generated by the gauge.

Besides common disturbances that can be eliminated with the use of a proper filtration algorithm, there exists a special situation during the measurement on a rolling mill that is too difficult for standard algorithms to cope with. The measured strip running through the gauge brings on its surface some particles coming from lubricant removing equipment sometimes. Under some circumstances, a particle can be caught by a measuring transducer. In this situation, the transducer looses contact to the strip partially and starts jumping. The measured value does not correspond to the real strip thickness. Recording of gauge output in this situation is visible in the middle of the chart in Figure 40.

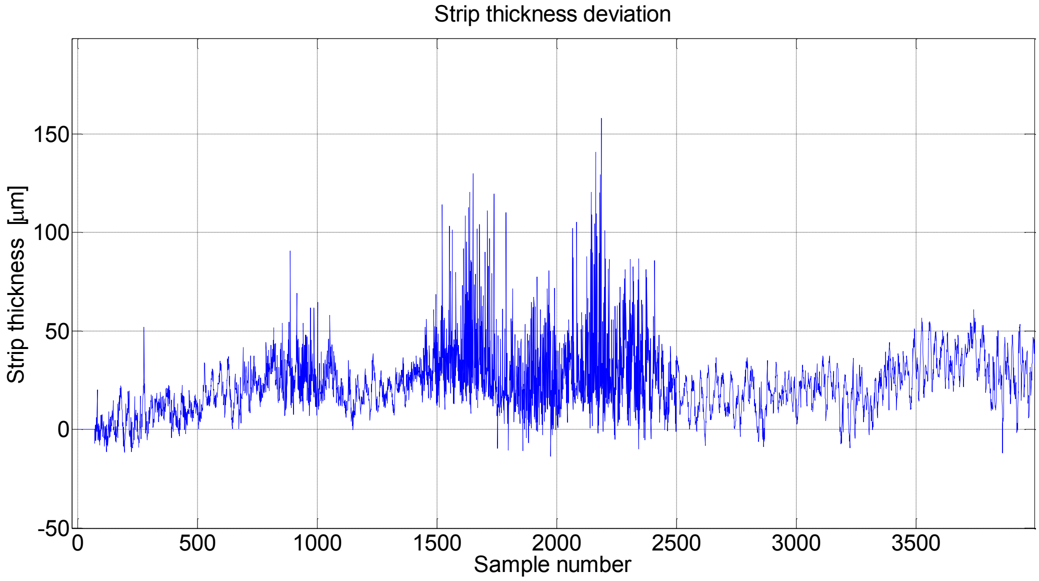


Figure 40 Output of thickness gauge if a particle was caught by transducer

The central part of the recording represents the problematic situation. For the detection of this situation a method of time-frequency analysis was used. A spectrogram corresponding to this situation is displayed in Figure 41.

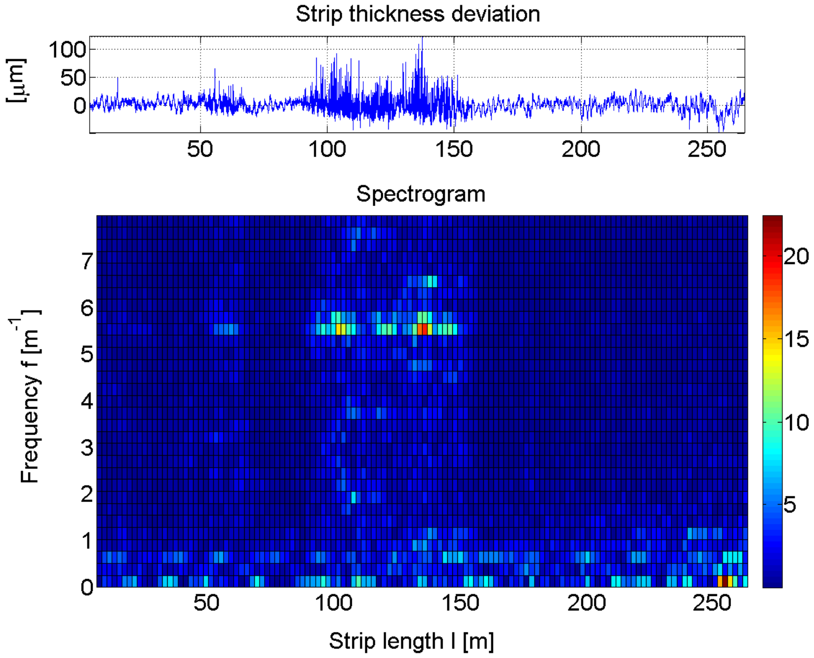


Figure 41 Recording of gauge output in the situation of gauge malfunction (upper plot) and the corresponding spectrogram

The spectrogram clearly shows occurrence of higher frequencies during the malfunction of the gauge. Frequencies corresponding to standard gauge output are much lower and so it is easy to distinguish the standard and the malfunction frequencies. One of possible methods is visible in Figure 42.

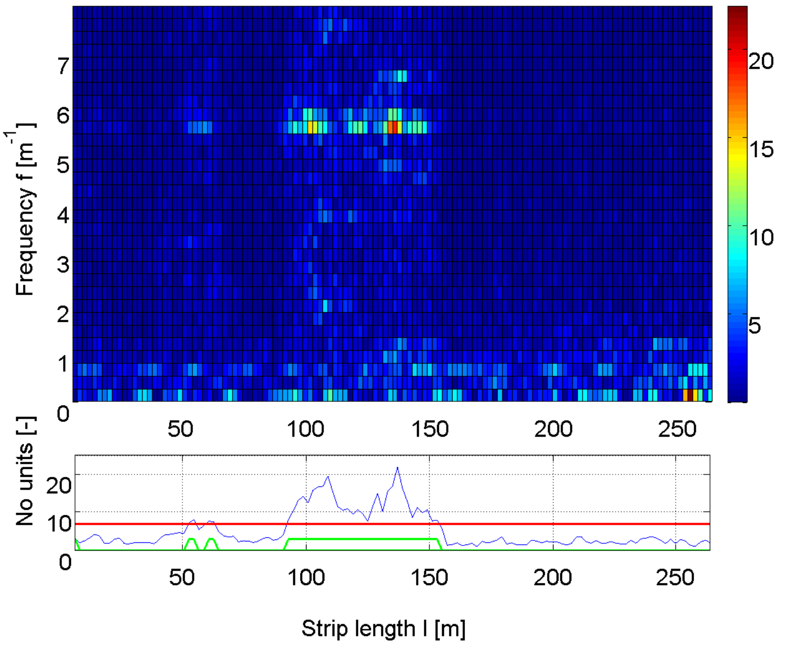


Figure 42 For each X-axis range of the spectrogram the vector of amplitude values is summed to one value only (blue line in lower chart). A threshold (red line) is set. If the blue line goes beyond the threshold, alarm signal is set to 1 (green line).

The threshold for the signalization of the gauge malfunction to the operator can be set empirically or as an average of values from historical data.

4.5.2.2 Use of Kullback-Leibler Divergence

After the verification of the key probabilistic functions of the advisory system, an idea emerged to use these principles for complicated diagnostic tasks too. This diagnostics is intended for recognition of process malfunction which cannot be easily revealed by analysis of particular single signal only but analysis in multidimensional data space must be involved instead. Main principle of the advanced diagnostic method consists in finding a representation of process behaviour in a short history by a historical mixture. Process behaviour in the latest time period is represented by actual mixture. Difference between historical and actual mixtures is evaluated by calculation of Kullback-Leibler divergence. Mixtures and divergences are calculated repeatedly in time and a big change in the divergence value can be used as a source of alarm for non-standard process behaviour.

This topic was published and is described in detail in [42], key ideas follow here.

In some situations, the standard relation between process variables changes suddenly. The reason can be malfunction of a sensor, hardware failure in signal transmission, unmeasurable change of technological conditions, etc. From the diagnostics point of view, we would like to detect the situation and warn the operator.

Following algorithm was developed for the detection of these problematic situations:

- All process variables are recorded during the production process.
- Production time is divided into relatively short periods (in order of seconds).
- Data in each time period are approximated by a mixture of Gaussian functions.
- Kullback-Leibler divergence between the mixture representing the latest time period and the mixture from previous time period is calculated repeatedly.

- Big change in the sequence of Kullback-Leibler divergence values indicates a non-standard situation.

The principle of the algorithm will be demonstrated on problem coming from the steel strip production again.

Strip comes to the rolling mill usually in the form of a coil. If the spires are reeled too loosely, the input tension can sometimes decrease suddenly for a short time. The spires are tighten at that moment. As a result of this, the output thickness changes slightly up and down. But a more serious problem is, that the tighten spires scratch the surface of the strip. If this situation is not detected, scratched surface can be revealed as late as at the customer and can result in a complaint. Let us mention that tension measurement is usually not precise enough so that this situation can be recognized with the help of tension signal only.

The algorithm is simplified for this purpose. The mixtures are calculated for input and output thicknesses only, so we are able to display the mixtures in two dimensions. Other process variables are taken for constant. See Figure 43.

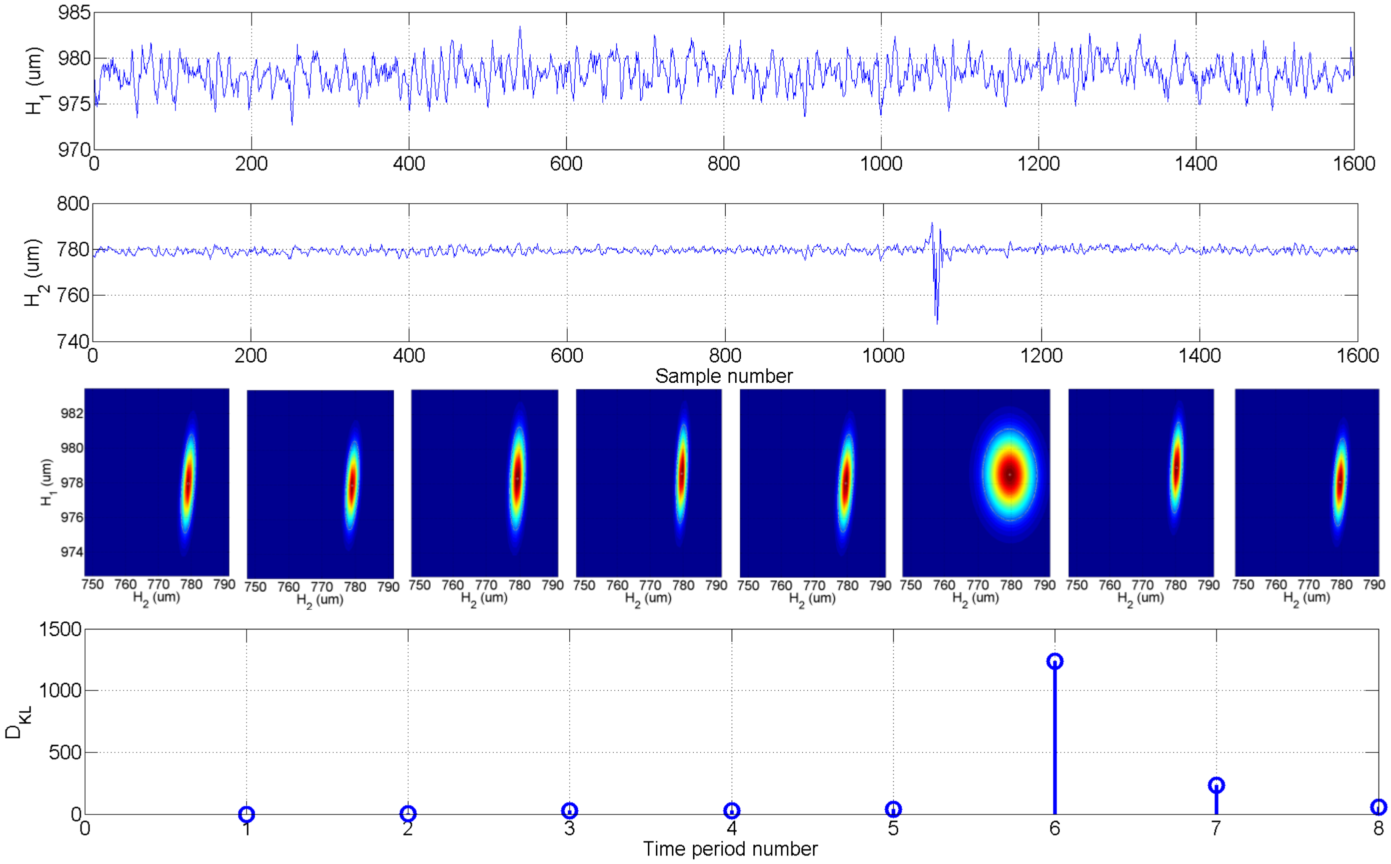


Figure 43 Big change in Kullback-Leibler divergence (D_{KL} in the bottom chart) indicates problematic situation in the process of metal strip rolling

Eight time periods with 200 samples each are shown. First chart represents the input thickness. Second chart displays output thickness with sudden change near the sample number 1050. Eight small charts show mixtures calculated for particular time periods. Mixture representing the sixth period is apparently different. The last chart displays values of Kullback-Leibler divergence. Big change is visible at the end of the sixth time period where the divergence from mixture 5 to mixture 6 was calculated. This big change can be easily transformed into an alarm signal that can be presented to the operator and inform him about the problematic situation.

5 Conclusion

In this work, we described the progress of development of probabilistic advisory system for support of operators of complex industrial processes. The advisory system and related theoretical background together with software technologies were developed in the frame of several successful research projects. The author of this work was a member of core working group in all of them. Topics of these projects were focused on the use of results for industrial applications.

The researchers succeeded in creation of an advisory system which is:

- modular,
- powerful,
- equipped with a well-developed data processing and
- verified in several industrial applications.

An international group of researchers cooperated on the development of the advisory system and underlying theories in each particular project.

At the beginning of the work on the advisory system, a detailed survey of related published works was carried out. Based on this, the advisory system is not intended as a solution for all possible processes. It is composed as a solution for a class of industrial applications, especially for branches the researchers were interested in. In this respect, a success was achieved because the system met expectations of all project participants after the evaluation in applications related to their branch of interest.

The main stress was laid on underlying probabilistic theory and used software technology. The probabilistic theory using the mixtures of probability density functions is the fundamental part of the advisory system. The probabilistic theory is explained in this document in basic principles only, with respect to its complexity. The basic principles are discussed in detail for better understanding of data mining techniques and of the whole advisory system. Principles are demonstrated with the use of several examples.

Quite a big part of the work was devoted to the data acquisition because the availability of the sufficient amount of process data is one of the main preconditions for achievement of expected results. In this field, necessary software technologies for high-performance inter-process data exchange were developed. These software tools enable efficient cooperation between the developed advisory system and existing control systems in the phase of data acquisition. This cooperation avoided an expensive creation of autonomous connections to process signal and enabled the utilization of process data acquired by existing control systems.

Data processing is the key part of the whole advisory system. Besides the use of standard well-known methods for signal reconstruction, several new algorithms for the enhancement of signal quality were developed and verified. Big effort was put into performance enhancement of data mining methods calculating historical mixtures in the offline stage of the data processing. This enabled to gain (in reasonable time) the historical mixtures with areas of high probability density representing process parameter adjustments that are desired for high-quality production, e.g.

Performance enhancement was of great importance to the online stage of data processing especially, because in this phase, actual working point of the process and operator's aim are transformed into the target and advisory mixtures while the process is working. Performance issues of calculation-intensive data processing were rather solved by the distribution into cooperating network nodes than by the use of tailor-maid hardware that is always problematic in the respect of sustainability of the industrial applications.

In the phase of presentation of advisory system outputs to the operator, a special approach had to be used because the form of presentation was very dependent on the nature of a particular operator. Several variants of visualization had to be prepared as a base for particular tailor-maid presentation screens for operators of a given process.

Recently, some advanced functions were added with the aim to improve the quality of advisory system outputs. These functions concern signal quality enhancement and advanced diagnostics. These extensions were developed not in the frame of a research project but fully by the author of this document.

Now, the advisory system is in a stage enabling its application in industrial projects. According to a requested configuration, particular modules can be selected and partially adjusted for the given application. This takes some effort of course but it is expected in projects of this type.

5.1 Pros and Cons

Modularity of the developed advisory system belongs to its main advantages. The system can be used both as a complete whole and as a set of modules solving a data acquisition task with offline process analysis only, e.g.

Another advantage is that the system covers not only a special process but it is suitable for a branch of continuous industrial processes.

On the other hand, the system is not suitable for event driven processes or situations where communication with operator is expected in the manner of a dialog.

Also the dependence on a big amount of historical data can be a limitation in some cases, namely a completely new processes.

Current performance issues resulting from calculation-intensive data processing algorithms are expected to be overcome in the future.

5.2 Prospects of Future Work

Actual status of the development of the advisory system creates a good basis for future extended applications. The probabilistic theory is well-developed and only little work on further improvements is expected.

Recent application projects show that it will not be effective to develop the system to a final form enabling repeated application without any change. A more realistic strategy is to use all the developed modules as a basis for future applications and adjust the modules according to the particular application as late as the application comes into account.

From this point of view, following improvement and tuning work can be expected:

- Performance increase of calculation-intensive nodes with the help of GPUs.
- Further methods for signal quality improvement (similar to those from chapter 4.5.1).

- Further methods for advanced diagnostics of signals (similar to those from chapter 4.5.2).

Especially the last two points are very probable, because results of these extensions would be very useful for common applications of standard control systems, even if the advisory system is not a part of the solution.

6 References

[1] I. Nagy, P. Nedoma, M. Kárný, L. Pavelková and P. Ettler, “Modelování chování složitých systémů pro podporu operátorů,” *Automa,* pp. 54-57, 11 2002.

[2] M. Kárný, J. Böhm, T. V. Guy, L. Jirsa, I. Nagy, P. Nedoma and L. Tesař, Optimized Bayesian Dynamic Advising, Berlin: Springer, 2006.

[3] P. Ettler and P. Nedoma, “Data-based adviser to operators of complex processes,” in *Proceedings of the 2002 International Conference on Control Applications, 2002*, Glasgow, UK, 2002.

[4] J. P. Keller and M. Agarwal, “Decision Support System for Value Engineering in Flour Mills,” in *Proceedings of ICINCO 2013*, Reykjavvík, Iceland, 2013.

[5] S. Calderwood, W. Liu, J. Hong and M. Loughlin, “An Architecture of a Multi-Agent System for SCADA, Dealing With Uncertainty, Plans and Actions,” in *Proceedings of ICINCO 2013*, Reykjavvík, Iceland, 2013.

[6] Y. C. Shin and A. J. Waters, “Framework of a machining advisory system with application to face milling processes,” in *Journal of Intelligent Manufacturing*, London, 1998.

[7] B. Dow and J. Belaskie, “Improving drilling results with a real-time performance advisory system,” *World Oil,* vol. 6, no. 1., June 2012.

[8] F. D. Felice, “Research and applications of AHP/ANP and MCDA for decision making in manufacturing,” *International Journal of Production Research,* pp. 4735-4737, 21 August 2012.

[9] M. Dytczak, G. Ginda and M. Pergol, “Possibility and Benefits of MCDA Application for Decision Making Problems Support in Printing Activities,” *International Circular of Graphic Education and Research,* pp. 32-49, 2009.

[10] Y. Yanagihara, T. Kakizaki, K. Arakawa and A. Umeno, “Multi-modal Teaching-Advisory System using Complementary Operator and Sensor Information,” in *RO-MAN'95 TOKYO, Proceedings., 4th IEEE International Workshop on Robot and Human Communication*, Tokyo, 1995.

[11] M. Anutosh, B. Saurabh, G. Chiranjeeb and P. Sanjoy, “An Integrated Transport Advisory System for Commuters, Operators and City Control Centres,” in *Vehicular Traffic Management for Smart Cities*, Dublin, 2012.

[12] S. J. Lee, K. Mo and P. H. Seong, “Development of an Integrated Decision Support System to Aid the Cognitive Activities of Operators in Main Control Rooms of Nuclear Power Plants,” in *Proceedings of the 2007 IEEE Symposium on Computational Intelligence in Multicriteria Decision Making (MCDM 2007)*, Honolulu, HI, 2007.

[13] T. Kraft, K. Okagaki, R. Ishii, P. Surko, A. Brandon, A. DeWeese, S. Peterson and R. Bjordal, “A hybrid neural network and expert system for monitoring fossil fuel power plants,” in *Proceedings of the First International Forum on Applications of Proceedings of the First International Forum on Applications of Neural Networks to Power*

SystemsNeural Networks to Power Systems, Seattle, WA, 1991.

[14] C. Eaves-Walton, K. Hunt and S. Redfod, “Intelligent online process monitoring and fault isolation,” in *IEE Colloquium on Condition Monitoring and Failure Diagnosis - Part 1*, London, 1988.

[15] J. Bushman, C. Mitchell, P. Jones and K. Rubin, “ALLY: an operator's associate model for cooperative supervisory control situations,” in *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, Cambridge, MA, 1989.

[16] C. D. Rogers and J. J. Hudak, “The ANN (Assistant Naval Navigator) System,” in *IEEE Conference on Technologies for Homeland Security (HST), 2012* , Waltham, MA, 2012.

[17] Y.-K. Yang, “EPAS: An Emitter Piloting Advisory Expert System for IC Emitter Deposition,” in *IEEE Transactions on Semiconductor Manufacturing*, 1990.

[18] J. Liu, K. W. Lim, W. K. Ho, K. C. Tan, R. Srinivasan and A. Tay, “The Intelligent Alarm Management System,” in *IEEE Software*, 2003.

[19] J. Braman and D. Wagner, “Energy Management of the Multi-Mission Space Exploration Vehicle using a Goal-Oriented Control System,” in *IEEE Aerospace Conference, 2011* , Big Sky, MT, 2011.

[20] B. B. P. F. Elzer, “OPERATOR SUPPORT SYSTEMS IN S&C OF LARGE TECHNICAL SYSTEMS,” in *International Conference on Human Interfaces in Control Rooms, Cockpits and Command Centre*, Bath, UK, 1999.

[21] D. Patnaik, M. Marwah, R. K. Sharma and N. Ramakrishnan, “Temporal Data Mining Approaches for Sustainable Chiller Management in Data Centers,” in *ACM Transactions on Intelligent Systems and Technology (TIST)*, New York, NY, USA, 2011.

[22] Xenomai, “Xenomai: Real-Time Framework for Linux,” [Online]. Available: www.xenomai.org.

[23] RTAI, “RTAI - the RealTime Application Interface for Linux,” RTAI, [Online]. Available: www.rtai.org.

[24] OPC, “OPC - OLE for Process Control,” OPC Foundation, [Online]. Available: https://opcfoundation.org/about/opc-technologies/opc-classic/.

[25] D. Jansen and H. Buttner, “Real-time ethernet the EtherCAT solution,” *Computing & Control Engineering Journal,* March 2004.

[26] Siemens, “PROFINET The Industrial Ethernet Standard,” in *Proceedings of 8th IEEE International Workshop on Factory Communication Systems COMMUNICATION in AUTOMATION*, Nancy, FR, 2010.

[27] M. Felser, PROFIBUS Manual [Elektronische Ressource] : A collection of information explaining PROFIBUS networks, Berlin: epubli GmbH, 2011.

[28] I. Puchr and P. Ettler, “Embedded System for Fast Data Acquisition Based on Cooperation of Two Operating System Platforms,” in *Proceedings of MECO 2012*

Mediterranean Conference on Embedded Computing, Bar, Montenegro, 2012.

[29] I. Puchr and P. Herout, “Signal Pre-processing Subsystem for the Purpose of Industrial Control,” in *Proceedings of ICINCO 2011, 8th International Conference on Informatics in Control, Automation and Robotics*, Noordwijkerhout, NL, 2011.

[30] P. Ettler, I. Puchr and J. Štika, “Combined Approach Helping to Reduce Periodic Disturbances in Speed Measuring,” in *Proceedings of PSYCO 2010 Conference*, Antalya, TR, 2010.

[31] I. Nagy, P. Nedoma, M. Kárný, L. Pavelková and P. Ettler, “O bayesovském učení,” *Automa,* pp. 56-61, 7 2002.

[32] P. Nedoma, M. Kárný, J. Böhm and T. V. Guy, “Mixtools Interactive User's Guide,” 2005. [Online]. Available: http://invenio.nusl.cz/record/35111.

[33] I. Nagy, E. Suzdaleva and M. Kárný, “Bayesian estimation of mixtures with dynamic transitions and known component parameters,” 2011. [Online]. Available: http://www.kybernetika.cz/content/2011/4/572.

[34] I. Nagy, P. Nedoma, M. Kárný, L. Pavelková and P. Ettler, “Modelování chování složitých systémů pro podporu operátorů,” *Automa,* pp. 54-57, 11 2002.

[35] J. Andrýsek, “Estimation of Dynamic Probabilistic Mixtures,” 2005. [Online]. Available: http://www.utia.cas.cz/node/631/0026117.

[36] A. Gut, An Intermediate Course in Probability, Dordrecht: Springer, 2009.

[37] R. Wu, B. Zhang and M. Hsu, “GPU-Accelerated Large Scale Analytics,” HP Laboratories, 2009.

[38] P. Ettler, I. Puchr, L. Jirsa and L. Pavelkova, “Probabilistic Inspection of Multimodally Distributed Signals,” in *Proceedings of The 12th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies*, Oxford, UK, 2015.

[39] A. Jøsang, “Conditional reasoning with subjective logic,” *Journal of Multiple-Valued Logic and Soft Computing,* pp. 5-38, 2008, 15(1).

[40] K. Dedecius and P. Ettler, “Overview of Bounded Support Distributions and Methods for Bayesian Treatment of Industrial Data,” in *Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2013)*, Reykjavik, 2013.

[41] I. Puchr and P. Herout, “Time-frequency Analysis of Controller Input Signals Helps to Improve Production Quality of Metal Strips,” in *Preprints of IFAC 2017 World Congress*, Toulouse, FR, 2017.

[42] I. Puchr and P. Herout, “Probabilistic Advisory System for Operators Can Help with Diagnostics of Rolling Mills,” in *Proceedings of 21st International Conference on Process Control*, Štrbské pleso, Slovakia, 2017.

Appendix 1 List of Author's Publications

Ettler P., Valečková M., Kárný M., Puchr I., “Towards a knowledge-based control of a complex industrial process”, in *Proceedings of the 2000 American Control Conference*, Chicago, US, 2000.

Ettler P., Puchr I., “Coping with time delay while controlling annealing furnaces”, in *Proceedings of the 6th IFAC Workshop on Time-Delay Systems*, L‘Aquila, IT, 2006.

Ettler P., Puchr I., Štika J., Křen J., “DAR and Achievements in the Metal Processing Domain”, in *Proceedings of 5th International Workshop on Data – Algorithms – Decision Making*, Plzeň, CZ, 2009.

Ettler P. Puchr I., Štika J., “Combined Approach Helping to Reduce Periodic Disturbances in Speed Measuring”, in *Proceedings of the PSYCO 2010 IFAC Workshop*, Antalya, TR, 2010.

Puchr I., Ettler P., “Continuous Decision Making for Specific Tasks Related to Metal Processing Industry”, in *Proceedings of the ROADEF 2011, 12e congrès annuel de la Société française de Recherche Opérationnelle et d’Aide à la Décision*, Saint-Étienne, FR, 2011.

Puchr I., Herout P., “Signal Pre-processing Subsystem for the Purpose of Industrial Control”, in *Proceedings of the ICINCO 2011, 8th International Conference on Informatics in Control, Automation and Robotics*, Noordwijkerhout, NL, 2011.

Puchr I., Ettler P., “Embedded system for fast data acquisition based on cooperation of two operating system platforms”, in *Proceedings of the Embedded Computing (MECO), 2012 Mediterranean Conference*, Bar, Montenegro, 2012.

Ettler P., Puchr I., Dedecius K., “Bayesian Model Mixing for Cold Rolling Mills: Test Results”, in *Proceedings of the 2013 International Conference on Process Control (PC2013)*, Štrbské Pleso, SK, 2013.

Ettler P., Puchr I., “Utilization of MATLAB Classes to Streamline Experimental Software”, in *Proceedings of the International Conference Technical Computing Prague (TCP 2013)*, Praha, CZ, 2013.

Ettler P., Puchr I., Jirsa L., Pavelková L., “Probabilistic Inspection of Multimodally Distributed Signals”, in *Proceedings of the Twelfth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies (CM 2015/MFPT 2015)*, Oxford, UK, 2015.

Ettler P., Puchr I., “Probabilistic Estimation of the Strip Thickness in the Rolling Gap for Cold Rolling Mills”, in *Proceedings of the 9th International Conference STEEL STRIP 2016*, Mikulov, CZ, 2016.

Puchr I., Herout P., “Probabilistic Advisory System for Operators Can Help with Diagnostics of Rolling Mills”, in *Proceedings of the 21st International Conference on Process Control*, Štrbské Pleso, Slovakia, 2017.

Puchr I., Herout P., “Time-frequency Analysis of Controller Input Signals Helps to Improve Production Quality of Metal Strips”, in *Preprints of the 20th IFAC World Congress*, Toulouse, FR, 2017.

Puchr I., Herout P., “Advisory System for Operators of Complex Industrial Processes Extended by Diagnostic Functions”, in *Journal of Engineering and Applied Science*, Medwell Journals, 2018 (accepted for publication).

Appendix 2 Real-time Database—Description of Principles

The basis of the RDb technology is a memory resident database, a set of tables containing objects called RDb signals or simply signals. Signals are of different types according to usual data types in general:

RDb signal type	Description
D	Standard floating point 64-bit double.
F	Standard floating point 32-bit float.
A	Analog input. 16-bit word for write operations and 32-bit float for read operations (after recalculation to physical units).
L	Standard 32-bit long integer.
I	Standard 16-bit integer.
B	Standard 8-bit byte.
T	Text / string with the length of max. 255 characters.
G	Group / structure of signals of different types. (It will be described later in detail.)

Table 7 RDb signal types

G signal type enables to create groups or structures of signals similarly as data structures in a programming language. Group can contain signals of same type (an array) or different types (data structure). A **G**-signal can contain **G**-signals together with other signal types. Main features of **G**-signals are:

- atomicity of read / write operations that ensures consistency of the whole data structure for each read and write operation,
- effectiveness of read / write operations, much less system overhead is spent than for signals being read / written item-by-item.

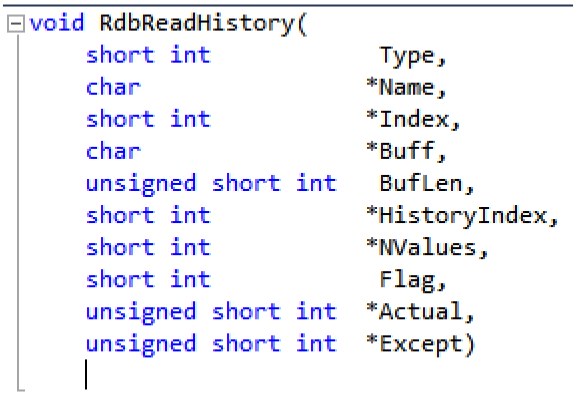
Each signal has the following basic properties:

Property name	Description
Type	Data type of signal, see Table 7.
Name	Symbolic name of signal. Together with **Type** uniquely identifies the signal.
Index	Index in table of signals of same type. Together with **Type** uniquely identifies the signal. (It will be described later in detail.)
IniValue	Initial value, valid before first write operation.
Value	Actual (latest written) value.
HistoryLength	Length of history. Signal history will be described later in detail.
HistoryStep	Step of history. Signal history will be described later in detail.

Table 8 Basic properties of RDb signal object

Signals are generally identified by **Type** and **Name** but **Type** and **Index** may be used which is much more effective. During the first operation with a signal, **Index** is converted to **Name**. If the **Index** is remembered by the calling task and provided together with name as parameter to subsequent operations, operations spend much less processor time because no search by name must be done and signal is addressed by **Index** directly.

Signal history is a special feature of RDb. Each signal with **HistoryLength>0** has a cyclic buffer assigned. With each write operation the written value is stored beside the actual value to the head of the history buffer. Parameter **HistoryStep>1** enables not to store each value in history buffer. With **HistoryStep=2**, every second value written to the signal is stored to history buffer etc. History buffer is filled by standard write operations while for reading a special function is defined:



```
void RdbReadHistory(
        short int               Type,
        char                   *Name,
        short int              *Index,
        char                   *Buff,
        unsigned short int      BufLen,
        short int              *HistoryIndex,
        short int              *NValues,
        short int               Flag,
        unsigned short int     *Actual,
        unsigned short int     *Except)
```

Figure 44 Function header of RdbReadHistory function (in C language)

Meaning of parameters is explained in the following table.

<table>
<tr><th>Parameter name</th><th>Description</th></tr>
<tr><td><b>Type</b></td><td>Input: Type of signal, history of which is read. Values 'D', 'F', etc.</td></tr>
<tr><td><b>Name</b></td><td>Input: Pointer to null terminated string representing symbolic name of signal.</td></tr>
<tr><td><b>Index</b></td><td>Input/output: Pointer to index of signal. Before first referencing of signal should be set to -1. In first call, correct value of index is returned and in subsequent calls serves as input parameter holding direct reference to signal table and avoids searching of signal by name.</td></tr>
<tr><td><b>Buff</b></td><td>Output: Pointer to buffer where the read history values should be stored.</td></tr>
<tr><td><b>BufLen</b></td><td>Input: Length of buffer in bytes.</td></tr>
<tr><td><b>HistoryIndex</b></td><td>Input: Pointer to index to cyclic buffer of signal history where the reading should start:
<table>
<tr><td>-32768 to -1</td><td>Start reading at position relative to current index. -1 means recently written value, -2 previous one, etc. If the requested value reaches beyond values written since start of RDb or beyond history length, the oldest value is read.</td></tr>
<tr><td>0 to
HistoryLength - 1</td><td>Start reading at absolute position / index in cyclic buffer.</td></tr>
</table>
Output: Absolute position to cyclic buffer is returned, so that next call with this value of HistoryIndex can continue with next history value.</td></tr>
<tr><td><b>NValues</b></td><td>Input: Pointer to number of values to be read.
Output: Number of values actually read. It may be lower than requested if fewer new values are available since start or since last read value given by HistoryIndex.</td></tr>
<tr><td><b>Flag</b></td><td>Input: For future use.</td></tr>
<tr><td><b>Actual</b></td><td>Output: Number of bytes read.</td></tr>
<tr><td><b>Except</b></td><td>Output: Exception.</td></tr>
</table>

Table 9 Parameters of RdbReadHistory function

For data acquisition, the combination of G-signals and signal history is highly useful. A task in real-time environment acquires a structure of data cyclically with a defined period and writes it to a G-signal with history in local RDb. Data samples stored by this "producer" task are strictly equidistant and consistent in structure. "Consumer" task can run with lower priority in the same real-time environment or in a non-real-time part of the same node or even in another node and can process all samples without loss.

RDb Signals in Multitasking Environment of a Node

Basic data structures of RDb are taken as shared resource from the point of view of tasks running in the same node, in the same operating system environment. Concurrent access to this shared resource is solved by following concept.

RDb data structures are placed in a block of shared memory. Each task gets the base address of this memory in the initialization section. These addresses may differ because of different memory mappings of particular tasks. That is why there are no absolute pointers stored in data structures in the shared memory but offsets to the base address. The tasks use their shared memory base address together with offsets for addressing of RDb data structures residing in shared memory.

Each RDb signal is represented by a data structure in the shared memory. All signals of a type are represented by a one-dimensional array of data structures. This trivial arrangement enables that each signal of a type can be addressed in a simple way and thus quickly. If each task gets index to the array of signal data structures for each used signal as early as in initialization section, then the task can address each signal by two parameters only (`SignalType` and `SignalIndex`). Then, the access to signal is direct, free of search operation. This maximizes the efficiency of access to Rdb signals and speeds ups the operations with signals. In this aspect, it is possible for the tasks to use RDb signals directly in calculations and algorithms without making copies in local variables, because it has almost no impact on performance.

From the point of view of concurrent access to RDb signals, it is necessary to ensure atomicity of operations ([43] page 66) with RDb signals. The access methods can be divided into two groups. The first group contains the simplest signal operations where the atomicity of operations can be ensured without help of operating system calls for mutual exclusion. To this group belong mainly read and write operations with RDb signals of simple data types without history (`HistoryLength=0`). For simple data types, RDb signals of `D`, `F`, `A`, `L`, `I`, `B` types are taken. In this case, the atomicity of read / write operations can be ensured on the instruction level. Atomicity is guarantied if multi-byte value is written or read within an instruction.

All this mentioned about atomicity guarantied on an instruction level is valid for single-processor / single-core systems. In these systems, if the instruction begins, it cannot be interrupted before its completion and multi-byte value is written or read as a whole. Other situation is in multiprocessor or multi-core (much more frequent case with nowadays PC hardware platforms) systems. In these systems, the read / write operations executed by an instruction cannot be taken for uninterruptible, because the memory location can be accessed from multiple processors or cores simultaneously. This situation must be solved in RDb technology too, because multiprocessor or multi-core systems become standard even in industrial computer platforms.

There exist at least two possibilities how to solve this problem:

- to ensure that all tasks accessing RDb signals run in one processor / core only,
- to use `LOCK` prefix at instruction level.

The first possibility is easy to ensure. In Windows environment, there is the AFFINITY switch of START command that enables to attach a process to a selected CPU in multiprocessor or multi-core system. The following example starts an application and assigns CPU 0 to this application:

```
START /AFFINITY 0x1 RDbApp1.exe
```

In Linux environment, we must distinguish between standard Linux and real-time Linux environments. In standard Linux a started process can be bound to a CPU by taskset command with -c switch, as in the following example a process with PID=12345 is bound to CPU 0:

```
taskset -c 1 -p 12345
```

In RTAI real-time Linux extension, the situation is dependent on task scheduler currently used, but in general, a task can be assigned to a CPU by calling the rt_set_runnable_on_cpus function with the following definition:

```
void rt_set_runnable_on_cpus(RT_TASK *task, unsigned int cpu_mask);
```

In Xenomai real-time framework for Linux, a real-time task can be assigned to a CPU in time of creation. rt_task_create function is used for it:

```
int rt_task_create(
      RT_TASK    *task,
      const char *name,
      int        stksize,
      int        prio,
      int        mode
 )
```

where in mode parameter, several bits are reserved to affine the new task to a CPU.

The second possibility to ensure the atomicity of simple read / write operations in multiprocessor or multi-core systems on instruction level is characterized by the use of LOCK instruction prefix. In this context we assume Intel x86 processors and successors. The LOCK instruction prefix can be used for a limited set of instructions only. As the MOV instruction is not among them, XCHG is the first candidate. Let us remark that XCHG instruction has LOCK prefix by default and locking mechanism is applied regardless of the presence or absence of the LOCK prefix. The locking mechanism ensures exclusive access of the CPU to a shared memory during the execution of instruction. Details of this locking mechanism varies with particular processors and besides external memory, cache memory is locked too.

The other group of access methods to RDb signals contains more complex operations concerning mainly G signals and signals with history (HistoryLength>0). In this case the atomicity of operations cannot be easily ensured at instruction level. Consistency of more complex data structures must be kept. For this purposes, standard operating system calls are used from the group of system calls for mutual exclusion of concurrent tasks. In all operating system platforms, solution with critical section (see [43] page 17-30) is accepted. The construction of RdbEnterCriticalSection and RdbLeaveCriticalSection functions differ in particular operating systems.

In Windows environment, mutex object is created and WaitForSingleObject system call is used in RdbEnterCriticalSection function.

In standard Linux environment, semaphore object is used for construction of critical section. Semaphore is created and its maximum value set to 1, thus creating binary semaphore. `semop` function is called in `RdbEnterCriticalSection` and `RdbLeaveCriticalSection` functions then.

In Xenomai and RTAI real-time Linux environments, POSIX threads standard is used as unifying platform because it is implemented in both environments. Pthread mutex is created and `pthread_mutex_lock` and `pthread_mutex_unlock` functions are called inside `RdbEnterCriticalSection` and `RdbLeaveCriticalSection` functions respectively.

Let us remark that mutex is in principal the same object as binary semaphore. In this respect, critical section is implemented on base of the same object in all platforms.

The atomicity problems on instruction level in RDb with multiprocessor and multi-core systems are not fully sorted out and are the subject of further development.

Appendix 3 Description of MixTools Library

Global Variables

All functions work over global variables. List of main global variables follows:

- `TIME` is dynamic time, it is denoted as t in equations in this document.
- `DATA` is matrix of data where particular data channels (signals) are located in rows, `DATA(channel,TIME)` denotes value of data channel `channel` in time instance `TIME`.
- `ACTIVE` identifies the currently active component of a mixture. If a process is described by a particular mixture, active component is the component that represents or models the current state of the process.
- `DEBUG` is a global flag that controls amount of debugging information displayed in runtime.

Objects

In spite of the fact that MixTools is not object oriented in the terminology of object oriented programming, we will use the term *object* for software structures used for representation of mixtures, components and other MixTools entities. Main objects used in MixTools are mixtures (of probability density functions) and components creating the mixtures. In previous chapters, mixtures and components were described. Moreover, *factors* are used for the representation of components in MixTools. We will explain factors here.

Factors

We will explain the decomposition of a component into factors on the case of a bivariate version of $f(d_t|d(t-1),\Theta_c,c)$ component from *(11)*. Component $f\left(d_{1,t},d_{2,t}\middle|d_{1,t-1},d_{2,t-1},\Theta\right)$ (c identifier of component is omitted for simplicity) can be decomposed according to the chain rule as follows:

$$f\left(d_{1,t},d_{2,t}\middle|d_{1,t-1},d_{2,t-1},\Theta\right) = f\left(d_{2,t}\middle|d_{1,t},d_{1,t-1},d_{2,t-1},\Theta\right).f\left(d_{1,t}\middle|\, d_{1,t-1},d_{2,t-1},\Theta\right) \qquad (20)$$

Probability density function of two random variables is replaced by the product of two univariate probability density functions. This decomposition is also called *factorisation* and two functions on the right side are called *factors* ([2] page 55). Factor is probability density function describing particular data channel. This form of mixture component was chosen by authors of MixTools as the most convenient for software representation and operations.

Demonstration of factors was done here with the use of only two dimensional data space. Chain rule in its general form for probabilities of events (see [44] page 11) shows how the factorisation can be constructed in multidimensional data space.

$$P(A_1 \cap A_2 \cap \ldots \cap A_n) = \\ = P(A_1)P(A_2|A_1)P(A_3|A_1 \cap A_2) \ldots P(A_n|A_1 \cap A_2 \cap \ldots \cap A_{n-1}) \qquad (21)$$

For the use in MixTools, factors are expressed in other forms. We show one of these forms in the example for two data channels:

$$d_{1,t} = a_{1,1}d_{2;t} + a_{1,2}d_{1;t-1} + a_{1,3}d_{2;t-1} + a_{1,4} + e_{1;t} \qquad (22)$$

The equation *(22)* tells that value of data channel 1 in time instant t depends on linear combination of delayed values of the same channel and on values of the other channel, delayed and/or not delayed. Parameter $a_{1,4}$ is offset of the data channel and $e_{1;t}$. is called noise. $e_{1;t}$expresses the other unknown influences that $d_{1,t}$depends on. $d_{1,t}$ channel is called *modeled* channel.

In Mixtools, a factor is represented by a data structure. Main structure items are:

Identifier	Description	Data type
`ychn`	Data channel represented by the factor.	scalar
`str`	Factor structure. It is a two dimensional matrix with two rows. In the first row, there are numbers of channels and in the second row, there are numbers indicating time delay of corresponding channels. See below for explanation.	matrix
`type`	Factor type.	scalar
	Other structure items depend on factor type.	

Table 10 Main items of factor data structure

The meaning of `str` will be explained by way of an example. Factor structure for channel 1

$\begin{bmatrix} 1 & 1 & 2 & 2 \\ 1 & 2 & 0 & 1 \end{bmatrix}$ means that data channel represented by the factor is dependent

- on channel 1 with delay 1 (`DATA(1,TIME-1)`),
- on channel 1 with delay 2 (`DATA(1,TIME-2)`),
- on channel 2 with no delay (`DATA(2,TIME)`) and
- on channel 2 with delay 1 (`DATA(2,TIME-1)`).

Factor structure represents the structure of regression vector.

Factor type differentiates type of factor representation in the form of MATLAB data structure. On the factor type, the other structure items depend. These items express in different forms the probabilistic nature of the factor. Different forms are suitable for different factor operations. See [32] page 14 for details.

We also differentiates *dynamic* and *static* factors. This division is based on the dependence of the modeled channel value in time instance t on delayed values of this and/or other channels. Regression vector of static factor expressed by factor structure contains zero-delayed values only ($d_{i;t}$). On the contrary, dynamic factor has in its regression vector at least one delayed value ($d_{i;t-1}, d_{i;t-2}, \ldots$).

Components

Component is a multivariate probability density function that describes behaviour of selected channels called *modeled channels*. Behaviour of these channels may depend on other channels called *non-modeled* channels.

Components are expressed with the help of factors as described in *(22)*. In this basic form, the component is represented as a list of factors, as a *cell array* in MATLAB terminology. This form is suitable for MixTools estimation functions. There are other forms of mixture representation suitable for simulation, e.g.

Mixtures

As mentioned above, mixture is a linear combination of parameterized probability density functions. In MixTools, the mixtures are represented by data structures of several different types. One possible representation of a mixture in MixTools is stated in the following table.

Identifier	Description	Data type
`Coms`	Array of components.	cell vector
`ncom`	Number of components.	scalar
`dfcs`	Degrees of freedom of components. After normalization to sum of 1, it represents probability of particular components.	vector `1 x ncom`

Table 11 Representation of mixture based on an array of components.

Another possible representation of mixture based on a list of factors is the data structure items of which are listed in the following table.

Identifier	Description	Data type
`Facs`	Array of factors.	cell vector
`coms`	Matrix expressing which factor belongs to which component. Number of rows corresponds to the number of components. Number of columns is the number of factors each component consists of. (Number of factors in each component equals to the number of modeled channels `nchn`.)	Matrix `ncom x nchn`
`dfcs`	Degrees of freedom of components. After normalization to sum of 1, it represents probability of particular components.	vector `1 x ncom`

Table 12 Representation of mixture based on an array of factors.

Similarly to components, different mixture representations are used for different operations (simulation, estimation, ...)

Function Categories

All functions in MixTools are divided into categories. List of main categories with a short description and function examples follows:

- Construction category contains functions used for creation of data structures representing mixtures, mixture components, factors and other objects and contains functions that enable various conversions between particular types of object representations. Example of a creation function is `mixconst` that creates a mixture from a set of components and their weights. Example of a conversion function is `mix2mix` that converts mixture from one representation type to another one.
- Pre-processing category contains functions that realize often used operations with data being investigated. Example of a useful pre-processing function is `scaledata` which is controlled by input string parameter that can e.g. equal to `'limit'` or `'scale'` which denotes limiting or rescaling of `DATA`. Filtering is done by `preinit` function that enables removal of outliers, smoothing and filtering of `DATA` based on several different algorithms.
- Estimation category represents the key category from the advisory system point of view. Functions collected in this category help to find the representation of `DATA` in the form of mixtures of probability density functions. `mixest` is a representative of this category that comprises a possibility to call several estimation algorithms. Input parameters enable to set prior information, number of iterations and to choose a particular estimation algorithm.
- Simulation category comprises functions that simulate / generate `DATA` on the base of a mixture. It is, to a certain extent, a reverse operation to the estimation. Results of simulation are also used for verification of estimation results. By estimation functions, a representation of `DATA` is found in the form of a mixture. Then the mixture is used as input parameter of simulation function that generates simulated `DATA`. Original `DATA` and simulated `DATA` are compared and thus success of estimation can be measured.

There exist more categories in MixTools but we stated only that ones containing functions used for the purposes of the advisory system.

All substantial functions are available in MEX format as well (besides the M format). MEX modules are functions executable in MATLAB environment. They are written in C and compiled. This reduces the execution time substantially in comparison to interpreted M modules.