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**Knowledge-based quality control
in manufacturing processes with application
to the automotive industry**



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1 Introduction

1.1 Quality and knowledge - The big picture

Quality as a success factor

Quality is a decisive success factor and one of the competitive edges of modern manufacturers. In many production scenarios, maintaining high product quality and production efficiency entails the extensive use of advanced process monitoring, control and adjustment techniques. In this regard, pertaining literature reports that quality related costs may run at 20-40% of sales [JURAN & GYRNA 1988, TAGUCHI et al. 1989]. In recent decades, researchers and international organizations stressed that the cost of quality is not the price of creating a quality product or service. It is the cost of not creating a quality product or service, hence, more intuitively known as the cost of poor quality [BESTERFIELD 1990].

Advanced process design and offline fault analysis methods do reduce failure risks [WHITNEY 1996]. But, offline methods alone are not enough since any process will drift if no control is applied [DEL CASTILLO 2002]. According to ROSS 1995, continuous adjustment, even within tolerance limits, is a must for more competitive products that bear minimized losses to the society. The premise that each failure has a root cause, causes are preventable, and prevention is cheaper [BESTERFIELD 1990] represents the underlying motivation for a number of research activities in the field of online quality control. Such research initiatives addressed process monitoring [ANAGUN 1998, BARGHASH & SANTARISI 2004], fault diagnosis and recovery [BALLÉ & FUESSEL 2000, BEN-GAL et al. 2003] and their integration [DEL CASTILLO 2002, GUH 2003] in order to deal with production disturbances, ranging from minor quality nonconformance to complete equipment failure.

In sharp contrast to research activities, a study of manufacturing priorities in the industrial and the consumer goods sectors (Figure 1.1) shows a rather paradoxical situation [A. T. KEARNEY 2005]. Increasing product quality and eliminating defectives are not on the top of the priority list when production costs are considered. The finding is alerting in the light of the impact of product quality on the overall performance and profitability. In spite of the current advances in quality engineering, this key function promises yet a greater profit potential in industrial practices if it is assigned more resources.

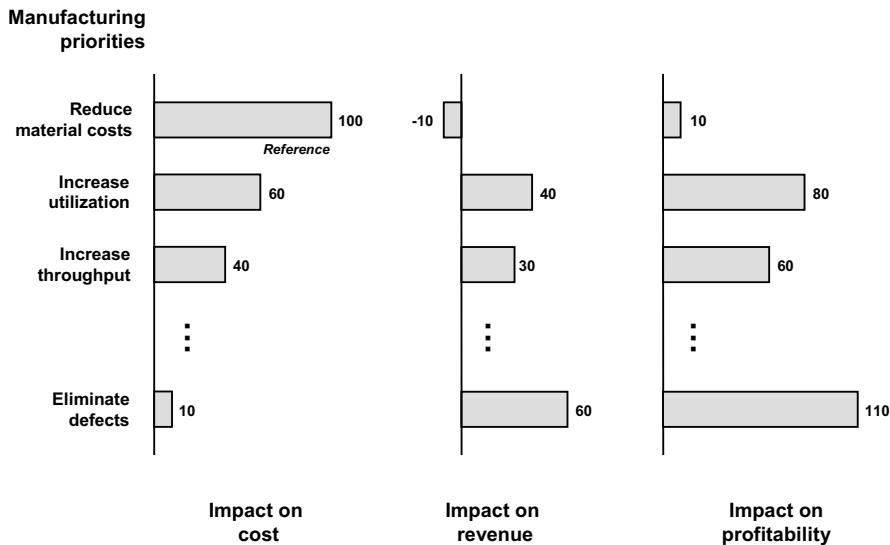


Figure 1.1: Impact of manufacturing priorities on cost, revenue and profitability [A. T. KEARNEY 2005]. All values are relative to the upper left entry marked as reference.

Quality as a shared responsibility

Quality, maintenance and operation personnel, often separate teams, cooperate to solve quality problems as quickly and as efficiently as possible. The know-how of the quality planning team complements the task. Such shared responsibilities and extensive experience involved in the fault recovery process have led to the development of computer-aided approaches (CAx) in the three areas to facilitate the interdisciplinary communication and to yield a more efficient production process.

The nature of quality problems

Generally, if complete failure or equipment stoppage occurs, e. g. due to crash, the fault cause is easy to identify and correct. Most original equipment manufacturers (OEM) have integrated standard diagnosis functions in their control software. Commercial product data management (PDM) systems offer further assistance in the monitoring and diagnosis of production machinery. The situation is different when dealing with quality problems of assembled products. In practice, manufacturers install quality inspection equipment in order to prevent defective products from reaching the customer. However, these systems have limited abilities as to fault identification, diagnosis, and recovery. Inferring a fault root cause or a recovery action based on the analysis

of a product's deviation from target quality characteristics depends heavily on the experience and the know-how of the involved personnel.

Knowledge as a success factor

Knowledge is regarded as one of the most important issues affecting the success of individuals and organizations. The role of knowledge in the industry has been emphasized in recent years [OETZMANN 2005, RUDOLF 2007], as companies have become more aware of their dependence on qualified staff due to increasing market pressure. Knowledge preserving measures, such as knowledge and competence management policies or the implementation of expert knowledge-based applications, contribute to sustaining and reinforcing the competitiveness of a company [HANNULA et al. 2003]. The most valuable asset in knowledge-related practices is by far the human expert who represents the ultimate decision-making *machine*. Figure 1.2 shows a simplified view of data processing into knowledge.

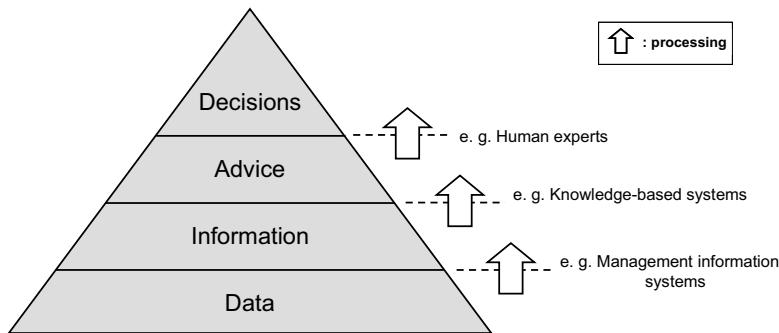


Figure 1.2: Volume versus value in data processing (after [HARRIS-JONES 1995])

1.2 Current situation in operative quality control

DEL CASTILLO 2002 summarizes the difference between quality control and traditional engineering process control (EPC) as given in Table 1.1. He suggests that these two apparently opposing viewpoints need to be reconciled and notes that the need exists for the increased application of EPC-based techniques for quality control.

Table 1.1: Process control versus quality control [DEL CASTILLO 2002]

	Process control	Quality control
Output(s)	Process variable(s)	Quality characteristic(s)
Input(s)	Process variable(s)	Process variable(s)
Control action	Automatic	Usually manual

Considering an arbitrary automated series production process, schematically represented in Figure 1.3, it can be said that the process control comprises two main tasks: data acquisition and control action. Acquisition of process and product data involves sensor technology, measurement principles and monitoring techniques. The control block handles aspects of data interpretation, reference process behavior, decision logic, and feedback of the control action.

Automated data acquisition has witnessed relatively more advances in recent decades than the automation of the control action. There are several reasons why automated inline inspection of product specifications has been applied: short reaction time, reduction of rework and scrap, reduction of logistic costs and high measurement capacity, to name a few. The basic disadvantage of inline measurement is the high initial cost. In addition, the accessibility of all needed quality criteria is not always guaranteed. Many applications allow equipment and process parameters to be monitored as well, such that alarms can be automatically signaled when unusual process conditions occur. However, this is highly process specific and is not always possible. For example, it is not feasible to automatically monitor the condition of fixtures in an assembly line.

Deducing the control action is more complex. Modern production processes pose challenging fault diagnosis tasks, which may entail costly scrap and lag until the fault is eliminated. Experience plays a significant role in assessing the fault severity; what a young engineer, by nature more conservative, considers as scrap might well be rework for a more experienced specialist. Moreover, in order to maintain a stable process, it is not only important to accumulate experience but to ensure its availability and accessibility also. A parallel factor adding to the difficulty of such diagnostic tasks is the often encountered lack of documentation since most manufacturers rely on short fault description in spreadsheet form. Noteworthy is that recent advances in PDM systems and computerized maintenance management systems (CMMS) have improved the situation. However, contrary to both acronyms, the focus on operative implementation, rather than on management, is still lagging. Specialized CAx tools for troubleshooting product quality problems and fault root cause analysis are a rare commodity in practical applications.

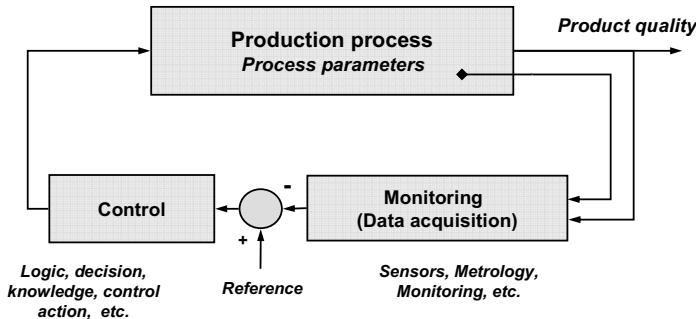


Figure 1.3. Control of a production process in a closed-loop representation

Among the different research directions initiated in response to the unsatisfactory situation was the implementation of model-based quality control techniques in analogy to conventional EPC paradigms [SACHS et al. 1995, DEL CASTILLO 2002, CARLSON & SÖDERBERG 2003]. Also, approaches rooted in the fields of artificial intelligence (AI) and knowledge engineering were used for the same purpose. Models for process stability analysis, fault diagnosis, decision support and corrective actions were successfully built in this way [CHANG & HO 1999, CHEN & HWANG 1992, CAIAZZO et al. 2004]. This thesis belongs to the latter category, and addresses the use of AI and knowledge-based systems (KBS) for quality control in automotive body-in-white production.

1.3 Problem definition

Body-in-white (BIW) production is a representative example of a class of complex automated manufacturing processes, where the aforementioned situation is witnessed. Figure 1.4 illustrates the result of a study conducted by CEGLAREK & SHI 1995 showing that maintenance problems dominate the production phase of the automotive body. Of the studied cases, 56% were related to subassemblies, 20% to framing and 2% to final assemblies. The remaining 22% were due to panel variations. The relations between the dimensional variation of the vehicle and its functional performance, as well as assembly line failures during production are not very clearly understood [HU 1997, CEGLAREK & SHI 1997, CARLSON & SÖDERBERG 2003]. As such, the process of fault elimination is highly subjective and vulnerable due to a number of factors that can be summarized as follows:

- Monitoring techniques, such as statistical process control (SPC), do not explain the root causes of defects [PAN 2002].
- The employment of pure engineering judgment brings an element of uncertainty to the decision making process.

- Regular employee rotations affect the level of available experience.
- Lacking fault documentation yields inefficient knowledge management.
- The link between planning and operation teams weakens after start of production (SOP).
- Fault handling is a shared responsibility between maintenance, quality and operation personnel, which adds organizational costs to the fault recovery process.
- The total losses due to fault diagnosis effort and time are often not fully quantified and the real costs of a fault are underestimated.
- The process stages are physically similar.
- It is difficult to predict product specifications since no accurate process models are available.
- Only end-of-line (EOL) measurements are possible.
- Monitoring all process parameters affecting the geometry, such as positions of fixtures, is not feasible.

BIW production in high-wage countries has developed into a nearly fully automated process with integrated inline quality monitoring solutions for 100% inspection, and, hence, is well suited for the application of online CAx tools. As detailed later in Chapter 3, a field study conducted at a German automotive manufacturer substantiated the necessity of exploiting further improvement potentials in the handling of quality problems (Figure 1.5).

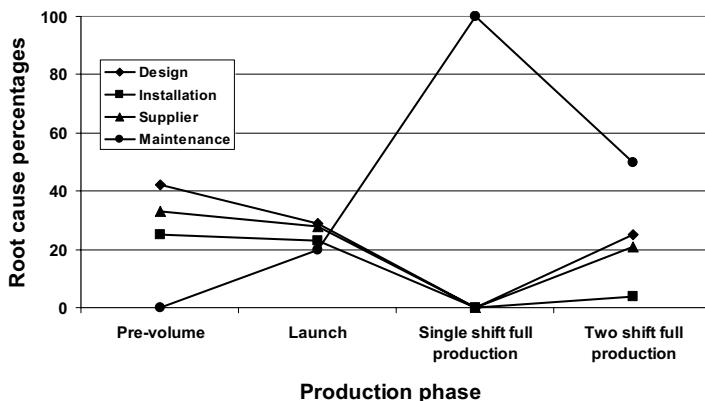


Figure 1.4: BIW dimensional fault root cause classification [CEGLAREK & SHI 1995]

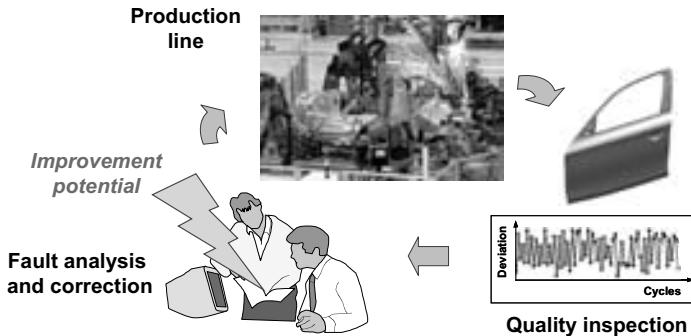


Figure 1.5: Current fault analysis procedures in BIW represent an improvement potential for the reduction of production costs

1.4 Objective and approach

Based on the previous discussion, the objective of this research can be formulated as:

The development of a knowledge-based system (KBS) for fault diagnosis and decision support in online quality control of manufacturing processes with the example of body-in-white production

The KBS aims at aiding the human analyst with tools for quantitative knowledge representation that can be annexed to existing monitoring systems. The objective can also be seen as an attempt to realize semi-automated closed-loop handling of quality problems. The term *knowledge-based* is generally defined by *Knowledge-based Systems*¹ as follows.

“Knowledge-based systems support human decision-making, learning and action. Such systems are capable of cooperating with human users and so the quality of support given and the manner of its presentation are important issues.”

Throughout the thesis, the focus will remain on the automotive BIW production, as described in the problem definition. Data obtained from a field study and recommendations from the literature will be used to identify the solution requirements and to design a modular diagnostic system, with a fault knowledge base as its core compo-

¹ *Knowledge-Based Systems* is the international, interdisciplinary and application-oriented journal on KBS. <www.sciencedirect.com/science/journal/09507051>

ment. The three shaded blocks in Figure 1.6 represent the three basic tasks that will be investigated in the course of this research, which are:

- Fault recognition: the detection of abnormalities in the process
- Fault identification: associating an abnormality with a special cause
- Decision: applying or deferring a process adjustment

The scope of this research does not include the measurement system. Neither will the implementation of the corrective action be addressed in the sense of physical manipulation of the process parameters.

1.5 Thesis structure

This chapter presented an introduction to the research problem and the objective of the thesis. Chapter 2 reviews pertaining literature on process monitoring, fault diagnosis and related issues. Previous approaches to integrating fault knowledge databases in online control are also presented. Findings from a field study conducted at an automotive production facility are included in Chapter 3. Chapter 4 gives an overview of the architecture of the proposed diagnostic system. The development of the system components is described in Chapter 5, Chapter 6 and Chapter 7. Chapter 8 illustrates an exemplary application scenario and a software prototype of the integrated system. A technical and economical assessment of the system is given in Chapter 9. A summary and perspectives for further research can be found in Chapter 10. Table 1.2 gives an overview of the thesis.

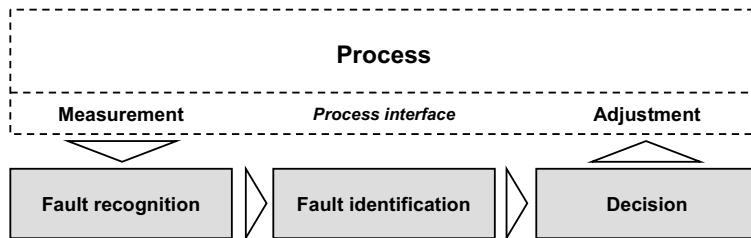


Figure 1.6: Basic tasks in the fault recovery loop

Table 1.2: Overview of the thesis

Chapter	Content
1	Introduction, problem definition and objective
2	Review of pertaining literature in order to establish the theoretical need for further KBS research in a quality control context
3	Field study showing the situation in a BIW production facility and establishing the practical need for alternatives in operative quality control
4	Overview of the proposed solution consisting of a modular structure of specialized submodels
5	Details of the fault recognition module responsible for triggering alarm signals in the case of quality deviations
6	Details of the fault identification module responsible for determining the fault root cause for the quality deviation and providing the user with troubleshooting instructions
7	Details of the decision module responsible for issuing a recommendation to the user in case immediate process interruption is required
8	Discussion of the system integration and a software prototype
9	Discussion of the impact of the proposed system on the overall performance of BIW production in technical and economical terms
10	Summary and future research directions

2 Literature review

2.1 Overview

The chapter reviews recent research activities pertaining to the issues of monitoring, diagnosis and control of manufacturing processes. The discussion is intended for applications in the areas of quality control and fault diagnosis. The onset of the chapter gives an overview of some definitions related to quality control, fault diagnosis and knowledge engineering. These definitions represent the larger context for understanding more specific issues detailed later in the thesis. The section titled process monitoring discusses the aspect of fault recognition in technical processes. A following section handles the fault identification task including modeling for diagnosis purposes as well as KBS design in process diagnostics. A third section introduces some exemplary diagnostic approaches that integrate decision support aspects and closed-loop approaches in quality control. Finally, the conclusion of the chapter summarizes important findings and trends in the surveyed literature.

2.2 Terms and definitions

2.2.1 Quality control and fault diagnosis

DIN EN ISO 9000:2005 defines quality as the degree to which a set of inherent characteristics fulfills requirements. Quality management is explained as the body of coordinated activities to direct and control an organization with respect to quality. Quality control is the part of quality management that is focused on fulfilling quality requirements. DIN EN ISO 9000:2005 also describes a process as a set of interrelated or interacting activities which transforms inputs into outputs. A product is thus the result of a process.

A product that exhibits quality nonconformity is a faulty product. This is explained by the definition of a fault as the state of an item characterized by the inability to perform a required function [DIN EN 13306:2001]. According to DIN EN 13306:2001, a *fault* is a state and is distinguished from *failure*, which is an event. Failure is defined as the termination of the ability of an item to perform a required function, i. e. a permanent interruption. A failure (or fault) cause is the reason leading to a failure (or fault). For the most part of the thesis, states are more relevant than events, and the term fault will be used more often in further discussions relating to quality defects or production disturbances.

A fault may also be defined as an unpermitted deviation of a characteristic(s) of an item or a system [ISERMANN & BALLÉ 1997]. Some publications, such as ABU-

HAMDAN & EL-GIZAWY 1997 and BAYDAR & SAITOU 2001, use the terms *error* and *fault* interchangeably in the context of assembly processes, which is confusing. ABU-HAMDAN & EL-GIZAWY 1997 define error propagation as carrying an undetected error from a previous task and coupling it with another error during a proceeding task. In BAYDAR & SAITOU 2001, the development of a fault pattern is described as an error propagation mechanism. Classically, the term *error* is more often used to describe deviations or uncertainties. Hence, the better practice is to adhere to the definition of *error* as the deviation between computed or measured values and their true or theoretical value [ISERMANN & BALLÉ 1997].

Inspection is a check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item. Monitoring is a manual or automatic activity intended to observe the actual state of an item. It is distinguished from inspection in that it evaluates changes with time [DIN EN 13306:2001]. Fault diagnosis includes actions taken for fault recognition, fault localization, and cause identification [DIN EN 13306:2001]. Fault localization refers to the identification of the faulty item. A diagnostic model can be defined as a set of relations which link specific input variables – the symptoms – to specific output variables – the faults [SIMANI et al. 2003].

It is reported that the terminology in the field of fault diagnosis is not clearly defined [ISERMANN & BALLÉ 1997, SIMANI et al. 2003]. For example, quality defects or product faults arise due to root causes in the process. However, these root causes represent faults as well – process faults. The classification of fault diagnosis methods and techniques is similarly problematic. Most developments and applications of diagnostic systems rely on combinations of different methods. A sharp categorization of such hybrid approaches even to acknowledged standards is difficult and in many cases of little practical value [GUTMANN 2005].

The topics handled in the rest of the chapter will be categorized according to the two main tasks of fault diagnosis: fault recognition (Section 2.3) and fault identification (Section 2.4). The other sections discuss related issues such as process control, decision support and the human role. The presentation of the topics in this way is more suited to the rest of the thesis. The definitions given in Table 2.1 refer to the use of the corresponding terms in the scope of this thesis. The given terms conform to the standards stated above. However, no claim is made on the formality of the definitions at this point. The use of the term *fault identification* in this thesis combines the fault localization and the root cause identification tasks as given by DIN EN 13306:2001 and used in SIMANI et al. 2003. Finally, the use of the term *decision* refers to the differentiation between immediate and deferred corrective actions upon detecting a fault.

Table 2.1: Terms and definitions used in the thesis

Term	Definition
Fault	The instance of one or more quality characteristics exhibiting deviation from the specification, regardless of it being an incipient or an abrupt fault
Fault pattern	The description of the observed deviations in the quality characteristics in vector form
Fault (root) cause	The process parameter responsible for the quality deviation, such as a fixture or a robot
Fault recognition	The instance of detecting deviation in the monitored quality characteristics
Fault (root cause) identification	Establishing an association between a possible root cause and the observed fault pattern
Process	General term describing the manufacturing procedures. A process is usually multistage. The term may be used to describe a single stage or the application of a certain technology in the production cycle as well.
Decision	The decision whether to adjust the process immediately after fault recognition or to defer the corrective action to a later point

2.2.2 Knowledge-based systems

Knowledge, knowledge base and inference

Knowledge is a combination of experiences, values and contextual information that may be grouped into explicit and tacit knowledge [DAVENPORT & PRUSAK 1998]. It is the source of the expert's ability to perform. In a similar way, knowledge storage and representation is the heart of any expert system (ES) or KBS. It is the function of such systems to store expert knowledge, to retrieve knowledge from storage and to infer new knowledge when required [GONZALEZ & DANKEL 1993, HARRIS-JONES 1995, JACKSON 1999].

The components of knowledge [ROLSTON 1988] can be generally viewed as:

Facts: true statements relative to the subject domain
(factual knowledge)

Procedural rules: invariant rules describing sequences and relations relative to the subject domain (procedural knowledge)

Heuristic rules: general rules or rules of thumb extracted from relevant experience suggesting actions, sequences and relations when invariant rules are not available (heuristic knowledge)

In an ES or KBS, the two basic components that act as knowledge *containers* are the knowledge base and the inference engine. In manufacturing processes, the stored knowledge is more domain-specific than expressive of generic expert behavior.

The knowledge base contains factual, procedural and heuristic knowledge. Factual and procedural knowledge are that knowledge of the task domain that is widely shared, typically found in textbooks or journals, and commonly agreed upon by those knowledgeable in the particular field. Heuristic knowledge is the less rigorous, more experiential, more judgmental knowledge of performance. In contrast to factual knowledge, heuristic knowledge is rarely discussed, and is largely individualistic. Thus, knowledge bases consist of some encoding of the domain of expertise for the system. This can be in the form of semantic nets, procedural representations, production rules or frames [GRIFFIN & LEWIS 1989].

The inference engine is the component with the ability to infer new knowledge from existing knowledge using predefined rules and, hence, respond to varying situations or inputs. In many cases, there is no sharp boundary between the two components and a clear differentiation is not necessary and sometimes not possible.

Knowledge engineering

Knowledge engineering (Figure 2.1) is the process of acquiring domain-specific knowledge and building it into the knowledge base. The knowledge engineer is the person who transforms the acquired knowledge in accordance with a knowledge representation convention [ROLSTON 1988]. Knowledge acquisition is not a well defined process and knowledge may vary from primitive to complex statements and relations [JACKSON 1999]. KASABOV 1998 describes four general approaches for knowledge representation: statistical methods, symbolic AI rule-based systems, fuzzy systems and neural networks (NN).

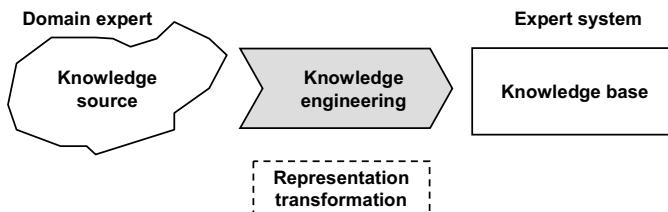


Figure 2.1: Role of knowledge engineering in ES design and maintenance

Expert systems

An ES is a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice [JACKSON 1999]. ES derive originally from the research discipline of AI and are used to perform a variety of complicated tasks otherwise performed by highly trained human experts [ROLSTON 1988]. The general architecture of an ES is given in Figure 2.2. An ES is distinguished from conventional applications in that it simulates human reasoning and is capable of storing and retrieving specific knowledge and inferences. Furthermore, it solves problems by heuristics and approximate models. An ES also differs from other AI applications in its capability to deal with problems of realistic complexity that normally require a considerable amount of human expertise [JACKSON 1999].

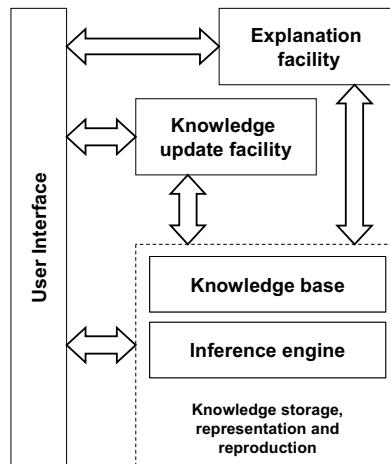


Figure 2.2: Typical ES architecture (after [ROLSTON 1988])

Knowledge-based systems

Very often, KBS and AI are mistakenly assumed to be one and the same [GONZALEZ & DANKEL 1993]. KBS emerged in the 1960s and 1970s as a new branch of AI research (Figure 2.3). It is the branch of AI which has, by far, seen the most success in terms of practical implantation. KBS is also sometimes used as a synonym for ES. However, strictly speaking the former is more general [JACKSON 1999, COUNCIL FOR SCIENCE AND SOCIETY 1989]. A vast number of definitions exist for KBS that have developed and changed through the last decades. One recent general definition of KBS is “*any system that performs a task by applying rules of thumb to a symbolic representation of the world*” [JACKSON 1999].

3 Field study

3.1 Overview

The chapter outlines a field study conducted in cooperation with the companies BMW AG and Perceptron GmbH.⁶ The study attempted to stand on current practices in the BIW production process and to identify trends and future requirements related to quality control of BIW products. The assessment of losses incurred in terms of product quality deficits, types of faults encountered, and building a representative sample of faults for later verification are points that lie in the focus of the chapter.

The investigated BIW production facility is first described. The economical performance from a quality control perspective is then analyzed. A following section portrays the design, operation and inspection practices in BIW. A short account on the sources of variation in the stamping process is presented. The door assembly is closely examined as it will serve test and validation purposes at a later stage.

3.2 Description of the investigated production facility

3.2.1 General information

The automotive body production facility of the BMW AG factory 6.1 in Regensburg, Germany has a staff of approximately 2100 employees and produces approximately 1000 car bodies per day. The production is highly automated (>95% of the value added) and involves 971 welding robots. To finish a 332 kg BMW 1-series body, 5349 weld spots, 2.3 m weld seam and 41.5 m adhesive seam are needed. On average, a car body includes 550 parts which are principally assembled by robots with a small portion of manual activities. The employees, thus, focus more on quality assurance issues rather than on the production process.⁷

Vehicle assembly begins by adding single parts together into subassemblies. Basic subassemblies include the underbody, the motor compartment, the rear, the side frames, and the roof. These components are assembled into the main body structure. Doors, hoods, and deck lids are subassembled separately and added to the body at a later stage. Hence, BIW refers to the assembly process of stamped body parts into a complete vehicle body. The direct upstream process of BIW is stamping (press shop)

⁶ The field study was part of the research project ForWerkzeug-C2 funded by the Bavarian Research Foundation. The cooperating industrial partners were BMW Group <www.bmwgroup.com>, KUKA Roboter GmbH <www.kuka.com> and Perceptron GmbH <www.perceptron.com>.

⁷ Source: <www.bmw-werk-regensburg.de>, accessed on February 1st, 2005

and the downstream process is the paint shop. Following the paint shop, the chassis, the motor, and the trim (windshields, seats, upholstery, electronics, etc.) are installed.

3.2.2 Facility performance from a quality control perspective

The facility produces seven different body models and implements inline product inspection in addition to offline measurement stations and a coordinate measurement machine (CMM) room. The investigated period included the SOP of two new models.

The overall equipment effectiveness (OEE) [NAKAJIMA 1988] is the main performance metric applied in the factory and is obtained by the multiplication of three ratios:

Availability ratio: time during which the equipment is actually available for operation divided by planned production time

Performance ratio: actual production rate divided by maximum capacity

Quality ratio: quantity of prime grade products divided by total production

On 28% of the working days in a period of thirty weeks, OEE violations were recorded. Table 3.1 gives a breakdown of the latter statistic for four door production lines. The unsatisfactory performance was mainly attributed to the availability ratio. The relatively long time needed for fault recovery was a major problem, while equipment performance and product quality were acceptable. This coincides with previous studies where waiting time was reported to take up to 90% of the total downtime [INGEMANSSON & OSCARSSON 2006]. It was found that costs pertaining to scrap, rework and adjustment, without consideration of the recovery time and effort, amounts to 1-2% of the production budget. Figure 3.1 gives an example of rework time of two vehicle models.

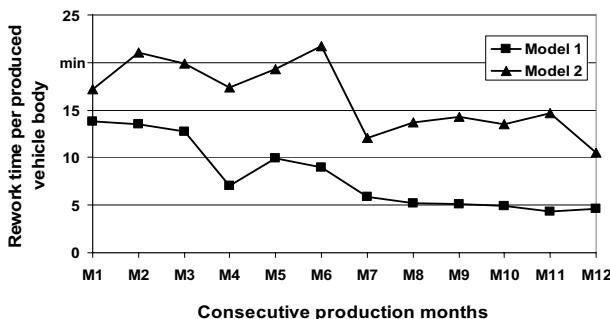


Figure 3.1: Rework time per produced vehicle for a period of twelve months

Table 3.1: OEE violation in four production lines

	Total production days considered	Planned OEE	Percentage of days where OEE was not maintained
Line 1	150	90%	4.7%
Line 2	147	90%	8.7%
Line 3	152	90%	6%
Line 4	150	90%	12%

Table 3.2 illustrates the significance of fault analysis costs and proper fault documentation. The table shows a sample, where analysis time was recorded for production faults of an underbody assembly line. Clearly, the time invested in fault analysis is much higher than that needed for the actual adjustment of the process. Such costs are usually regarded as overheads and are left out of any financial balance [TSAL 1998]. PLUNKETT & DALE 1988 note that the failure costs would increase drastically compared to appraisal and prevention costs if these overheads were included in the cost calculation.

Remark 1: Considering the observation results, it is clear that a change in the way quality related problems are handled is inevitable.

3.3 Vehicle body development process

3.3.1 Design and planning procedures

From requirements definition up to SOP, the product goes through a number of phases. BIW assembly is regarded as the least flexible in the overall vehicle assembly process [SEKINE et al. 1991]. The early planning phase combines available experience from previous models with new styling concepts. The process yields a project order and a preliminary proof of feasibility in the form of tolerance calculations.

Table 3.2: Sample showing fault analysis time versus equipment adjustment time (active maintenance time)

Fault case	Category	Analysis time	Adjustment time	Ratio of analysis time to adjustment time
1	Geometry	1 h	20 min	3
2	Equipment	2 h	10 min	12
3	Not documented	7 h	30 min	14
4	Geometry	1 h	15 min	4
5	Welding	20 h	2 h	10
6	Buffer	1 h	10 min	6
7	Geometry	7 h	30 min	14
8	Buffer	1 h	15 min	4
9	Geometry	2 h	1 h	2
10	Equipment	1 h 30 min	30 min	3

The concept phase identifies possible assembly schemes in agreement with established practices and experience. The gap target values provided from styling teams are then implemented to locate risk areas in the assembly operations and release a first dimensional concept of the vehicle, i. e. a first validation of the vehicle tolerance chain compatibility. The project then moves into the series development phase. This phase involves exhaustive simulations to assess and modify tolerance chains and risk areas. The goal is to develop a feasible tolerance scheme for preassembly tests.

The next phase is the pilot production, where the build process and tolerance chains are verified using hardware setups. Measurement schemes in line with the gap configuration and risk areas are then developed. Subassemblies are checked separately using cubings and later assembled into complete vehicles. Based on the observed deviations due to part and subassembly faults or due to process faults, the build process is revised. The result is an optimized build of the vehicle. Before transferal to operations, the product goes through the prevolume production phase, which includes process capability tests and final adjustments. The launch phase follows and is dominated

by activities for variation source identification and reduction. During full production, maintenance and quality control tasks are prevalent.

As early as the concept phase, quality planning personnel are heavily involved in the development process. Thorough documentation of the results and intermediate approvals are maintained throughout the whole process. However, once the responsibility is transferred to the plant for series production, much of the process knowledge generated in the planning phases loses transparency. Final results, such as CMM measurement plans, are delivered to operation in more detail. But, a few of the operation staff gain an overview of the conducted fault root cause analyses, and the contributors to geometrical deviations.

Remark 2: Much of the information needed for online fault analysis during operation is generated during the design and planning phases.

3.3.2 Stamping operations and BIW

Sheet metal parts assembled in BIW are the product of the upstream stamping process. Stamping variation is mostly expressed either as within-run or as run-to-run variation.⁸ Other expressions for the variation include part-to-part variation, mean-bias deviation, and begin-end-of-run variation. The stamping operations in the production facility were not part of the field study. According to the experts in the production facility, limited success is reported in achieving low variation of stamped parts to design specifications. Recent research results supporting this opinion and describing solutions to overcoming the problem are found in ASP 2000a, CEGLAREK et al. 2001, HUANG & CEGLAREK 2002 and HOFFMANN et al. 2007.

Numerous factors affect the dimensional quality of the stamped parts. Steel grade and coating, part shape and size, die and press variables are among many factors that make the assignment of accurate design tolerances a tedious job. With such difficulties, some manufacturers operate presses outside statistical control. In a study by Auto/Steel Partnership⁹ on stamping process variation [ASP 2000a], none of the participating manufacturers could successfully maintain a C_{pk} of 1.33 on all part dimensions using the original specifications.¹⁰ This is particularly true for larger, less rigid body panels. Such parts are difficult to measure since fixtures often overconstrain the part and cause

⁸ Within-run refers to variations within the same batch of blanks, while run-to-run variation refers to the variation between different batches of blanks.

⁹ Further information on Auto/Steel Partnership is found at <www.a-sp.org>

¹⁰ A generally acknowledged standard value for minimum acceptable C_{pk} by automotive manufacturers

4 Overview of the proposed system

4.1 Proposed system structure

This chapter serves as an overview of the proposed solution and the system components that will be detailed afterwards. It also sheds light on the rationale of the system structure based on the results of the literature review and the field study.

The proposed system, as seen in Figure 4.1, consists of six components in three modules that accommodate the tasks of fault recognition, fault identification and decision on the recovery action (refer to Figure 1.6). The six components must guarantee proper representation of the knowledge needed to answer the six questions listed in the conclusion of the previous chapter (Section 3.5).

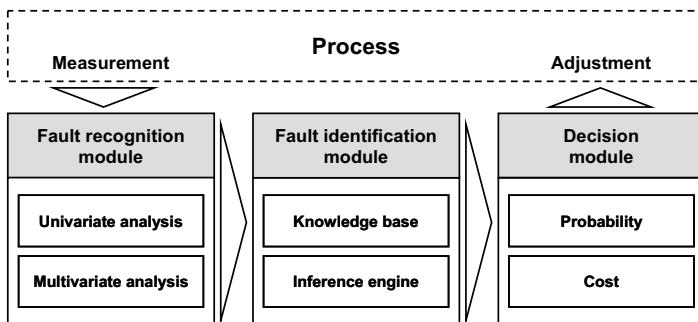


Figure 4.1: Components of the proposed system

The fault recognition module is responsible for process stability assessment. The goal is to enhance the early detection capability of existing monitoring systems w.r.t. univariate and multivariate abnormalities. It is proposed to use a neural network (NN) approach to build the module as discussed in Chapter 5.

The fault identification module (Chapter 6) consists of a knowledge base of the product faults and an inference engine that compares measured data with modeled fault cases and identifies the possible root cause. Thus, it is possible to shorten the fault diagnosis time, reduce costs and increase the reliability of the corrective action.

The decision module (Chapter 7) determines the statistical and economical validity of the recovery action at a certain moment. Given that the first two modules signaled and identified a fault, the two dedicated decision components determine whether a process adjustment should be conducted immediately or deferred to a later point. The a poste-

priori fault probability according to Bayes' Theorem is implemented as a measure for statistical validation. For process economy considerations, an approach based on the QLF is developed.

4.2 On the rationale of the proposed system structure

From a knowledge engineering viewpoint, the problem of fault analysis in BIW demands high experience and requires dealing with an abundance of data. Such a case can be best handled through hybrid knowledge representation techniques (Figure 4.2) [KASABOV 1998]. Hybrid methods promise a number of advantages in this regard such as combining heuristic and analytical knowledge, modularity, clear hierarchy and inherent stability. The proposed system structure can be seen to consist of a KBS core, a preprocessor for monitoring and a postprocessor for decision-making. It includes lower level elements for recognition, matching and classification as well as higher level elements for decision rules and strategic reasoning.

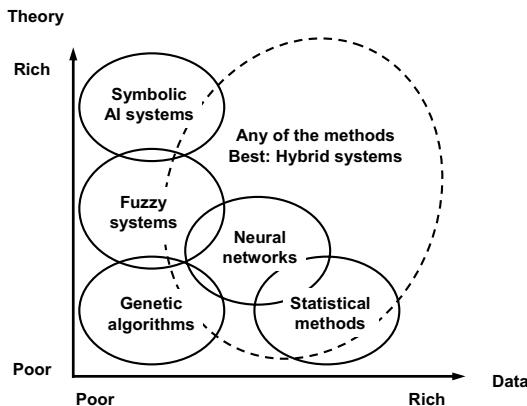


Figure 4.2: Usability of different methods of knowledge engineering and problem-solving depending on availability of data and expertise (theories) [KASABOV 1998]

For process monitoring, NN offer a number of advantages in statistical inference, such as the ability to model nonlinearities, minimal need of a priori knowledge or model assumptions, besides being adaptive, stable and robust in nature (refer to Section 2.3.4). Combined with 100% inspection, NN technology offers a competitive alternative to standard threshold-based alarm schemes. To overcome the disadvantages of NN as a black box approach, a multi-neural network (MNN) structure will be developed

5 Fault recognition module

5.1 Overview

The goal of this chapter is to develop a generic structure for monitoring multiple product quality characteristics. The module focuses on the early recognition of fault patterns in the product. The term *early* refers to the detection of faults while the process is still within the allowed tolerance field. A NN approach is followed for the fault recognition task. The monitoring strategy and the statistical data distribution model are addressed before presenting the module structure. The NN are iteratively optimized and test results are described. Finally, a summary and remarks on the practical implementation of the module are given. Figure 5.1 shows the two major components of the module.

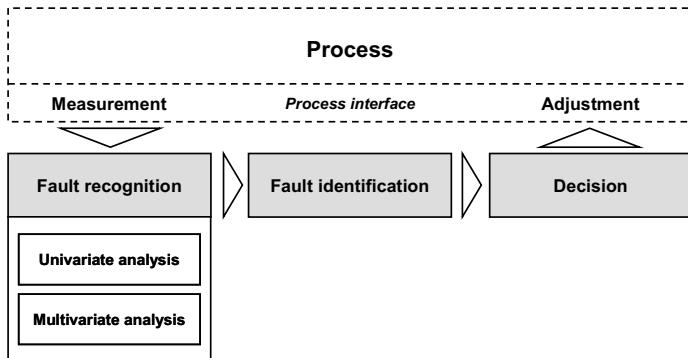


Figure 5.1: Components of the fault recognition module

5.2 Process considerations for network design and training

5.2.1 Monitoring strategy

The monitoring strategy applied in the studied production facility is similar to precontrol (refer to Section 2.3.2). The tolerance or alarm limit is set to 75% of the specification limit for all MP. This is generally true for the door assembly as well as for other BIW assemblies. The most common unnatural patterns according to the field study were mainly sudden shifts or trends in the process mean that may be accompanied by

increased variation. Other patterns, such as systematic or cyclic variation, were only occasionally observed. Therefore, the module considers monitoring shifts and trends of the quality characteristics only. Both small and large process mean deviations as well as correlation analysis have to be addressed.

In order to generalize the use of the module, absolute measurement values are avoided in the training process. The NN training data depends on the standard deviation (σ) of the process as a measure of process stability. The amount of deviation from the desired target value is expressed in units of σ . Three categories of deviation are defined as follows: small ($\leq 1\sigma$), moderate ($>1\sigma$ and $\leq 2\sigma$) and large ($>2\sigma$). Consequently, a large shift is one where the process mean moves suddenly beyond the 2σ limit. Similarly, a large trend is a trend that moves the process more than 2σ away from the desired target value within a defined window. According to this definition, a process with $C_{pk} \geq 1.33$ that exhibits a small mean shift still lies within the tolerance boundaries. Consequently, if the recognition module is sensitive to deviations less than 1σ , fault detection takes place before the product is rejected, which is the case with the door assembly process.

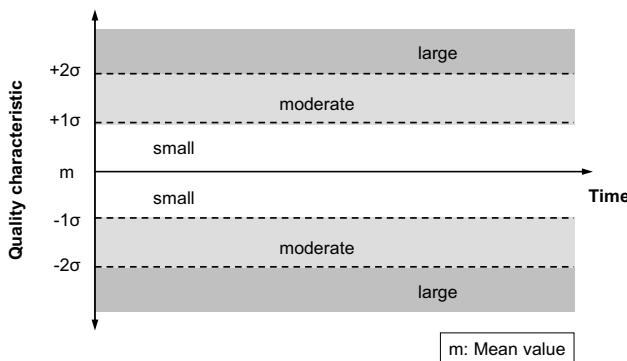


Figure 5.2: Deviation classes w.r.t. standard deviation

5.2.2 Statistical distribution model of monitored characteristics

To generate the NN training data, it is necessary to gain knowledge of the statistical distribution model of the monitored characteristics. For this purpose, process data was tested¹⁵ for their actual distribution models and for normality. Three different sample sizes were chosen to represent long and short process sequences. Long sequences had

¹⁵ Tests were conducted using the software packages QS-Stat and Matlab.

a sample size of 1000. For short sequences, sample sizes of 100 and 50 were tested. The longer sequence gives a more true distribution of the considered characteristic. The smallest sample size was chosen to represent the typical window size for short-term process monitoring. The behavior of such small sample sizes is interesting for network training since a smaller window size leads to quicker fault recognition. The fact remains, however, that smaller sample sizes are associated with greater uncertainty of the distribution model.

In the conducted tests, the same distribution model for each quality characteristic was obtained regardless of the sample size. The distributions varied between Weibull, mixed and normal distributions. Two normality tests were applied next. The Shapiro-Wilk test calculates a statistic that tests whether a random sample comes from a normal distribution. The higher the value of the test statistic, the closer the expected distribution is to normality. The test performs very well in comparison studies with other goodness-of-fit tests¹⁶. It is particularly efficient in checking the tail regions of the distributions, which are of special interest in quality applications [DIETRICH & SCHULZE 1999, FUKUNAGA 1990, MONTGOMERY 2001].

The second test is the Lilliefors test or the Lilliefors modification of the Kolmogorov-Smirnov test. The Kolmogorov-Smirnov test and its Lilliefors modification are sensitive to deviations in the midrange, which are not usually the kinds of deviations that lead to inference problems. The Lilliefors test evaluates the hypothesis that a data sequence has a normal distribution with unspecified mean and variance, against the alternative that it does not have a normal distribution [FUKUNAGA 1990, MONTGOMERY 2001].

A confidence level of 5% was implemented for both tests. Random sequences were obtained from the investigated production line at periods where the process mean was stable. The fifteen quality characteristics (Figure 3.5) met the normality requirements of both tests for 100% of the tested sequences at sample sizes n=100 and n=50. For a sample size of n=1000, a minor fraction of the sequences failed the normality tests. Table 5.1 gives an overview of the results.

Similar studies show that the assumption of normality is a valid approximation in geometrical tolerance chains. MANNEWITZ 2004 stated that for a four-element linear tolerance chain and more than fifty samples, a normal distribution can be assumed with sufficient accuracy. Most tolerance chains in the automotive body fulfill these conditions. In a study on quality cost estimation, GUH 2002a and GUH 2002b report that if the process is performing well, data non-normality affects the recognition very slightly. WHEELER 1995 and HOERL & PALM 1992 take the same position and regard the assumption of independence and normality as a welcome generalization in industrial practices. ZORRIASSATINE et al. 2005 argue that, even with expert knowledge of a

¹⁶ Goodness-of-fit tests are statistical tests of the validity of a certain hypothesis without the specification of an alternative hypothesis.

system, it can be difficult to predict how distribution properties and correlations will change when abnormal states start to occur. Based on the presented test results and relevant literature, the independence and normal distribution of the training and test data will be assumed.

Table 5.1: Percentage success of normality tests

Sample size	Shapiro-Wilk	Lilliefors	Both tests
50	100%	100%	100%
100	100%	100%	100%
1000	95%	99%	95%

5.2.3 Error type I and error type II

A well designed monitoring technique is one that reconciles effectively between error type I and error type II. Error type I refers to identifying in-specification products as defects, i. e. false rejection, while error type II refers to defects being identified as in-specification, i. e. false acceptance. The errors type I and type II are also known as the false alarm rate and the escape rate, respectively. The training process will attempt to reduce these errors to a minimum.

Another quantitative measure of this problem is the average run length (ARL). The ARL is a widely accepted measure used to evaluate and compare monitoring methods. Any sequence of samples that leads to an out-of-control signal is called a *run*. The ARL is defined as the expected number of samples taken until an out-of-control signal is issued [DIETRICH & SCHULZE 1999, KUME 1985]. The NN will be trained to generate signals as quickly as possible if the production process is out-of-control (ideally $ARL=1$) and as late as possible (ideally $ARL=\infty$), if the production process is in-control.

5.2.4 Evaluation criterion

To evaluate the classification capability of the module components, a classification rate is defined as

$$\text{Classification rate} = \frac{\text{Number of correctly recognized patterns} \cdot 100}{\text{Total number of patterns}} \% \quad (5.1)$$

The classification rate depends on the choice of a suitable numerical truth value or a threshold. When the output of the NN corresponding to a certain unnatural pattern exceeds the assigned truth value, the pattern is assumed to exist and an alarm signal is

triggered. Thus, the truth value represents a balance between error type I and error type II.

5.3 Module structure

The proposed module structure shown in Figure 5.3 resulted from preliminary trials to fulfill the process requirements discussed in Section 5.2. The module is designed to recognize unnatural patterns in univariate data as well as correlations in bivariate manner in two separate stages. Each of the shaded blocks in Figure 5.3 represents a single NN with a reference index. For example, NN-123 refers to network 3 in step 2 of stage 1. Measurement data from all monitored quality characteristics is fed sequentially to the module using a multiplexer function. The measured quality characteristics represent the input to the module. The output of the module includes an assessment of the stability of each measured quality characteristic (univariate) as well as the identification of correlations between the measured characteristics (multivariate).

The first stage of the system is a two-step classifier that assigns the input measurement data of any arbitrary quality characteristic into one of five categories. The five categories are normal behavior, upward shift, downward shift, upward trend and downward trend. This is repeated for all monitored characteristics using the same network system. The first step of the stage is a general-purpose network trained to recognize all five deviation patterns. It acts as the main fault pattern classifier. A second classification step consists of five special-purpose networks corresponding to the considered deviation patterns. The networks of the second step have a two-fold purpose. Firstly, they retest the measurement data for the existence of the unnatural pattern, thus improving the classification accuracy. Secondly, the output values of NN-121 to NN-125 are indicators of the deviation magnitudes.

The second stage is a correlation observer that implements a novel monitoring concept. The results of stage one, and not the original measured data, are compared in bivariate manner to detect pattern similarities. The two NN of the second stage categorize the correlation patterns between the measured product characteristics into five different correlation classes to construct a correlation matrix: weak positive, strong positive, weak negative, strong negative and no correlation. In this way, unnatural behavior in subsets of the monitored characteristics can be readily detected. This is advantageous in contrast to many multivariate control charts, where the evaluation is based on an overall statistic [NIAKI & ABBASI 2005]. This concept also offers beneficial perspectives in dealing with nonlinearly correlated data sequences.

The proposed structure is a MNN with serial and parallel processing. The use of MNN architectures, in contrast to a single network, is the better approach for achieving more intelligent behavior [MADANI 1999]. MNN are characterized by enhanced overall training efficiency and superior generalization. For example, if only one network is

6 Fault identification module

6.1 Overview and module structure

The purpose of the fault identification module is to identify possible fault root causes through comparing measured process data with stored knowledge or fault patterns. Fault identification is triggered when the fault recognition module signals instabilities in the production process. Two major aspects of the KBS architecture will be handled in this chapter: the development of a knowledge base and the design of an inference engine. Both components make up the fault identification module (Figure 6.1).

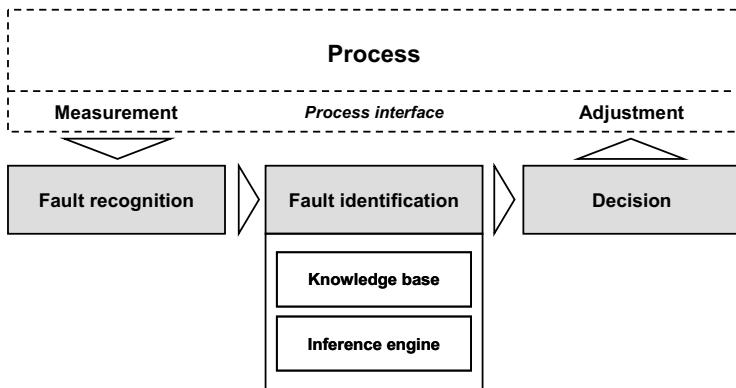


Figure 6.1: Components of the fault identification module

Knowledge representation formalizes and organizes available knowledge. One widely used technique is the production rule, which consists of an IF part known as the premise and a THEN part known as the consequent. The IF part lists a set of conditions in a given logical combination. If the premise of the rule is satisfied, the rule is said to be triggered and the consequent is executed. KBS whose knowledge is represented in rule form are called rule-based systems.

In the knowledge acquisition phase, a combination of simulation results and experience guided principles are implemented to derive the rule base. The inference engine applies fuzzy set theory to trigger consequences or actions according to the input data and the rule base structure. Fuzzy set representation is chosen to accommodate uncertainty, partial matching and input data noise. Figure 6.2 shows relevant tasks of the KBS that will be discussed next. The chapter concludes with a summary of the main results and a note on practical implementation.

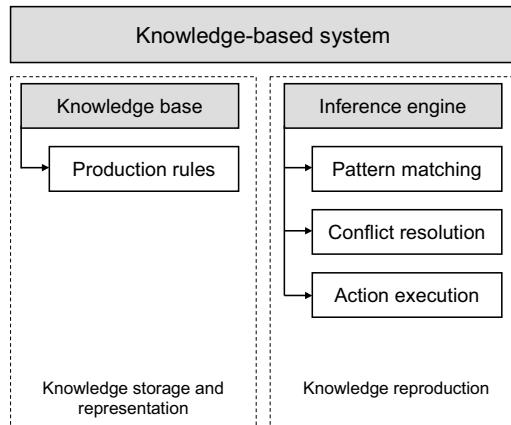


Figure 6.2: Tasks of the fault identification module in a KBS context

6.2 Knowledge acquisition

6.2.1 Procedure

The knowledge acquisition for BIW fault identification is conducted through general-purpose as well as case-specific tools that are implemented in BIW assembly design and operation phases. Using the door assembly as an example, factors affecting the dimensional integrity of the BIW product are included in the knowledge base. Figure 6.3 gives an overview of the used methods and tools.

6.2.2 General-purpose tools

Interviews, experience and documentation

In the course of the field study, several interviews and meetings were conducted with the responsible personnel in order to generate the rule base. The interviews had mostly a one-on-one character. However, in regular group meetings, one-on-many interviews were conducted as well. The interviews followed the basic semi-structured scheme [GUBRIUM & HOLSTEIN 2001], i. e. only guidelines for the discussion were prepared. Thus, the interviewee had the opportunity to express personal opinions and relate to

Knowledge acquisition tools			
General-purpose tools	Experience 	Interviews 	Documentation 
	Process analysis (P-FMEA) 	Fault analysis (FTA/ETA) 	Previous fault data 
Case-specific tools	CAD/part characteristics 	Fixtures/tools characteristics 	Mathematical formulation $\begin{aligned} X &= AX + BU \\ Y &= CX + DU \end{aligned}$
	Meshing 	FEA/simulation 	Tolerance analysis 

Figure 6.3: Implemented knowledge acquisition tools

similar experience where appropriate. This process extended for a year and was conducted on-site. An additional source for general rules was found in pertaining literature. Several authors addressed fine details and best-practices for modeling BIW assembly [CEGLAREK 1998, MERKLEY 1998, ADCATS 1999, HUANG et al. 2000, CEGLAREK et al. 2001, CAMELIO et al. 2003, DING et al. 2004, HUANG & SHI 2004, DING et al. 2005].

Systematic analysis of available fault reports

The analysis of previous fault cases had a two-fold purpose. The first is to obtain heuristic laws and guidelines for an extended Failure Mode and Effect Analysis (FMEA) [HERING et al. 1994, FRANKE 1989] that followed this stage. The second purpose was to formulate specific diagnostic rules for the studied production line. The relatively low granularity of the fault documentation (Table 6.1) added to the difficulty of the knowledge acquisition process.

Table 6.1: Typical granularity of BIW fault documentation (source: BMW AG)

Serial	Fault / Troubleshooting	Group	Part index	Operation index	Date
111	Weld Pts. 39423 and 39425 adjusted	TVL-E87	7069625	502A6243	15.4.2005
117	Handling Rob 4R1 substituted	TVL-E87	7069625	104A8	...
165	Side frame St. 3+7 adjusted	TVL-E87	7069625
191	Welding gun 3R1 gap adjusted	TVL-E87	7069625	502A6243	15.4.2005
231	Clamps St. 6 beveled				
:	:				
:	:				

FMEA

FMEA is a design-evaluation procedure used to identify potential failure modes and determine the effect of each on system performance [MOBLEY 1999]. This procedure formally documents standard practices, generates historical records and serves as a basis for future improvements. The FMEA procedure is a sequence of logical steps, starting with the analysis of lower-level subsystems or components. Two types of FMEA are highly relevant in manufacturing environments: design-FMEA and process-FMEA. The design-FMEA is implemented at an earlier stage than the process-FMEA. A process-FMEA examines the ways failures in manufacturing and assembly processes can affect the quality of a product or service.

FMEA comprises an analytical part and an experiential part. The analytical part determines the fault cause and the effect and relies mostly on qualitative analysis, simulations and process history. The experiential part determines the severity, risk and probability of a fault. A common method for collectively expressing these factors is the risk priority number (RPN) [FRANKE 1989, MÜLLER 2006]. The RPN is equal to the product of the three quantities S, fault severity, O, fault likelihood, and D, fault detectability, each estimated on a scale of ten (Equation 6.1).

$$RPN = S \cdot O \cdot D \quad (6.1)$$

Fault tree analysis/Event tree Analysis (FTA/ETA)

FTA is a top-down technique for assessing the way in which several failures can cause a single outcome or a system failure [BAYDAR & SAITOU 2001]. It is different from FMEA in that it is restricted to identifying system elements and events that lead to one particular undesired event. ETA is a forward technique, which may be used to examine the propagation of an initiating event with the presence of a number of other events, faults or conditions. FTA and ETA may be applied during the design stage of the assembly system in order to predict possible propagated failure situations [BAYDAR & SAITOU 2001]. Thus, they provide an objective basis for justifying system changes, performing trade-off studies and demonstrating compliance with safety and environment requirements. The analogy between the build sequence of the assembly process and the FTA is established in the next section and is used later to construct the rule hierarchy.

6.2.3 Case-specific tools

Hierarchical representation and diagnosability levels of the assembly process

An intuitive way to capture fault knowledge in assembly is to use a hierarchical representation of the assembly process. In many cases such a representation is equivalent to the assembly precedence graph. Using the door assembly as an example, the tree-shaped hierarchy in Figure 6.4 represents the build sequence. The hierarchical representation is helpful since it offers a unified framework for representing knowledge of different fault types: assembly fixture related, welding gun related, stamped part related and material handling related. Clusters of fault sources can be assigned to each assembly operation in any of the hierarchy levels. The hierarchy also reflects a possible structure of the rule base, where the rules can be categorized into levels analogous to those of the assembly sequence. For example, in Figure 6.4 the fault specification level generally increases moving top down.

Another critical notion in this context is that of diagnosability. If there is one and only one root cause for any given fault, the assembly is called fully diagnosable. Otherwise, the assembly is non-diagnosable [DANAI & CHIN 1991]. HU 1997 concludes that in order to achieve full diagnosability in serial assembly, the number of measurement points must be equal to or higher than the number of variation sources. He further states that parallel assemblies are not fully diagnosable no matter how many measurement points are used. One common practice is to differentiate between station-wise and element-wise diagnosability, as suggested by CARLSON & SÖDERBERG 2003 and DING et al. 2002c. An example in DING et al. 2002c shows that in-process sensing involving fewer measurement points is generally capable of higher diagnosability than EOL sensing in multistation manufacturing processes. The disadvantage, however, is the technical and economic feasibility of the additional measurement stations.

7 Decision module

7.1 Overview and module structure

The two previous modules handled the recognition of process instabilities and the investigation of their root causes. This information is indeed helpful to the quality practitioner, but not sufficient to make a decision whether to interrupt the process immediately or to allow further production. The module described in this chapter is, hence, labeled *decision*. The module proposes modeling the knowledge necessary for the latter task by means of two criteria. A statistical criterion examines the probability of the identified fault and a cost criterion estimates whether it is economical to continue production with the current deviation or to adjust the process (Figure 7.1). Only if both criteria are fulfilled, a recovery action is recommended by the diagnostic system. An illustration of the underlying theoretical background and implementation is included in the following sections. Practical examples demonstrating the validity of each component are presented. A discussion of the results concludes the chapter.

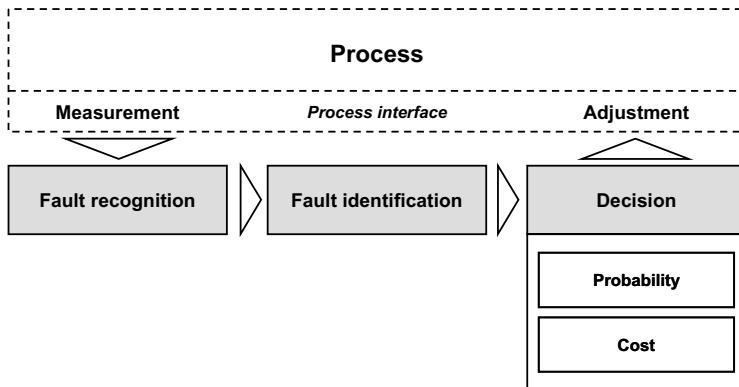


Figure 7.1: Components of the decision module

7.2 Fault probability criterion

7.2.1 Objective of fault probability consideration

If the value of a quality characteristic lies outside the allowed tolerance, the product is sorted out and either scrapped or reworked. A quality practitioner would not adjust the process then unless it is plausible to believe the fault is due to an assigned root cause and not just due to common cause variation or an outlier. Doing so, he measures the fault likelihood against a subjective threshold according to his experience. The fault probability criterion subjects the alarm signals from the fault recognition module to the same statistical analysis the human expert naturally conducts. The analysis is known in the literature as probabilistic reasoning [ROLSTON 1988, SACHS 2004]. Bayesian statistics stand as a widely accepted area in probabilistic reasoning for applications involving subjective postulations [GELMAN et al. 2004].

7.2.2 Bayes' Theorem

Bayes' Theorem implements a postulated a priori probability (subjective knowledge) of an event to infer the a posteriori probability of a dependant event [GELMAN et al. 2004, SACHS 2004]. Thus, the theorem makes use of available sample data (objective knowledge) to dynamically update the required conditional probability. Bayes' Theorem can be generally formulated as in Equation 7.1:

$$P(A_i | B_j) = \frac{P(B_j | A_i) P(A_i)}{\sum_i P(B_j | A_i) P(A_i)} \quad (7.1)$$

where

- | | |
|-------------------------------------|--|
| A _i | states of nature (possible, mutually exclusive, underlying events) |
| B _j | observable events (possible, mutually exclusive) |
| P(A _i) | a priori probabilities (unconditional probabilities also known as priors, i. e. before observing an event B _j) |
| P(B _j A _i) | likelihoods (conditional probabilities of each observable event given each state of nature) |
| P(A _i B _j) | a posteriori probabilities (i. e. after observing an event B _j , also known as posteriors) |
| $\sum_i P(B_j A_i) P(A_i)$ | marginal likelihood |

The marginal likelihood is a normalizing constant that ensures the posterior adds up to unity; it can be computed by summing up the numerator over all possible values of A. Accordingly, the posterior can be expressed in a simpler form as given by Equation 7.2:

$$\text{Posterior} = \frac{\text{Likelihood} * \text{Prior}}{\text{Marginal likelihood}} \quad (7.2)$$

Thus, the idea is to use the qualitative information of a process evaluator to form a prior distribution and the statistical information of an outcome evaluator to update the prior and obtain a posterior distribution [VANDE VATE 1982]. The Bayesian approach in statistics has many advantages, especially in sequential applications, such as production processes [SACHS et al. 1995]. One advantage is that it elicits the assumptions for the parameter of interest from the user by having him explicitly specify the prior distribution for the parameter. The value of probability is recalculated each time using the previous posterior as the new prior [GELMAN et al. 2004].

7.2.3 Implementation

Given that an alarm is signaled, the a posteriori probability of a fault occurring in the production line $P(F | A)$ is given by Equation 7.3.

$$P(F | A) = \frac{P(A | F) P(F)}{P(A | F) P(F) + P(A | \sim F) P(\sim F)} \quad (7.3)$$

where A is the event of an alarm signal being issued by the fault recognition module and F is the state that an assigned cause of the detected instability exists. $P(F | A)$ represents the required conditional probability of an unstable process. $\sim F$ is equivalent to $(1 - F)$ and is read “not F”.

$P(A | F)$ stands for the probability of recognizing a fault, given that it actually exists. Its value depends on the monitoring system characteristics and is obtained from the results of the fault recognition module. The average classification rate of the univariate stage was 93.2% (refer to Section 5.5.2). Accordingly, the value of $P(A | F)$ is 0.932. $P(A | \sim F)$ represents the probability of alarm, given a normally running process. In other words, it is equal to the type I error or the false alarm rate. Referring to the results of the first module, its value is 0.01.

The remaining critical parameter is the prior $P(F)$. The prior is a quantification of the expert knowledge on the probability that a certain fault occurs in a known setting. For instance, in the case of the door assembly, the field study showed that the assembly line is adjusted two to five times per week. Considering a five-day week and 700 doors per day, an overall prior fault probability of 0.001 can be safely assumed, with no regard to the nature of fault. Figure 7.2 shows the result of updating the a posteriori fault

probability given that successive alarm signals are issued. The figure suggests that one alarm signal is not a sufficient proof of process instability. However, if the alarm signal is repeated, the probability of a fault increases rapidly. Due to the relatively good fault recognition capabilities achieved in the fault recognition module, errors in predicting the prior $P(F)$ have negligible effect on the posterior. With lower values of priors, a higher number of alarm signals is needed to infer statistical plausibility of a recovery action.

The probability criterion is considered to be fulfilled if and only if a predefined threshold value is exceeded. A threshold value of 80% was suggested in the literature for this purpose [BAYDAR & SAITOU 2001]. The alarm signal counter may also consider a defined production interval and not only strictly successive alarm signals. For example, for $P(F)$ of 0.0001, three alarm signals are enough to exceed 80% posterior probability. The counter can be programmed in this case to consider three alarm signals within the last five measurement cycles as successive.

The a priori probability can be determined for each fault category separately, and thus attains much lower values than the overall prior. The values can be obtained from process history or through FMEA, tolerance analysis studies and simulations. The result is related to the estimated fault occurrence probability (O') in the adapted FMEA (refer to Section 6.2.4.3). If the effect of the prior is low, as in the case at hand, an exact estimation of the prior is not required. A further positive aspect of Bayes' Theorem is that the designer and the terminal decision maker may have different prior beliefs corresponding to their different experiential rules. The theorem gives space for such discrepancies and simply updates the available rule with the new postulation.

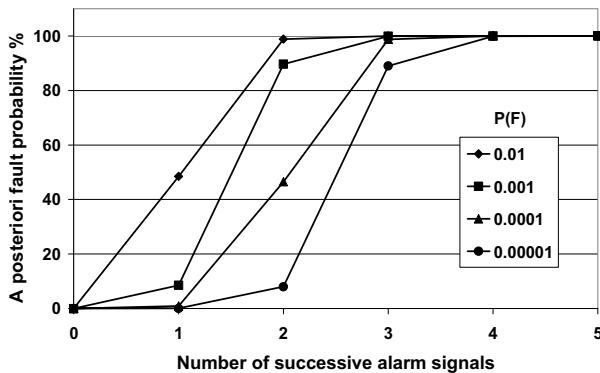


Figure 7.2: Relationship between postulated a priori probability and the calculated a posteriori of an arbitrary fault case

7.3 Recovery cost criterion

7.3.1 Objective of recovery cost consideration

Quality control schemes such as SPC do not include the production costs in the assessment of process stability [GUH & O'BRIEN 1999]. However, in many cases, the observed deterioration in product quality does not justify a corrective action. Given that a fault in the production process is identified, the quality engineer will still want to consult the process economics before deciding on a recovery action. The basic concept here is to compare the loss incurred due to a quality defect (magnitude and development of the deviation) to the cost of prevention or recovery at the instant of fault recognition. In batch production, the batch size would be a governing factor for the decision. Thus, the decision would be whether to immediately adjust the process or to complete the running batch and then adjust the process. Similarly, in series production, the maintenance schedule plays the same role.

The following section attempts to construct a theoretical model for the described trade-off. Using available knowledge and current process measurements, the model delivers a recommendation to the user. A quantification of the available quality margin for the latter case is also provided.

7.3.2 Theoretical background

7.3.2.1 Prevention-appraisal-failure (PAF) quality cost model

Quality related expenditures are probably the most controllable within the whole production budget [JURAN & GYRNA 1988] and pose a large savings potential if wisely allocated. Figure 7.3 gives a simplified overview of the elements of production costs [TAYLOR 1989]. Operating costs of quality are divided into prevention, appraisal and failure costs, also known as PAF. The three highlighted blocks in the diagram represent the two sides of the aforementioned trade-off: prevention and appraisal costs being on one side and internal failure costs being on the other. A notional representation of the three components was given in Figure 2.9. PAF costs do not include a quantification of quality deterioration. Taguchi's QLF presents a complementary approach covering the latter deficit.

8 Integration and reuse

8.1 Overview

The previous chapters addressed the components of a KBS for diagnosis and decision support in quality control activities. The components are contained in three modules, each having a specific functional area: recognition, identification and decision. This chapter describes the integration of these three modules into one homogeneous system as well as the integration of the diagnostic system with an existing measurement station. A prototype was realized for this purpose. An exemplary case summarizes the complete fault handling procedure. In addition, a reuse scenario is discussed to indicate the applicability of the proposed system to a diversity of production environments.

8.2 Experimental setup

The experimental setup shown in Figure 8.1 and Figure 8.2 was built to emulate a typical BIW measurement station and to test the developed software prototypes and their data interfaces. The communication medium was Ethernet and fiber-optic cables (FOC). A Perceptron® FlexiCam® sensor mounted on a KUKA® robot type KR-15/2 with a KRC control constitute the flexible measurement system. Part fixturing followed the 3-2-1 principle. The measurement reports are exported in XML-format²³ to the analysis PC through a local ftp-server²⁴ and read into the Matlab® environment.

8.3 Prototype of the integrated system

The developed diagnostic modules were cast into a software prototype programmed in Matlab®. Loose coupling [MEDSKER 1995] was implemented for data transfer between the modules. Loose coupling in its simplest form refers to communication through the export and import of separate data files. It decreases the complexity of the overall system and poses higher demands on the modularity of single system components. Figure 8.3 gives an overview of the information flow between the three modules.

²³ Extended mark-up language

²⁴ File transfer protocol

9 Impact on production performance – An assessment

9.1 Overview

This chapter presents a brief discussion of the technical and economic advantages, drawbacks and further potentials of the proposed diagnostic system. The technical assessment addresses common aspects of KBS implementation in production environments. The economic benefits are demonstrated in the terms of performance and profitability.

9.2 Technical assessment

The discussion in this section concentrates on four general assessment criteria of CAx applications in manufacturing that are often quoted in the literature and implemented in the industry: time, quality, reuse and synergy [EIGNER & STELZER 2001]. The criteria are addressed for the proposed system as compared to conventional inline measurement systems. In addition, user acceptance is briefly discussed as an important aspect relating to the organizational feasibility of the KBS approach [KINGSTON 2004]. An assessment of the specific technical details of the system modules was integrated in chapters 5, 6 and 7 and is not included in this section.

Time

MÜLLER 2006 estimates the time lost in maintenance, fault recovery and parameter adjustments in weld robots at 10% of the total production time. The figure indicates the potential for increasing the production efficiency if earlier fault recognition can be achieved. To the same end, the presence of a fault knowledge base, which provides the user with instructions for suitable countermeasures, is an additional time-saving factor.

On the contrary, the implementation of the system requires time for design and operation. In order to accurately quantify the required time, the knowledge base and parameter identification for cost and probability models must be integrated in a new vehicle launch project. However, the implementation time is expected to decrease with repeated implementation in compliance to common learning curves.

Quality

The focus of the thesis was to achieve stable quality levels through modeling the knowledge and the actions of the human expert. It was not attempted to achieve higher product quality in the sense of decreased tolerance fields or reactive mechanisms that affect the process. Thus, from a conservative viewpoint, the system does not contribute to higher product quality levels. Nevertheless, timely adjustment of the process leads

10 Summary and future research

Quality is a key element to long run success of engineering businesses [ONO & NEGORO 1992, KONDO 1995]. In many industries, 100% monitoring has become an established quality inspection strategy that saves valuable time when reacting to faults. It reduces risks and guarantees customer satisfaction by eliminating all defects. However, monitoring techniques are not capable of diagnosing faults or suggesting recovery actions. The latter aspect depends heavily on human experience in analyzing faults and conducting proper process adjustments in an economical way that contributes to improved profitability.

The outset of the thesis identified some disadvantages in current quality control practices in manufacturing facilities. A field study in the automotive industry showed that the analysis of quality defects and the elimination of their root causes is an underestimated task that exploits considerable resources. In many industrial applications, monitoring capabilities are restricted to the use of alarm thresholds. Also, the process of fault analysis is highly subjective as it depends on human expert judgment. In addition to the complex nature of quality problems in BIW production, organizational aspects such as staff rotations and sparing fault documentation add to the difficulty of the task. The problem, thus, boils down to the way process knowledge is implemented in production operations, especially when related to quality and fault troubleshooting issues.

Based on the results of a field study and a literature survey, the objective of the thesis was to investigate the need, the architecture and the development of a KBS for fault diagnosis and decision support in online quality control of manufacturing processes with the example of BIW assembly. The developed system targets the reduction of fault analysis time while increasing the certainty of the fault analysis. The fault knowledge base thus stores human expertise in quantifiable form and offers an approach to automated fault documentation. For this purpose, the proposed approach breaks down the diagnosis problem into three modules each performing two major tasks.

The fault recognition module examines the monitored quality characteristics for univariate and multivariate unnatural patterns such as mean shifts and trends or correlations. The NN-based module reached an overall univariate recognition certainty of 93.2 %. Error type I and type II were 1 % and 5.2 %, respectively. The multivariate analysis relies on the results of the univariate stage and uses several consecutive bivariate comparison steps to determine correlations in the quality characteristics. The introduced concept outperformed the conventional linear correlation coefficient and achieved an overall certainty of 94.3%. The concept represents a robust alternative that can be extended without further changes to include further patterns of linearly and nonlinearly correlating characteristics.

The fault recognition module addresses the localization of fault root causes upon the recognition of quality defects. The module contains a fault knowledge base, where the

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