QFD as a Tool to Improve Quality Control in a Complex Manufacturing Environment

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Abstract

The paper outlines a comprehensive three-step approach to the development of advanced strategies for quality control of a complex machining process. The research framework is a developed concept for Integrated Supervisory Process Control. The promising results obtained demonstrate a non-traditional approach to the deployment of quality and productivity requirements set by the system users, whereby the efficiency and systematization of the development of quality control strategies can be significantly improved.

Key Words: QFD, Quality Control, Integration.

1. Introduction

The growing complexity of manufacturing systems and produced parts together with new tools and work materials, requires that monitoring systems provide a reliable basis for decisions taken during the machining operations in terms of acquisition, evaluation, modelling and prediction of process data, (Dornfeld and De Vries., 1990), (Barschdorff and Monostori., 1991), (Monostori and Nacsa, 1991), (Malakooti and Zhou, 1992) and (Monostori, 1993), (Bäckström and Wiklund, 2000) and (Jantunem, 2002) The development in the field of sensor and computer technology have opened new possibilities in process monitoring and have dramatically increased the availability of machining process data. It is no longer a problem to acquire data, the problem is to reduce the data volume and to handle the acquired data in an adequate way.

A lot of research work and development efforts today are aimed at optimization of manufacturing systems performance when the resources needed should be minimized simultaneously. The complex manufacturing systems are becoming more sensitive to disturbances and are not robust enough to handle unpredictable behaviour, in contrast to "stand-alone-machines", manually operated fifty years ago. Consequently, availability and reliability of process data and the ability to handle information in real-time have become important features of manufacturing control system strategies. The cutting tool is associated with a great deal of uncertainty and can be discussed as an example of how to deal with data reliability in a general sense.

Improved performance of manufacturing systems has become a commonly accepted goal. Consequently, the need for real-time process data for monitoring and control has become obvious. The complexity of manufacturing systems and the trend towards low-volume manufacturing limit the feasibility of applying traditional methods for process monitoring, or more specifically, acquisition of machinability data and tool condition monitoring. Extensive time-consuming tests and one-variable-at-a-time experiments have been the approach to acquiring data and to developing process models in the past. The consequence has been poor cost- and resource-efficiency of the experimentation procedure and of modelling results. Machinability data and tool life relationships have been analysed in the same way. The problem of evaluating the tool life in non-constant machining conditions remains to be solved.

Insufficient time, a limited volume of data available for process model development and control, increased quality requirements and shorter series are situations when traditionally applied quality control (QC) methods do not work properly, e.g. (Wiklund, 1999), (Cai et.al, 1999), (Tang et.al., 2000) and (Bäckström and Wiklund, 2000). This means that the control of process performance needs to be moved into the machining process and thus monitoring of in-process variables instead of traditional post-process data, such as e.g. part dimension.

The situation and role of the machine operator have to be considered since much of modern manufacturing is still handled manually by operators and system managers. As regards machining-related activities, the operator has to handle much of the setting up for machining, running in of the NC-programs and monitoring of the cutting process. In a factory, the planning of the machining is mostly done at a central planning department. This results in the operator only getting an order from the planning people for the next job in the machine. This job order often contains a list of tools that should be used, specifications of the work piece and the corresponding NC-program. The operator is in this case not involved in the technological background of the NC-code and this can lead to insecurity and time- consuming work to assure the validity of the NC-program and machining conditions.

The nature of the machining process as a multiply dependent activity brings in many factors which determine the machining performance and results. Even if we know all the pre-determined factors by name and size such as: working material and characteristics, fixturing situation, tool type, tool geometry, tool material, tool condition, cutting speed, cutting feed, cutting depth, NC-program quality etc., they all bring disturbances and uncertainty to the machining process. For the above reasons a machining process will need a system which has the capability to adapt the process control and model development according to process requirements and uncertainty.

This situation puts, in its turn, high requirements on the development of reliable, flexible and efficient systems for process monitoring and control. Difficulties in selecting among a high number of sensors available, developing adequate and advanced control modules and integrating developed monitoring applications and modelling techniques, are examples of central activities that have to be incorporated and integrated in such a systems solution. Recently the concept of integrated supervisory process control (ISPC) was presented as a systems approach dealing with multi-purpose control requirements by utilising the individual advantages of several modelling techniques, see (Bäckström and Wiklund, 1998a) and (Bä ckström and Wiklund, 1999). The ISPC concept was based on an integration of a variety of existing modelling techniques with necessary application modules and was aimed at improving the utilisation of available sensor systems and the performance of today's monitoring and control systems.

In order to develop the ISPC research platform a number of linked activities should be completed, all related to the selection and design of system components. In this paper the principles of quality function deployment (QFD), see e.g. (Akao, 1990) and (Mazur, 1994), has been utilised in a three-step transformation process of pre-specified systems requirements down to the selection of sensors and design of modelling techniques and applications.

The aim of the QFD-study has been to systemise the design and selection of sensors and modelling approaches in order to improve the cost-efficiency of the developed research platform in terms of overall quality and productivity requirements and criteria's.

2. The Concept of Integrated Supervisory Process Control

The ISPC concept is divided into three hierarchic levels, Figure 1. At the supervisory level, the actual systems requirements and goals of the machining process are co-ordinated and synthesised. Thereafter, the fused performance profile constitutes the basis for selection of needed functionality modules that trigger the selection and set-up of needed models and sensors at the set-up level.

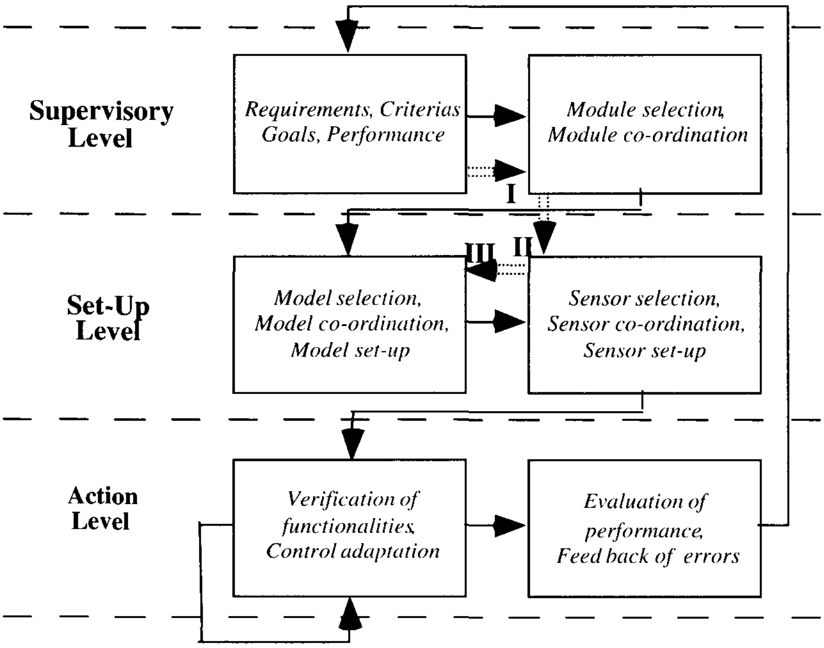

Figure 1. Different activity levels in the ISPC concept.

At the action level, the machining process is started and on-line data is starting to emerge. The decisions in the system have so far been based on accumulated knowledge and historical data. Verification is made as a safety precaution, first at the action level, to assure that the control actions carried out have the correct functionality.

The control of the machining process is adapted on the basis of the on-line signals and the previously established performance demands. At this level, the settings of model parameters are updated or altered but no changes to the model structure are allowed. Evaluation of the process performance is made continuously and any differences or errors are fed back to the supervisory level for eventual reconfiguration of the system.

The physical *ISPC* platform incorporates a five-axis Liechti Turbomill ST1200 machining centre, which represents the state of the art in machine tools, Figure 2. A prior research platform installation, see (Bäckström, 1996) and (Bäckström and Wiklund, 1998a), has given valuable experiences and know-how when dealing with the requirements, design and implementation of a new research environment. The working space and speed are defined of the axis configurations as:

X-axis: 1400 [mm], 30 [m/min], 2.3 [m/s^2]	Y-axis: 500 [mm], 30 [m/min], 4.0 [m/s^2]	Z-axis: 500 [mm], 30 [m/min], 6.0 [m/s^2]
A-axis: -90-45 [°], 5760 [°/min]	B-axis: -50-50 [°], 10080 [°/min]	Spindle: 24000 [rpm], 30 [kW]

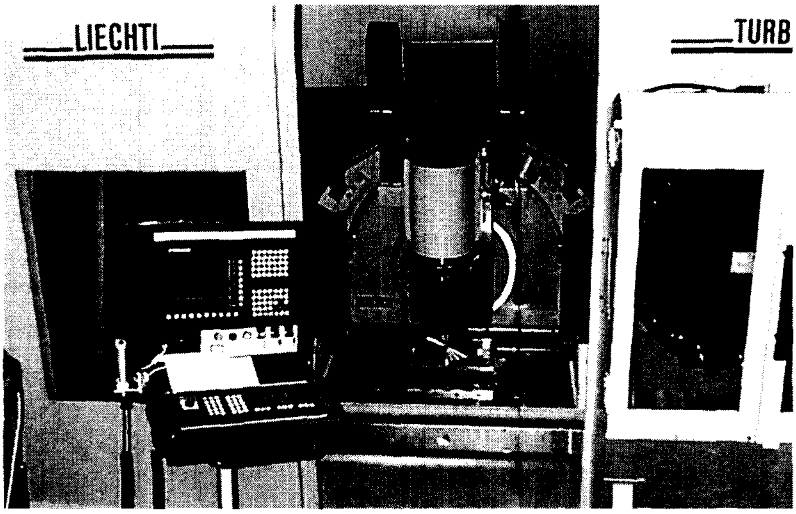

Figure 2. Liechti Turbomill ST1200 machining centre.

The control system is an Andron A 400 with the capability to perform spline interpolation. This, in combination with the digital Indramat drives and the SERCOS fibre optic servo coupling, renders the ability to perform motions with high speed and geometrical accuracy. In order to increase the available amount of process information an extensive sensor configuration is planned in the research platform (categorised as internal and external sensors) Figure 3. The internal information sources are originally fit in the machine and sensors denoted as external sensors are hardware sensors that have been retrofit to the machine.

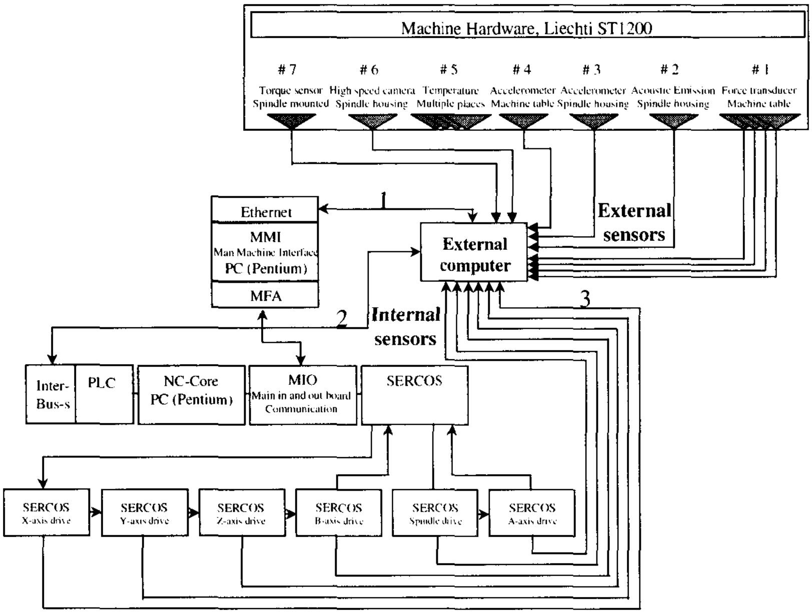

Figure 3. External and internal components in the research platform.

The internal information sources in Figure 3 are denoted 1-3, and constitute of: 1) Ethernet connection for NC-programs, tool pre-setting data, CAD-drawing etc.; 2) Interbus-S connection for PLC machine state register in- and output; 3) Digital drive connection for consumed power, axis position, torque, following error, axis speed and commanded position. Approximately 15 external sensors, such as force, acoustic emission, accelerometers, thermo elements and torque sensors have been discussed as possible sensors to be included in the platform.

3. The Deployment Process

QFD is a structured process that establishes customer's value using the voice of the customer (here systems requirements) and transforms that value to design, production, and supportability process characteristics. In this paper, the transformation is made in three design steps, from module design to model design. The result is a system engineering process that prioritises and links the product development process so that it ensures product quality as defined by the systems requirements. In Figure 4 a flow chart illustrates the different activities in the conducted study. Figure 5 illustrates the so-called planning matrix (also called House of Quality, HoQ)

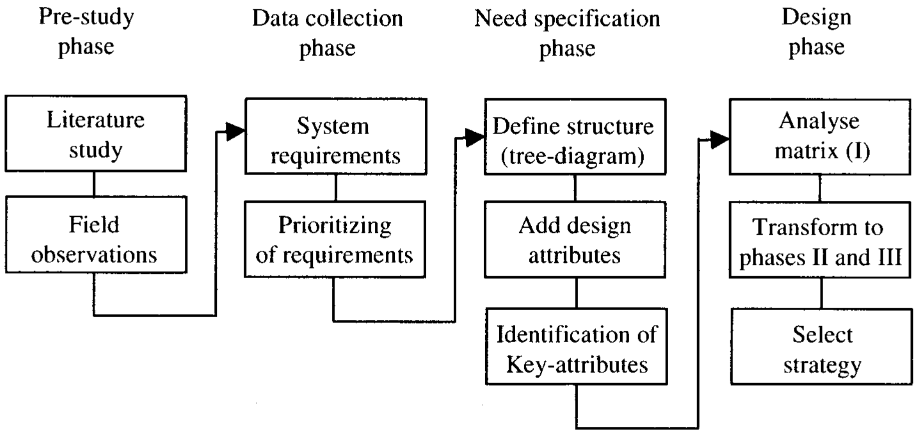

Figure 4. Activities in the study.

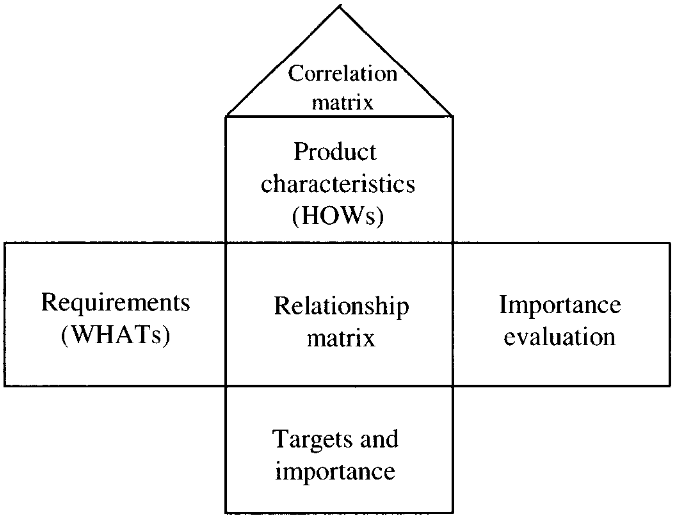

Figure 5. The planning matrix.

This process, based on the different phases of QFD, is aimed at transferring system requirements into system characteristics. The process follows the parts of the ISPC concept, Figure 1., and is divided into three different phases (I-III), see Figure 6.

In the first matrix (I) the system requirements are transferred to properties of system modules. In the next matrix (II) the system modules are transferred to the need of sensors and in the final matrix (III) the variety of process modelling techniques are designed. The first matrix (I) is illustrated in Figure 7 where the overall requirements on the ISPC system are specified.

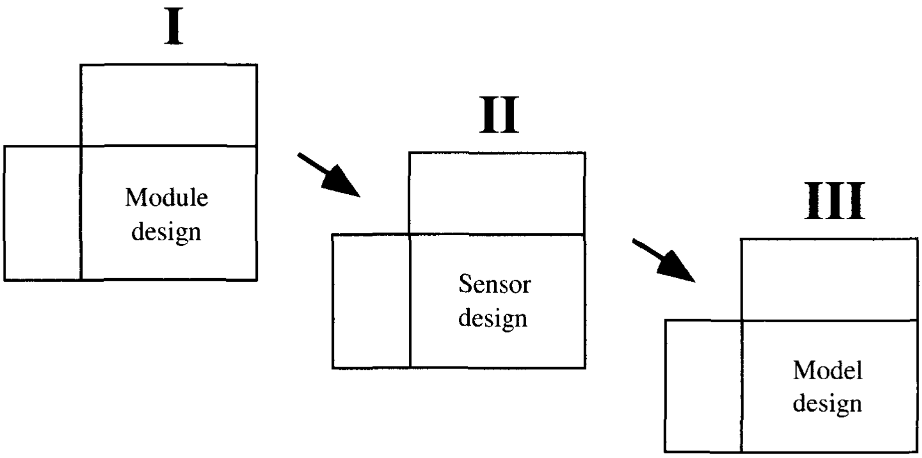

Figure 6. The deployment process.

Then, the relationships (correlations) between the requirements and the modules of interest are studied and marked with white, grey or black dots indicating the strength of relationship. A row with no black or grey dots indicates that there is no module that adequately handles the actual requirement and we therefore have to develop another module that satisfies the requirement. A column with no black or grey dots indicates that the actual module is redundant and may not be needed in the ISPC platform. For example, it is seen that the requirement "work piece protection" is satisfied in four or five of the modules while "high safety for the operator" is only satisfied in the "emergency stop"-module.

All of the dots in the different matrixes, Figure 7 have their own explanatory background and demand more space than available here to be fully described. However will some of the background and reasoning be outlined for the functionalities. Following the example of "high safety for the operator"- requirement and "emergency stop"-module into the second matrix (II), we can conclude that the sensors that are to be utilised to realise the functional module are primarily the cutting force, spindle power and torque.

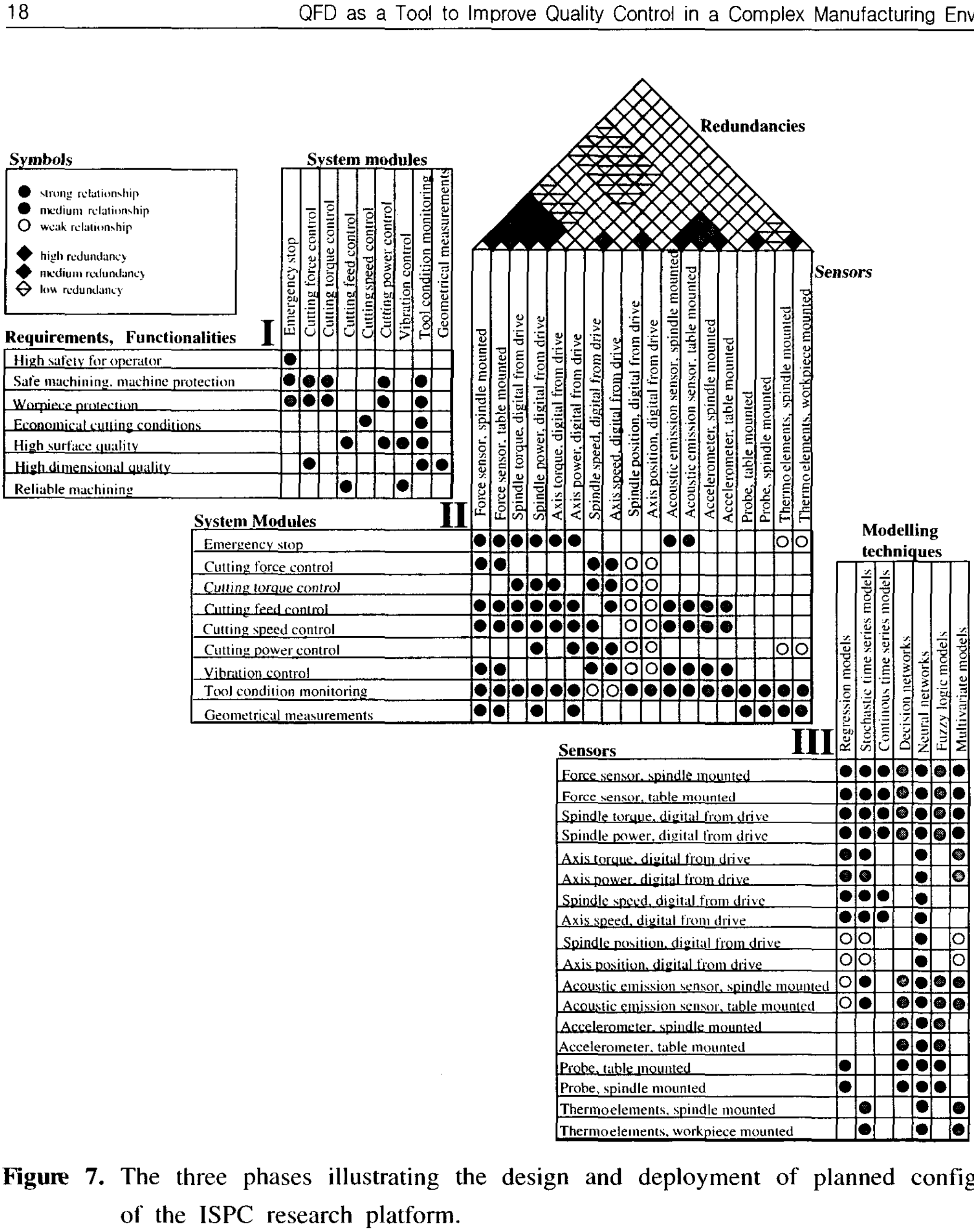

Figure 7. The three phases illustrating the design and deployment of planned configuration of the ISPC research platform.

Secondarily the axis power and torque should be used, and finally the thermo element sensors. Continuing this reasoning in matrix (III) the modelling techniques that are selected as most appropriate for the task are regression models, stochastic time series models and multivariate models. This is also possible to derive from matrix (III) by the strong correlations between the actual sensors and the modelling techniques. This exemplifies the deployment of system components originating from system requirements and resulting in suggestions of module, sensor and model design. The deployment technique also identifies the appearance of possible redundancies, which is illustrated at the top of matrix (II).

Examples of the background reasoning for the functionalities is as follows:

High safety for the operator: This is a basic requirement in machine systems when damage risks are obvious. The development towards higher cutting speeds and feed do also call upon a higher degree of active operator protection.

Emergency stop: This module is the only one that possibly could serve as an operators protection where in fact all moving parts in the machine have to be brought to a stand still as quick as possible.

Sensors: In this case do every sensor that could detect an overload or malfunction contribute in determining dangerous situations. Preferred are also sensors with a good resolution and sensitivity compared to the studied phenomena. Force sensors based on piezo-electric technique are good examples of fast and reliable sensor of dynamic forces and dangerous overloads can be detected and constitute an basis for machine shut down. Torque and power sensors are of value to detect abnormal levels in tooling, workpiece and machine elements. Acoustic emission sensors are favourable in detecting insert chipping and early warning in tool failure. Temperature sensors can assist in giving machine element status.

Modelling: Basic requirement on the models are that they have to be fast in order to prevent operator accidents. The level of sophistication do not have to be high, mainly could simple threshold values be used to determine the action.

In the ISPC environment, several modeling techniques are developed and adapted for tool condition monitoring, see Figure 8. The different techniques, such as ANN and a number of statistical methods, are in practice associated with both advantages and drawbacks and are therefore handled by the principles of active data acquisition (ADA), see (Bäckström and Wiklund, 1998b) and (Wiklund, 1999). Further, the methods are linked parts of different quality control (QC) activities where the developed methods and applications are integrated and post-process quality control is applied only as complement and for reference measurements.

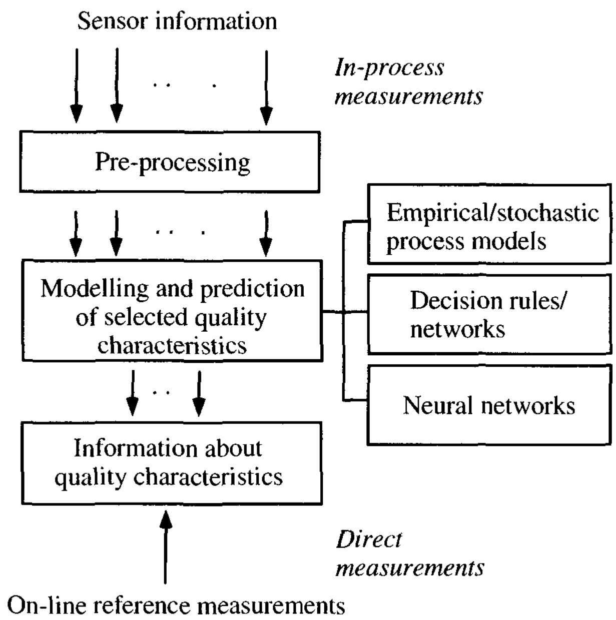

Figure 8. Principles of real-time quality control.

All QC activities are supervised and fed with information from the ADA system. The ambition has been to combine the advantages of different model-building methods and to facilitate increased process knowledge. Methods that adequately describe and predict the process and also increase process knowledge are given priority. If these fail to describe the actual process behaviour in an adequate way, priority is given to more computer intensive methods such as fuzzy logic and neural nets.

4. Conclusions

The ISPC concept and the research platform for its implementation are outlined. A "state of the art" high speed five axis machining centre equipped with an extensive sensor configuration constitutes the research equipment necessary for practical implementation.

In the paper, the principles of QFD have been utilised to develop the configuration of the ISPC concept and the system design is characterised by means of the deployment process. The deployment process includes the design and selection of modules, sensors and models, all derived from supervisory functional requirements of the system. The set-up of the system has been systemised and possible redundancies have been identified. The individual advantages of different sensors and modelling techniques are indicated and derived in relation to pre-determined requirements on productivity and product quality.

The total environment affecting the machining results are vast and relates to each other in complex ways and the QFD technique shows promising features in categorising and relating all necessary aspects in an integrated system.

The conducted deployment process indicate that the pre-specified requirements on the ISPC system, in terms of economy, quality and productivity expressed implicitly, are possible to satisfy by the developed system design and configuration. The promising results obtained demonstrate a non-traditional approach to the deployment of quality and productivity requirements set by the system users, whereby the efficiency and systematization of the development of process control strategies can be significantly improved.

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