

45<sup>th</sup> CIRP Conference on Manufacturing Systems 2012

## Social Aspects of Process Monitoring in Manufacturing Systems

K. Martinsen<sup>a,b,\*</sup>, H. Holtskog<sup>a</sup>, C.E. Larsson<sup>a,c</sup>

<sup>a</sup>Gjøvik University College Dept. of Technology and Management, Teknologiv 22, 2815 Gjøvik, Norway

<sup>b</sup>SINTEF Raufoss Manufacturing, PB 163, 2831 Raufoss, Norway

<sup>c</sup>Norwegian University of Science and Technology Dept. of Production and Quality and Engineering, 7491 Trondheim, Norway

\* Corresponding author. Tel.: +47 995 21 849; fax: +0-000-000-0000 .E-mail address: [Kristian.martinsen@hig.no](mailto:Kristian.martinsen@hig.no)

### Abstract

Many systems for process monitoring using in-process sensor measuring rely on human interpretation and reaction in order to control the process and achieve the desired effect from the monitoring. This paper reports from two industrial cases of process monitoring. The first case from piezo-electric force sensors tool condition monitoring on a machine tool, the other case a system for OEE monitoring. Results show that social-technical systems (STS) design and how humans learn are important elements on order to utilize the capabilities for the monitoring system.

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*Keywords:* Monitoring; Control; Social Aspects; Knowledge Creation

### 1. Introduction

Industrial use of process monitoring and control systems (PMC) utilizing in-process sensors has increased lately. The objectives are usually to enhance productivity through decreased downtime and minimized quality losses as well as decreased tooling and consumables costs [1], [2]. PMC include in many cases a human interpretation and analysis of measurement data and decision making on control actions, unless there is an automated regulatory system. Based on the information from the monitoring system, combined with other information about the process and a suitable process control strategy, decisions on necessary control actions are generated. The strategy itself depends on the knowledge and experience of operators and engineers. There have been developed decision-making support systems using cognitive computing methods to aid the operators [1]. The human factor is, however, still an important factor in the control loop and to achieve productivity gain from the monitoring system. Moreover, a PMC system can be a source for learning and information exchange. Some authors such as Zhao

and Xu [3] suggest that for a cognitive manufacturing system, process monitoring data can be used as feedback all the way to product development.

#### 1.1. Sensor measurements and control loop

The measurements in PMC system can be absolute and direct or indirect and relative. Statistical Process Control (SPC) is an example of a direct and absolute measurement of a quality output, with a measurement of direct quality features such as geometrical feature on a work piece. A typical example of an indirect and relative measurement is the use of piezo-electric force (strain) sensors [1-2, 4] for tool condition monitoring (TCM) of turning processes. The control strategy is to set control limits in advance and measurements outside the control limits will lead to actions such as rejection of parts or halting the process and give an alarm to the operator. In most cases there is a lack of mathematical models connecting the measured force to the actual process performance. The measurements are indirect or relative to the actual output of the process. The operators are typically using a trial and error approach in order to find the best-suited control limits with a minimum of Type I

(false alarm) and Type II errors (not discover failures harmful to quality or productivity) [5]. Too much Type I and/or Type II errors might lead to operators losing faith in the monitoring system. There are naturally a larger occurrence of Type I and Type II errors when the system is newly introduced and the control limits are still to be optimized. This might be a problem if there is a need to justify the investment and to convince operators and others about the usefulness of the monitoring system when the system is new.

Another dimension is the time span of the control loop. In the case where there are 100% in-process measurements and set control limits the control loop is more or less momentary. An out-of-limits measurement will typically cause an initial automatic control action; such as rejection of the part and/or halting the process. The operator needs then to make a diagnosis of the cause of the out-of-control measurement and choose the

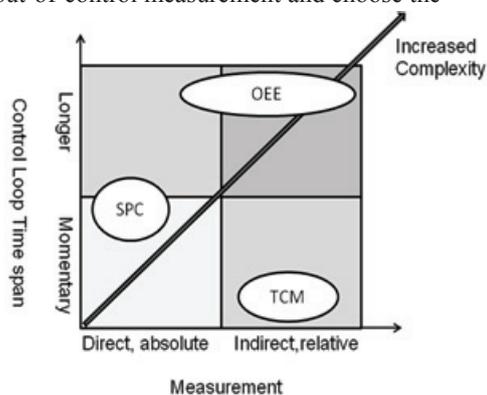


Fig. 1. Classification of Process Monitoring and Control systems

correct actions before starting the process again. SPC would be a more long term control loop since it is based on samples taken out at given time intervals, and since the monitoring of trends is an important part of the control strategy.

Similar to SPC and TCM, one can argue that also automated monitoring of Overall Equipment Effectiveness [6,7] using in-process sensor systems have a control loop, but with an even longer time span. Control actions here would be the actions of operators, maintenance and others to improve and sustain a high OEE.

There are, however, cases where the distinction is not that clear. If a PMC is, for example monitoring a temperature on an heat treatment oven for annealing of aluminium, there is not a direct measurement but still a well-known effect on material properties. The control action might be momentary when the temperature is out of limits, though also more long term in the case of looking at trends and fluctuations over a longer time.

Figure 1 is showing the two dimensions with an indication of the examples described. The upper left quadrant in the figure the monitoring system are typically more complex and more dependent be on human decision making. It is quite common with a combination of the different type of process controls where SPC, OEE and in-process monitoring co-exist at different levels and even being connected in a superior plant monitoring system.

### 1.2. From Aristotle to modern knowledge creation

Our modern understanding of knowledge creation can be seen as a combination between Ryle's knowing how / knowing that [8], and Polanyi's tacit and explicit knowledge [9, 10] and this is the foundation for Nonaka's theory of knowledge creation [11, 12]. Nonaka do not describe the original knowledge creation source, and what type of knowledge is created.

Lately there have been efforts to look back to the ancient philosophers thinking to gain more insight into knowledge types [13, 14]. This thinking is based on two dimensions; direction of interest (broadly practical or broadly theoretical) and from outside and above or from within and below [15]. This paper investigate the action concerned from within and below, and at the same time has a direction of interest going from the practical to more theoretical in order to trigger critical dialogue concerning human aspects of process monitoring and control.

As indicated Ueda et al. article [16] philosophy form the foundation for understanding social phenomena, following this reasoning knowledge types as described in philosophy, can give better understanding of knowledge when it is created. And it enables us have increased focus on the human side of the value creation process, as described in Ueda.

## 2. Human Aspects of PMC

All manufacturing systems have the characteristics of socio-technical systems with relationships between machines, between people and between machines and people. Only by jointly optimizing both the technical and the social systems can the best match be achieved [17]. Industrial learning and training is one of the key factors to achieve this. In this respect the socio-technical perspective is not only important while designing a system, but equally important in establishing a platform for learning and knowledge creation.

A process monitoring system can be one of the central aspects in the knowledge creation and inter-dependency between the technical and the social systems. Mavrikios et al [18] describes the Teaching Factory concept for integrating a manufacturing factory

environment with the classroom. The general idea originates largely from medical science and teaching hospitals where the learning and working environments are integrated and where realistic and relevant learning experiences arise. This could be the case for both continuous learning of operators and engineers as well as students at the university or as the authors write: (quote):

- Engineering activities and hands-on practice under industrial conditions for university students
- Second point
- Take-up of research results and industrial learning activities for engineers and blue-collar workers

Mavrikios et al identifies a set of learning methods such as: Discussions/Debates, Presentations, Tutorials, Case studies, Demonstrations, Simulations and Role plays. All of these methods can in a teaching factory setting benefit from a process monitoring system with access to instant feed-back as well as a library of monitoring data. The processes and their monitoring systems acts as a real life “living lab” for Role plays, demonstrations and Case studies and the monitoring data can be fed into simulations software for realistic modelling.

Process monitoring systems are, however, a potential source for creation of new knowledge and both process and product innovations. The “knowledge triangle” as shown is by the European commission used on macro level for strongly interdependent drivers of the knowledge-based society [19]. It can be argued that this is also the case on a micro level within a manufacturing plant and within a manufacturing team responsible for a manufacturing process.

Hence, learning becomes a feature of practice, which might be present in all sorts of activities, not just in clear cases of training and apprenticeship. If an operator is to act as a learner, system developer and optimizer this requires that certain conditions are fulfilled. Firstly, the operator must be knowledgeable about the process and how different variables within the process interact, both in a practical and an abstract theoretical sense. Secondly, being able to act heedfully in terms of assessing necessary actions requires experience.

The ability through interaction with the process to decide that a deviation is caused by e.g. an outworn tool and that the tool needs to be replaced which is a single loop learning process where the process is viewed to be correct is one outcome. The second outcome is to move into a process of double loop learning caused by a failure or deviation to perceive that the process in itself is incorrect and decide that the process needs to be changed. With the view to the classification of monitoring systems as shown in Figure 1, the long term control loop are typically double loop learning, as presented in Figure 2. While the ability to change a worn-out cutting tool at the correct time is single loop,

the ability to analyze the process outputs and monitoring measurements over time to improve the process (for example changing process parameters) would be double loop.

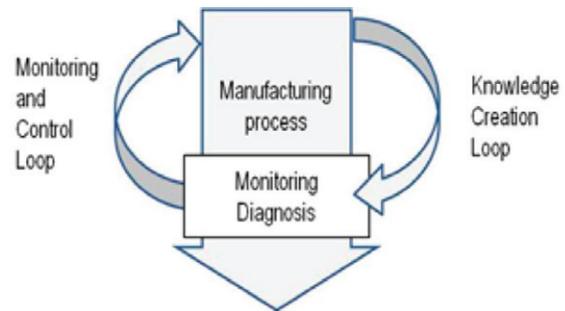


Fig. 2. Control Loop and Knowledge creation loop

### 2.1. Knowledge forms

Understanding how humans know is something that has occupied researchers for years. The social or human side is complex and advanced; to fully understand how operators learn and develop new knowledge a detailed understanding is needed. Polanyi once wrote; “we know more than we can tell” [20]. Tacit knowledge can be the hand and feel sensation, eyes and hand combination or feeling of a craftsman [21]. Ryle uses the distinction between ‘knowing what’ and ‘knowing how’ [22, 23]. ‘Knowing what’ is more theoretical and conscious knowledge that can be articulated. A person, with this type of knowledge, can serve as a teacher or researcher. ‘Knowing how’, on the other hand, is more in line with Sennett’s eyes and hand combination of the craftsman. It will have a tendency to be more unarticulated knowledge.

Aristotle called theoretical knowledge *theôrêsis* or *theôria* [24]. *Theôrêsis* is a “spectator speculation” where the aim is to achieve true statements, explanations and predictions by processing observation and speculation and the application of- or reduction to known concepts. *Theôria*, on the other hand, stands for insight, where the aim is perfection or excellence. While *theôrêsis* is external to the knower, the *theôria* is internal. To describe practical knowledge, however, an entirely different component is required. Knowledge as *empeiria*, is formed through practical training and experience from influencing and manipulating. Aristotle divided this type of knowledge (when he talked about production or change in external objects) into *téchne* (articulated variant) and *poiêsis* (unarticulated). A person, who wants to change or manipulate an external object, like a manufacturing process, does this by manipulation of- or intervening with variables in order to get the right result. *Téchne* and *poiêsis* is located within

the knower and has to be transformed into *theôrêsis* or *theôria* in order to be learn as a more general and common knowledge that is not situated to a specific context.

## 2.2. Social conditions for learning

Mastering different forms of knowledge goes in phases, from novice to expert or master [25, 26, 27]. Three phases (a simplification of Chi and Dreyfus et al.) can be novice, competent, and expert [28]. While the training of novices typically is a mix of apprenticeship and formal education, the progress of experts is a more informal social process. Situated learning as a social process that takes place in a participative framework based on interaction and co-participation, becomes a feature of practice which might be present in all sorts of activities not just in clear cases of studying, training and apprenticeship [29]. Wenger [29] argued for four social components of learning; becoming (identity), experience (meaning), doing (practice), and belonging (community), making up a Community of Practice (CoP). All four components have significant impact on the social environment for a novice to become an expert motivated by the growing use of practice. This process satisfies the basic needs of the individual for meaning and social belonging where the expert can act as mentors that guide and teach novice as an apprentice.

## 3. Case 1: Force sensor tool condition monitoring on multispindle lathes

To illustrate the use of socio-technical systems design, the authors have followed two different industry cases with experiences from implantation and use of monitoring and control systems. The 1st case is a force sensor tool condition monitoring on multispindle lathes at Kongsberg Automotive AS. The early phase of this case is previously described by Martinsen and Knutstad [30].

### 3.1. Initial problems after pilot implementation

At first the system was not considered successful. The main reasons was a large degree of Type I errors; false alarms where the machine was halted by the monitoring system without any quality failure on the product. This caused a reduced productivity and not the increased productivity as expected. Later studies have found that these initial problems were caused by insufficient training, underestimation of the process towards establishing suitable monitoring limits as well as lack of information sharing between operators at different shifts. The system is integrated with the machine and it is not possible to shut off the monitoring without shutting off

the entire lathe. Some operators did, however, find workarounds to “fool” the monitoring system by setting monitoring limits very wide. Since most out-of-limit events was a Type I error, operators restarted the process with wider limits without checking the actual tool condition.

### 3.2. On-the-job training (solution)

To change the bad reputation among operators, more emphasis was on-the-job training, with a focus on how operator should utilize the process monitoring signals as valuable additions to the operators’ process knowledge. An arena for exchanging experiences with the system was created, making co-ordination between the operators more formalized. A mentor was chosen among the operators, having special responsibility for the system and was given special training. The chosen mentor was an experienced operator with years of accumulated tacit knowledge. Not insignificant was, of course, that she/he could see the potentials in the monitoring system. Moreover, as a mentor to understand that his role is to guide the inexperienced into a modus of asking the right questions and thus increase understanding of the process. A mentor-apprentice system requires that the mentor and the apprentice follow each other for some duration of time. This mentor should share what she/he is sensing and how she/he is sensing the situation that causes a failure or stop. In other words the mentor needs to simultaneously reflect in and on action and share this reflection.

### 3.3. Observations on the socio-technical system

The process of decreasing the Type I and Type II errors described in this case has to do with a loop between *theôrêsis* /*theôria* and *téchne/poiêsis* as shown in Figure 3. To drive this loop is in many cases not easy. Theoretical knowledge can be difficult to transform to a practical use and vice versa. When the system is introduced there was an initial starting point of general established *theôria* and *theôrêsis* of the machining process as well as the initial *theôrêsis* behind the monitoring system. The case showed, however, the difficulty in the transition from *theôrêsis* to *téchne/poiêsis* and further back to *Theôria*. The operator was faced with both a difficulty of not having a well-founded *theôrêsis* within the company on one hand, and on the other hand the difficulty of transform his/her *téchne/poiêsis* –knowledge into systematic *theôria* and later establish a *theôrêsis* among the operators. Solutions to the Type I and type II errors have to be solved within the local *téchne/poiêsis*, but to generalize this it must be refined through *Theôria* and generalized through *Theôrêsis*.

On-the-job training is an effect of bridging the gaps between the *theôrêsis*, *theôria* and *têchne/poiêsis* in a proper way. Mentors are experts that possess a basic *theôria* and that make an effort to bring *poiêsis* to *têchne*. This way the overall system can converge into a functional process control loop.

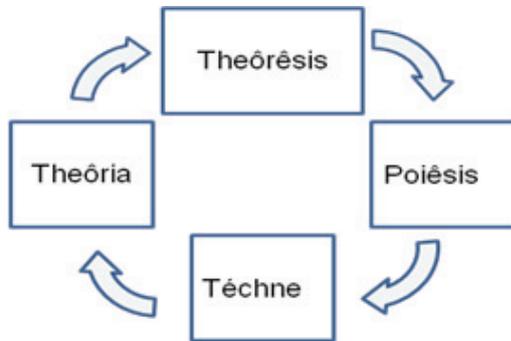


Fig. 3. Knowledge creation loop

#### 4. Case 2: OEE Monitoring system

Raufoss Technology AS (RT) is developing and manufacturing aluminium wheel suspension parts. The manufacturing system includes processes such as hot and cold forming, heat treatment, machining and assembly. They implemented a fully integrated OEE-monitoring system in 2000/2001. Scrap rate, unplanned stops etc. are automatically reported as well as the station the stop was initiated. In addition, there are a large number of process parameters monitored, (including power sensor cutting force monitoring). If the stop was caused by an out-of-limits process control value, this value is given. A case study made after 5 and 7 years are partly described earlier by Martinsen and Holtskog [31] and Larsson and Martinsen [32].

##### 4.1. Initial design

When designed, the system was planned to be a tool for knowledge creation and exchange with for example the possibility for operators to give written comments and messages to the next shift, maintenance personnel etc. about problems and stop causes. It serves as a representation of the firm's *theôrêsis*. A system of this kind will bring in a shared repertoire and a shared language. This in turn should lead to a rational ability to reflect on experience.

##### 4.2. Experiences after use

The operators do to some extent use the system in the briefing / debriefing between shifts building identity and documenting practice. There is some reflection in action

at the production floor by visiting other teams and sharing information making the CoP larger than just one team. The written comments and messages is a tool for the ongoing knowledge creation loop. In the effort to minimize unwanted breakdowns and productivity loss, the operators use the system to look at situations in the past and what happened on the previous shift.

There is a divergence in the acceptance of the system among operators at different process steps. While operators at the forming line find it valuable, the operators at the machining line do not. This is partly because the failure pattern at the machining line is repeatedly many small stops with the same case, and (so far) not a willingness to fix the root cause of the problem, which can be interpreted as meaningless. Moreover, as Larsson and Martinsen [32] writes; there is a lack of connection to other ICT systems, and a lack of update to the system when the actual plant is changing and to new emerging needs, an indication of an isolated CoP for the rest of the organization. The control loop of an OEE monitoring system will in many cases involve more than one human, and possibly across departments. Poor design of human work processes have caused a weak link between operators and the maintenance department, which leads to the actual control loop to be unclear and serve as a lack of glue for the social conditions for learning. When asked about the benefits of the monitoring system, however, the operators gave more or less equal answers and have the same idea of what changes could be made in order to make the system better. This implies that there is a level of common reflection inside the CoP.

#### 5. Discussion and conclusions

The process from novice to a competent operator starts with formal training. The continuation of the learning is to an increasing degree the responsibility of the operator. Two key factors were derived for successful learning: asking for advice and systematic problem solving. Both aspects are a contribution of the operator to the success of the training. The novice will only get access to *têchne* knowledge of whom he asks. Further, the novice has not developed a feeling of the craftsman. A competent operator will over time build a craftsman feeling for the machinery and process, this feeling is *poiêsis* kind of knowing. Taking the step from a competent operator to an expert has to do with the transformation of some *poiêsis* to *têchne* form of knowing. This is most often done by trial and error in the specific context. After several iterations an articulated knowing can occur. In this iteration process it is important to have several other experts or competent operators to discuss the problems with and learn together with. A more solitary transformation can lead to wrong

conclusions that in turn is learn back to new novices. Another way to make sure the right conclusions or knowledge is learned at the shop floor is to educate people in theōria. An insight into ‘know what’ will serve as a guide and a check of what new téchne that the operators talks about and teach to others.

Just as important as knowledge forms, is the social side of learning. What is learned and how it is learned is strongly related to social aspects. The cases show to some extent importance of strong identity building, and learning by doing. But the need to see how the team builds value for the company and how the community belongs to the wider organization is equally important. Signs, like ICT system not connected to the rest of the organization, will have a negative effect on the learning process and leave a feeling of alienation and isolation.

### Acknowledgements

The authors wish to thank the two case companies as well as the Norwegian Research Council which have sponsored parts of the work through SFI NORMAN, The BiA program and other previous funding programs.

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