Productive Metrology - Adding Value to Manufacture

H. Kunzmann[1] (1) , T. Pfeifer[2] (2), R. Schmitt[2] , H. Schwenke[1] (2), A. Weckenmann[3] (2)
[1]Physikalisch -Technische Bundesanstalt (PTB) – Germany,
[2] Univ. of Aachen – Germany
[3] Univ. of Erlangen – Germany

Abstract
Metrology has a stigma of being non-productive and in many cases the aim of production engineers is to reduce metrology costs to an absolute minimum. This paper analyzes the role of metrology in production and demonstrates, how metrology can generate value. It illustrates different ways to evaluate the benefit of metrology and gives metrologists guidance to sell metrology with economic arguments. The term productive metrology is introduced to emphasis the common interest of both production engineers and industrial metrologists to employ metrology to the best benefit of the product. Starting from information theory, the paper describes the role of metrology in production and gives basic recipes to evaluate and maximize the benefit of metrology investment. Examples from different fields of engineering illustrate productive roles of metrology.

Keywords:
Production Metrology, Information Technology, Deterministic Process Control

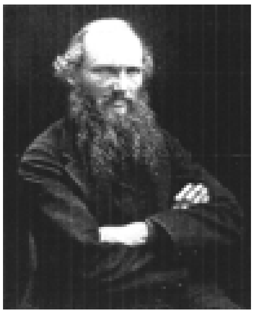

Figure 1: Lord Kelvin, 1886

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is meagre and of unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter may be."

1 INTRODUCTION

The fundamental statement of Lord Kelvin (Figure 1) is valid for all kinds of research and development in natural sciences and engineering technologies. Measurements are done to gain reliable quantified information about our world. But although metrology is generally accepted as having this important function, metrology in the manufacturing process is often seen as being a cost-factor and very seldom as being a value-adding activity. Often scientists and practitioners in manufacturing technology are confronted with statements like "These measurements must not cost more than ... ". It is the task of a metrologist in production technology, to take those arguments seriously into account, and bring the metrology into a position, where it is accepted as an enabling and supportive technology that is adding value to every step of the production process. The general development of manufacturing technology is directed towards better quality of products and a higher productivity. These objectives are achieved by optimizing the entire production system, whereby optimizing means to realize the technical requirements with the most economic means. The goal of this paper is to indicate approaches for quantifying the benefit of metrology (to "measure metrology") in a process and consequently provide tools to maximize the benefit.

2 METROLOGY, INFORMATION AND KNOWLEDGE

2.1 Measurement

The International Vocabulary of Basic and General Terms in Metrology [1] defines in its latest version measurement as the "process of experimentally obtaining information about the magnitude of a quantity". This definition is in general agreement with our understanding and meaning. Nevertheless the term "information" remains vague and needs to be clarified.

2.2 Information

The fundamental meaning of information was the subject of interest for a group of mathematicians during the second half of the 1940s. They examined how to define and quantify information and to make this quantity itself measurable. This group, invited by N. Wiener and J. v. Neumann defined information as "Content of a signal, given by a representing parameter [2,3]. For communication of information it is necessary to agree on a certain code". It was convenient to measure information in terms of numbers of "*yeses"* and "*noes"* and to call the unit of information a bit. "Information" is a valid unit also outside the IT world. Umstätter states in one of his papers [4]: "It is well known, that the bit is the smallest unit of information. But in most cases this unit is used for the memory of computers. So it can be observed often that people believe that bits can only contain the information in electronic systems but not in publications or in knowledge. This is like the assertion that a distance between two points can be measured by meters but not the length of a human person. It is necessary to make evident that scientific literature contains in many cases knowledge, i.e. information in compact form, or proved information." When "information" is gained from measurements, it is for the purpose of gaining specific knowledge on actual physical quantities or parameters of manufacturing systems and products.

2.3 Knowledge

The American Heritage Dictionary defines knowledge as "the state or fact of knowing; familiarity, awareness, or understanding gained through experience or study; that which is known; the sum or range of what has been perceived, discovered, or inferred". Peter F. Drucker [5] defines knowledge as "(…) the information that changes something or somebody, either by becoming grounds for actions, or by making an individual (or an institution) capable of different or more effective actions."

Consequently, knowledge is the desired result of experimentally gained information. It is the pre-requisite to make an idea, a conception, or a design of a functional model to become real. Drucker mentions two types of knowledge [6]: *Explicit Knowledge* and *Tacit Knowledge*. *Explicit knowledge* can be communicated by correct formal languages, mathematical expressions, manuals, etc. It can readily be transmitted to others and easily be processed by computers, transmitted electronically, and stored in databases.

On the other hand, *Tacit Knowledge* is very often embedded in individual personal experiences and involves intangible factors, such as personal beliefs, perspectives, and value systems. *Tacit knowledge* is difficult –but not impossible- to articulate in formal languages. Before *tacit knowledge* can be communicated, it must be converted into words, models, or numbers that can be understood. According to Nonaka & Takeuchi [7] tacit knowledge has to be subdivide into two dimensions:

- A technical dimension, which encompasses the kind of skill often captured in the term know-how. An example is the craftsperson, who has developed a high level of expertise after years of experiences, but has difficulty articulating the technical or scientific principles of his or her craft. Highly subjective and personal insights, intuitions, hunches and inspirations derived from experience fall into this dimension.
- A cognitive dimension, which consists of beliefs, perceptions, emotions and mental models that are so deeply ingrained in persons that they take them for granted. Though these beliefs and all the other emotional aspects cannot be articulated easily, this dimension of tacit knowledge shapes the way people perceive the world around them – and that includes the complex world of manufacturing technology.

These definitions seem to be very helpful when formulating the general requirements for an effective use of metrology.

2.4 Productive metrology

While [1] defines metrology as being "the field of knowledge concerned with measurement", we would like to introduce the term "Productive Metrology" according to previous definitions as the field of knowledge concerned with measurement to gain information and subsequently knowledge to change something or somebody, either by becoming grounds for actions, or by making an individual (or an institution) capable of different or more effective actions. This definition shall make clear, that the information gained by measurement must be used in an effective way.

2.5 Metrology generates information and knowledge

Measurements are done to determine specified quantities or functional process-parameters in numbers and units. These measuring results are content of information, which is transferred to some person or programmed information processing system for comparison with quantitative figures expected, set, or known by other experiments. Acquisition of knowledge is the target of a measurement and information transfer for being able to derive consequences from this knowledge for developing the know–how and finally the wisdom for managing improvements of manufacturing processes and products. Figure 2 sketches - with a few modifications from the original [7] - the gain of knowledge and wisdom (know-how) through experience and understanding. The starting-point of all is metrology.

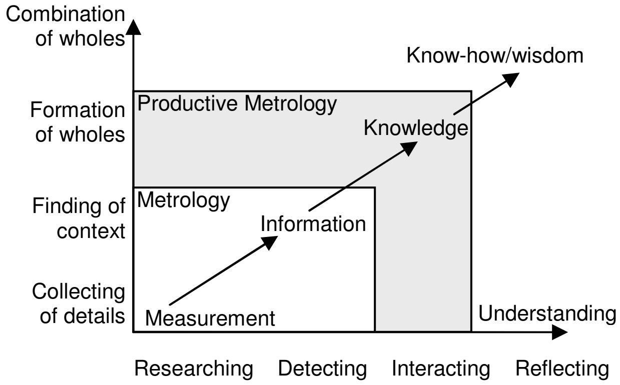

Figure 2: Gain of knowledge and development of wisdom / know-how as result of increasing experience and understanding.

2.6 Quantifying the increase of Information through measurements

Derived from a priori knowledge and without any particular measurement a quantity can be assumed to be within a realistically estimated interval (uniformly distributed probability assumed):

$$x_0 - \Delta x \le x \le x_0 + \Delta x \qquad (1)$$

The information, equivalent to the gain of knowledge, learning that x lies in a specific half of the interval $[x_0 - \Delta x, x_0 + \Delta x]$ is equal to 1bit. This information can be derived from a measurement result having an expanded uncertainty

$$U_1(k=2) = \frac{\Delta x}{\sqrt{3}} \qquad (2)$$

For the calculation of the increase of information through measurements the interval is conceptually divided into m sub-intervals of the width $2 \cdot \Delta x / m$. If the value of the quantity to be measured is equally likely to lie in any of the m sub-intervals, then the probability for x to lie in any particular sub-interval k is

$$P_k = 1/m, k = 1..m\,. \qquad (3)$$

After a measurement with an expanded uncertainty

$$U_m = U_1 / m \qquad (4)$$

the value of x is known to lie in a particular sub-interval. The information gained by this measurement is

$$H = -\sum_1^m P_k * \log_2(P_k) = \log_2 m \qquad (5)$$

Equation (5) shows that it is possible to quantify the increase of information through measurements. Figure 3 assigns a virtual monetary value to a bit of information and shows the benefit, costs and profit generated by measurements as a function of increasing measurement accuracy in terms of *m*.