DIGITAL LOAD CELLS

A COMPARATIVE REVIEW OF PERFORMANCE AND APPLICATION

WP0803

WEIGHING & FORCE MEASUREMENT PANEL

Originally published 2003
Reviewed and re-issued

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The Institute welcomes all comments on this Document and requests that these should be addressed the Institute. Users of this Institute of Measurement and Control Document shall be responsible for its correct application.

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1 FOREWORD

This Institute of Measurement and Control monograph reviews the performance and application of load cells that output their measuring signal in a digital format as opposed to conventional analogue signals. The performance of digital load cells is compared to conventional analogue load cells, particularly in the context of industrial process weighing applications.

It gives recognition to the need for a comprehensive and authoritative document for identifying the benefits of using this type of load cell in industrial process weighing systems. The incorporation of digital technology within a load cell may confer benefits to both the user and manufacturer. This document attempts to separate and identify the benefits of each feature.

This document is a guide for the technical personnel and organisations engaged in specifying and procuring load cells for industrial process weighing systems, and for those organisations supplying such systems.

2 SCOPE

This Monograph reviews all of the principal features relating to strain gauge load cells that incorporate signal conditioning electronics to provide measuring output signals in a digital form.

Most load cells which are sold as “digital load cells” are strain gauge based analogue load cells with built-in electronics to convert the analogue output into a digital output signal. A digital load cell, for the purposes of this document, therefore, comprises a measurement system illustrated in Figure 1. The load cells are presumed to be of the strain gauge type and the signal conditioning electronics is assumed to be contained within the envelope of the transducer housing. The signal conditioning electronics may have a minimum configuration such as an Analogue to Digital Converter to convert the analogue signal into a digital format for retransmission. It may incorporate additional electronic devices to store various load cell performance characteristics and optimise these by the use of software algorithms. Load cells that utilise some of the features of the digital load cell but whose electronics are separately housed or are not dedicated to a single transducer are not considered here.

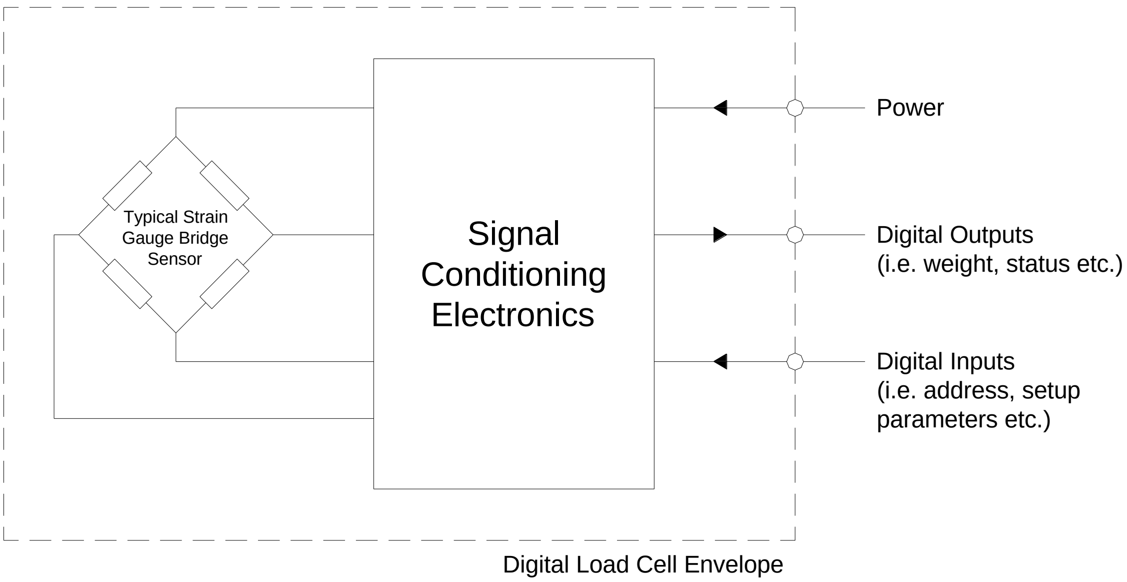

Figure 1: A schematic representation of a digital load cell

3 TERMS AND DEFINITIONS

This Monograph provides recommended terminology and definitions for the terms used herein. No attempt has been made to define those terms defined elsewhere in the document. Some of the acronyms are also included.

Where appropriate, these terms and definitions are based on the currently available British, European, or International standards or authoritative documents published by Learned Societies.

3.1 **ADC**
Abbreviation for analogue to digital converter

3.2
ALGORITHM
A well-defined set of rules for processing digital signals or solving a problem. Within the context of this document, this may be in the form of a software programme for temperature compensation of the “zero load” and “applied load” load cell outputs, or for linearisation of the load cell output

3.3 **DCS**
Abbreviation for distributed control system

3.4 **Diagnostics**
The set of tests to run through a system that determine whether or not the system is functioning correctly

3.5 **Digital filtering**
Mathematical techniques used to reduce or enhance certain aspects of a sampled, discrete-time signal

3.6 **EPROM**
Abbreviation for erasable programmable read-only memory. A read-only memory in which stored data can be erased, by ultraviolet light or other means, and reprogrammed by appropriate voltage pulses

3.7 **EEPROM**
Abbreviation for electrically erasable programmable read-only memory. Sometimes referred as E^2PROM

3.8 **Fieldbus**
Fieldbus is a method of connecting field instrumentation using a communications network linking the field instruments rather than connecting each field instrument individually to the control system. Fieldbus uses digital communication protocols, which allows information to be communicated between the control system and the field instrument in addition to the process signal. Instrumentation connected to a fieldbus network is always of the smart instrumentation type

3.9 **Full scale deflection**
Difference between the load cell or load cell system output at maximum calibration load and the output at zero load. In this document it is referred as fsd

3.10 **Load receiving element**
The element of weighing system intended to receive the load to be measured, such as a hopper, silo or ladle

3.11 Non-linearity

Maximum deviation of the measured output of the load cell or the load cell system, obtained for increasing loads only, from a best fit polynomial, calculated using the method of least squares. This covers any statistically-supported degree of polynomial, including straight line fits (for a detailed explanation of this term refer to [3])

3.12 Protocol

A set of formal rules describing how to transmit data, especially across a network. Low level protocols define the electrical and physical standards to be observed, bit- and byte ordering, and the transmission and error detection and correction of the bit stream. High level protocols deal with the data formatting, including such issues as syntax of messages, terminal to computer dialogue, character sets, and sequencing of messages

4 GENERAL CONSIDERATIONS

This section addresses the various factors that may inform the choice between a digital and analogue load cell for a particular process weighing application.

4.1 CALIBRATION

This sub-section considers the calibration of digital load cells and of weighing systems that incorporate them.

4.1.1 Load cell calibration

Much emphasis is placed by manufacturers on claims that digital load cells are pre-calibrated at source and that this fact makes for simple commissioning and service interchange. The definition of calibration used throughout this document is based on the JCGM's International Vocabulary of Metrology [6] and, insofar as it applies to the calibration of load cells, may be paraphrased as follows:

"**Calibration** is an operation that, under specified conditions, establishes the relationship between the value of force applied to a load cell and the corresponding value of the indicated load cell output, where both values have associated measurement uncertainties."

Establishing and documenting this relationship in the laboratory at the end of the manufacturing process is common practise for both digital and analogue load cells.

The fact that the output data from a digital load cell is in numeric form and can be linked to data identifying the individual device makes recording and data retrieval simpler for the manufacturer. There can also be benefits for the user in the ease of handling this data for purposes such as quality control or as a diagnostic tool.

When the load cell is used as a component in an industrial process weighing system, there are several influence factors that can affect the relationship between the force exerted by the material being weighed and the force being applied to the load cell. These are well-documented [1,2] and include installation issues such as load cell alignment and piping forces. For this reason, theoretical data on the original manufacturer's calibration of a digital or analogue load cell is acceptable only in applications where verification of performance is not critical or is not practical.

4.1.2 Rationalisation

It is accepted practice to adjust an analogue load cell's sensitivity, expressed in mV (output signal) /

V (excitation voltage), and its output resistance to nominal values within a tolerance band, in a process known as rationalisation. This is important for applications where these load cells are installed in a multiple load cell application and their outputs are connected in parallel in a junction box. This is a time consuming and costly operation especially in the case of high capacity load cells.

Digital load cells have their signal outputs matched utilising the software programmed into their conditioning electronics.

4.1.3 Load distribution

In many weighing systems utilising more than one load cell to support the load receiving element, the distribution of load between the individual load cells can vary considerably. In such applications the relative contribution of each load cell to the total output is clearly important.

When using analogue load cells which are not matched sufficiently well during manufacture, there is sometimes a need to introduce (and adjust by testing) compensating circuitry, usually located in the load cell junction box. This procedure can be time-consuming, technically difficult, and costly, but it is not relevant to digital load cells. Digital error correction is physically easier and can result in savings of both time and money, in applications such as the following:

- high performance platform weighing systems (such as those complying with statutory requirements for use in trade) - where in almost every installation analogue load cells require some adjustment during the commissioning phase of the application

- high performance vessel weighing systems, where the loading is asymmetric and where testing to establish the system output under such conditions is impractical

4.2 LOAD CELL PERFORMANCE

This sub-section reviews how parameters describing the performance of the load cell as a component may be modified by the use of digital techniques. The definitions used to quantify performance parameters are contained in [1,2,3].

4.2.1 Non-linearity

Digital load cells have the capability to allow the signals from the strain gauges to be linearised before being presented as the final output. This is an advantage to the manufacturer in that the performance of the basic transducer design can assume a lesser importance**.** An analogue load cell, which might meet a given specification for non-linearity, can be tuned to meet a better specification as a digital device.

The maximum performance in terms of non-linearity that could be achieved from a load cell, based on strain gauge technology can be improved by the use of digital techniques. Typically an improvement of the non-linearity by a factor of 30 is possible and a load cell having a non-linearity of 0.1 % fsd computed against a best fit straight line can be improved to 0.003 % fsd if a polynomial of a suitable order is used instead of a straight line. This is a very attractive facility available to the load cell manufacturer, the limiting factor being the repeatability of the device and the technique used in its calibration.

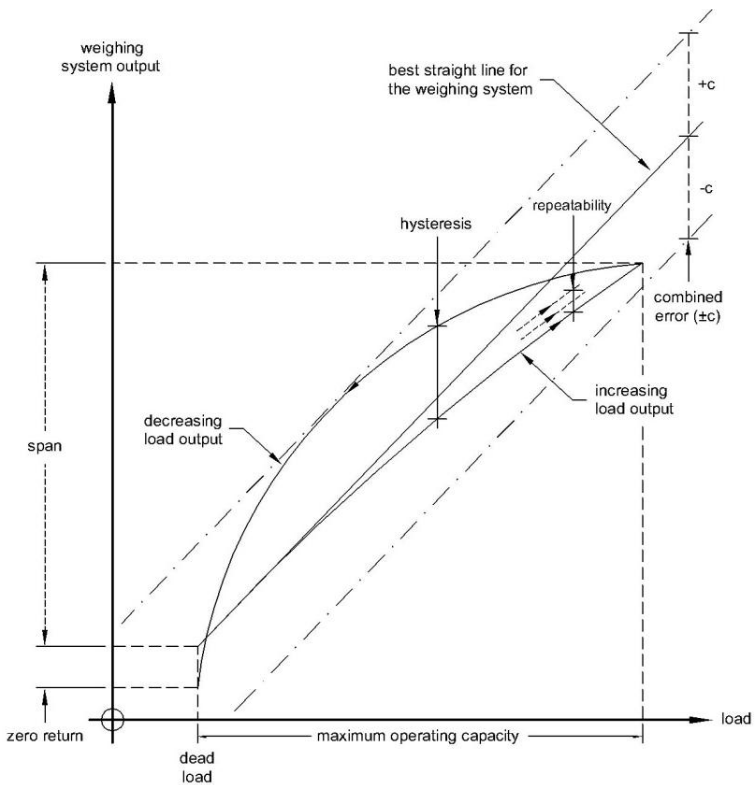

Figure 2: Performance parameter definitions based on the best straight line

However it should be remembered that the installed weigh system non-linearity is dependent on the method of applying load to the load cell and the system mechanical integrity. The improved non-linearity of a digital load cell may not always be a useful benefit to the industrial user.

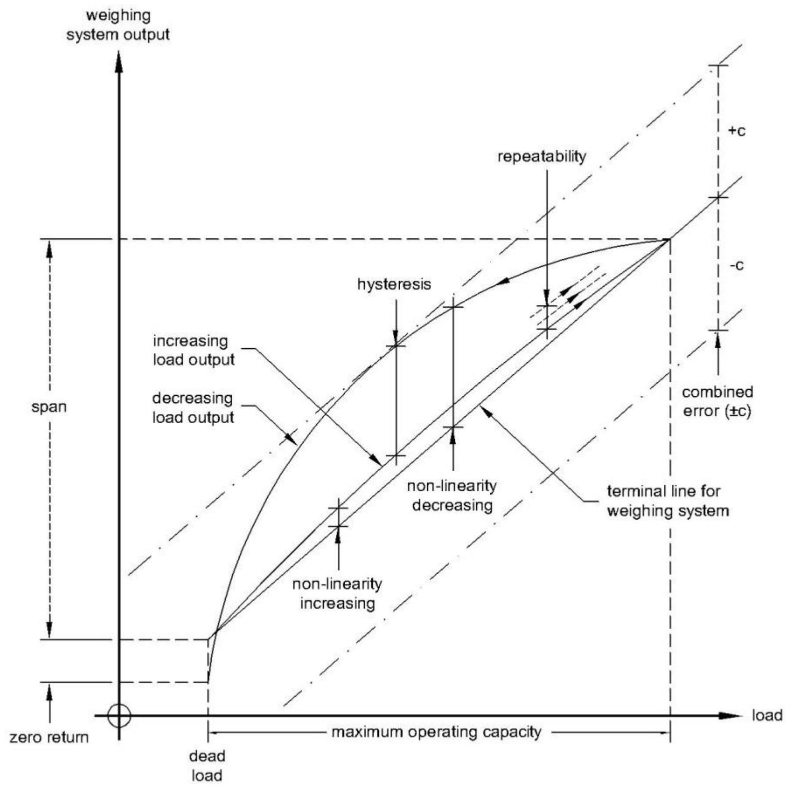

Figure 3: Performance parameter definitions based on the terminal straight line

4.2.2 Hysteresis

The strain gauge load cell exhibits an output, the value of which depends on whether the applied load is increasing or decreasing. Linearisation using digital processing capability of the decreasing load characteristic as well as the increasing characteristic is complex.

4.2.3 Creep

The output of a load cell following a change in applied load has a small time dependant element called creep. As with hysteresis, it is conceivable that this effect could be digitally modelled and this model can be used to provide compensation but at the time of publication it is not known to have been commercially implemented.

4.2.4 Temperature compensation

The bridge configuration of the strain gauges in a load cell provides substantial automatic temperature compensation for the resistance changes that occur in individual gauges. However the final output of a strain gauge load cell is temperature dependent due to changes in the elasticity of the measuring element and other factors. An analogue load cell utilises additional components within the transducer to compensate for these variations.

A digital load cell uses the relationship between temperature and output established during manufacture to compensate the output signals. The power of digital processing can be used to perform this compensation and the algorithms used can be complex and comprehensive. For example, different compensation models can be adopted for different loads.

These features are primarily an advantage to the manufacturer but may have some benefit to a user if tighter temperature specifications are achieved. This benefit would need to be evaluated for a particular load cell type and taken into account in the overall appraisal. There is little evidence that improved specifications are in fact on offer.

4.2.5 Resolution and repeatability

The discrimination of a load cell is the smallest change of load that can be detected and may be a very small interval. The repeatability of a load cell is a measure of the agreement between the resulting outputs of several repeated load applications. Provided that the discrimination is sufficiently small to allow the repeatability to be determined there is little point in facilitating resolutions of a much higher level than the repeatability.

The repeatability of a load cell can be determined in the laboratory to very high levels, but the industrial environment will limit the practical level of repeatability that can be demonstrated to about 1 part in 10 000. This level of resolution is available from both conventional analogue and digital systems.

4.2.6 Reliability

There is no evidence to suggest a difference in reliability between digital and analogue load cells and it is considered that any differences are unlikely to be significant.

4.2.7 Diagnostics

Analogue load cells have no integral diagnostic capability. In contrast, digital load cell systems may have the functionality to employ diagnostic techniques to give confidence in the integrity of each individual load cell. Although these load cells often work in conjunction and may be connected together by their power supply and/or communication outputs, they are stand-alone units and can be individually addressed.

For system diagnostics see 4.3.6.

4.2.8 SAMPLING TIME

A digital load cell presents its output as discrete sequence of data. This inherently leads to timing issues, which will be affected by the number of transducers communicating on a single transmission line as well as the speed and complexity of the data being transmitted. These factors should be evaluated to ensure that relevant data can be available in a timely fashion, particularly in applications involving fast processes.

4.3 SYSTEM PERFORMANCE

This sub-section reviews the factors that may inform the choice between a digital and analogue load cell in terms of the performance of the complete weighing system. Whatever the type of load cell used, total system accuracy heavily depends on the mechanical integrity of the weighing system. Whichever type of load cell is selected, it will not solve the problems of a badly designed weighing system. The definitions used to quantify performance parameters are given elsewhere [1,2].

4.3.1 System combined error

This is an aggregate figure relating to the precision of the measurement that includes non-linearity, hysteresis, and repeatability. Whilst the load cell error characteristic is an important contributor to the overall system combined error, the influences of the mechanical installation and environment are likely to be equally important factors for many, if not most, industrial process weighing systems. To achieve an overall combined error in such systems better than ±0.02 % of weigh range is unlikely and to achieve ±0.01 % of weigh range is considered the absolute practical limit. If this is accepted as reasonable, there is little to choose between digital and analogue load cells from this performance viewpoint.

4.3.2 System temperature error

The arguments relating to temperature induced error are similar to those presented in sub-section 4.2.4. Temperature induced error is always present to some degree in a process application and has many causes, the dominant ones usually being mechanical or other indirect factors. Where the mechanical influences are absent or minimal, such as in weigh scale type systems or free standing tanks or hoppers, there could be benefit arising from the use of digital load cells with enhanced temperature coefficients.

4.3.3 Load distribution error

Applications involving uneven load distribution between the various load cells supporting the load receiving element are very common. Apart from obvious examples like weigh scales and hoppers containing solid materials, all weighing systems utilising four or more load cells are statically indeterminate, i.e. the load supported by each load cell cannot be calculated and indeed will vary with time and the status of the installation mechanics.

Systems that use analogue load cells can deliver high performance in such circumstances but only if the individual transducers have been matched in relationship to each other during manufacture [1].

Production costs usually dictate the tolerances of this matching procedure and even the best of load cell production output streams will have some mismatch in the output parameters. It may be possible to specifically select matched sets of analogue load cells however in all but the simplest platform situations it is practically impossible to improve these matching characteristics by testing on site. Even where such testing is possible and compensation is provided, using additional resistors that are incorporated into the local summation junction box, there are inevitable time and cost implications.

This is an area where digital load cells can offer some significant advantages. Since their individual outputs are observed as a value in actual weight units and arithmetically added together, correction of errors due to uneven load distribution is simplified. This advantage will manifest itself in terms of both the time and cost of field calibration procedures.

It must however be pointed out that that there remains a requirement to install the load cell correctly so that the its original calibration result remains valid in the field.

4.3.4 Vibration induced error

Vibration present in an industrial environment can make weight measurements difficult. There is the capability to include, within the processing circuitry of digital load cells, advanced filter algorithms that can reduce the effects of vibration significantly. However, the same techniques can be employed by a weight transmitter connected to conventional analogue devices, so this is considered a neutral feature.

4.3.5 Synchronisation error

A weighing system incorporating more than one load cell and subject to any form of dynamic loading raises issues about how the individual load cell signals are combined.

In an analogue system the cells are almost always summated electrically in a local junction box and the combined output is available instantaneously. If the load distribution changes with time, such as in the presence of agitation, the combined output will remain unaffected providing there is no change in total load.

In a digital system there is the potential for time delays to occur in the observation and summation of the individual loads. This requirement for synchronisation needs to be considered in the final digital summation processor. The user should satisfy himself that such consideration has been given to all the data collection components in the system.

4.3.6 Diagnostics

The analogue load cells in a conventional multiple load cell weighing system are connected in parallel in a junction box. The resultant combined signal output is the arithmetic average of the output of these load cells. Failure of one load cell in such a system may not be noticed. To overcome this, additional electronics such as an intelligent junction box which can scan the output of each load cell may have to be installed in place of the conventional junction box.

In weighing systems using digital load cells, additional diagnostics may be built in the system software where individual load cells are monitored for influence factors such as excessive loads, rapid changes of loads and excessive temperature changes. The main benefit here is due to the ability to be able to monitor each load cell separately. An example of this would be raising an alarm if the load distribution on individual load cells changes beyond the accepted weight distribution when weighing a self-levelling product on a multiple load cell weighing system. The use of historical data to provide a ‘normal’ reference loading profile against which current behaviour can be compared has also been suggested as a diagnostic tool.

4.4 HUMIDITY

Strain gauges, if not properly protected, are very sensitive to moisture. The load cell itself depends on the integrity of its encapsulation in both the short and long term for protection and there will be no significant difference between digital and analogue devices in this respect.

The same is not true for the interconnecting cables. The higher level output signals in digital cables will be substantially more immune from moisture ingress problems.

4.5 ELECTRICAL STORMS, EMC, AND ELECTRICAL CONNECTIONS.

The energy contained in a lightning strike is at such a high level that any electronic device subjected to a direct incident will be damaged. In vulnerable digital and analogue load cell applications, additional protection will be indicated. Similarly, damage caused by electrical welding adjacent to weighing systems is a potential hazard for digital and analogue load cells alike.

For lower levels of electromagnetic radiation the digital load cell, with its inherently higher voltage transmission, will have greater immunity from corruption. However, all systems sold in the European Union are required to comply with the relevant EMC directives and systems used in trade must comply with the more stringent requirements for errors induced by electrical fields as stated in EN 45501 [4].

The cost of cabling can be lower for a digital load cell system, mostly due to the reduced need for a high specification cable type. There are also some possible savings available if the digital load cell outputs become part of a common bus system.

The interfacing aspects of a digital system must also be considered. The ideal concept of a factory populated by weighing systems all linked to an output device by a single cable carrying standard fieldbus compatible data may not be realisable or indeed, from a reliability point of view, desirable. Many digital systems require special interfaces to permit the individual load cell signals to be made usable by an external system. The implications of the cost and maintenance of these interfaces should not be neglected.

4.6 SERVICE AND MAINTENANCE ASPECTS

This sub-section reviews the consequences on the long-term ownership of a system incorporating digital load cells.

There are a number of factors that may be listed including:

- ease of service replacement
- digital storage and retrieval of calibration data in a computer
- facilities for initial set-up
- facilities for diagnostics.

4.6.1 Service replacement

The impact of the failure of one digital load cell in a multi load cell application will depend on the system software. Replacement of a failed digital load cell can be implemented fairly speedily with the same type of load cell provided that the system software has the facility to store its past performance in that location. An analogue load cell will often be provided with a manufacturer's calibration certificate which may enable the user to compute and input the replacement performance parameters into the final signal processor. In either case, the load cell replacement could be carried out and the weighing system used, without reverification of the system. The feasibility of this approach will depend on the performance specification and the quality control procedures in place. In the case of a legal-for-trade weighing system, the system will require reverification in accordance with the requirements of OIML R76 [5].

Weighing systems that provide measurements that have an impact on the quality criteria laid down for a process should be reverified after service intervention by an accepted calibration procedure [2].

4.6.2 Interchangeability

At the time of publication there is little harmonisation between digital load cells from different manufacturers. Each digital weighing system may use unique communication protocols, and unique algorithms incorporated in the load cell, necessitating replacement load cells having to be obtained from the original supplier. This is in contrast to analogue weighing systems where the load cells and the rest of the electronics may be provided and maintained by different suppliers.

4.7 SYSTEM COST

The cost of a digital load cell is likely to be higher than that of its analogue counterpart simply because of the additional components required for each load cell. However, although the raw cost of a digital load cell may be higher, the cost of the complete system and its ongoing use may not be, for a number of reasons.

A comparison in the initial capital cost of a digital versus an analogue system may be affected by:

- probable higher cost of the individual load cells
- reduction in cable cost
- cost reduction caused by the omission of weighing instrumentation
- costs associated with interfacing the load cell signals to rest of the users system.

Additionally there will be cost of ownership issues. These will usually be more difficult to quantify and may be subjective, but may be a major contributor to the decision making process. Factors to be considered are:

- costs associated with initial calibration and commissioning
- production costs relating to performance differences
- cost impact on the process of a fault diagnosis facility
- costs due to vulnerability to a single source supplier
- total cost of after sales support including training, technical support, replacement and reverification.

5 REFERENCES

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6 FURTHER READING

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