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Jaime Beltrán Jesús Muñuzuri Miguel Rivas Enrique Martín

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Jaime Beltrán
IAT (Innovation and Technology), Seville, Spain
Jesús Muñuzuri
School of Engineering, University of Seville, Seville, Spain, and
Miguel Rivas and Enrique Martín
IAT (Innovation and Technology), Seville, Spain

Abstract

Purpose – The evaluation of management systems is usually based on a series of assumptions which are never questioned. The purpose of this paper is to focus on two of these assumptions, in order to further develop a quantitative model to evaluate metrological management in companies, based on the ISO 10012:2003 standard.

Design/methodology/approach – First, the paper uses structural equations to identify the underlying relations between the different variables of the model and conclude that it follows the typical continuous improvement cycle formulated by Deming. And second, the paper processes the opinion of experts using analytic hierarchy process (AHP) techniques in order to prove that not all the variables included in the model are equally relevant in metrological management.

Findings – The first SME analysis validates the model itself and its integration with the other management schemes in the company, all based on the Deming cycle. The second AHP analysis leads to a reformulation of the model, assigning weights to the different variables and providing better guidelines for companies to improve their metrological management.

Originality/value – This constitutes a development of the management guidelines contained in the ISO 10012:2003 standard for metrological management, establishing the appropriate evaluation procedures.

Keywords AHP, Structural equations, Metrological management, Multicriteria analysis, AHP technique, SEM technique

Paper type Research paper

1. Introduction

This work represents a step forward in the line of research initiated in 2006 by Beltrán (2006), which set the basis for a quantitative model to evaluate the degree of maturity of metrological management in companies, following the corresponding international standard (ISO 10012:2003, 2003). This quantitative model offered the possibility to assign a score to the metrological management system in a company, and many companies where the model was tested found in it a simple and attractive validation and decision-making tool. The model was later incorporated into the associated

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Spanish standard (UNE 66180:2008, 2008), and has since then known several further developments and empirical applications (Beltrán *et al.*, 2007a, b).

Nevertheless, the model relied strongly on two assumptions which were not questioned before its formulation. The first one was the hypothesis stating that the ISO 10012:2003 (2003) standard follows the continuous improvement cycle proposed by Deming (ISO 9001:2008, 2008, see Figure 1). Should this hypothesis hold, improvements in any one of the cycle elements would necessarily lead to an improvement in the next one, resulting in continuous synergies and an overall progressive improvement of the metrological management system.

Second, the maturity level of metrological management (MLMM) in a company, according to the model, was assumed to be the result of the evaluation of five different management areas or chapters (X_1 through X_5). These five chapters were evaluated as construct variables, each one of them based on a different number of components (x_{ij}), where each component resulted from the assessment of a given aspect of metrological management according to the model and the UNE standard. The model was then formulated as follows, with the interpretation of each chapter and component shown in Table I:

$$
\begin{aligned}
&MLMM = X_1 + X_2 + X_3 + X_4 + X_5\\
&\textit{with}\\
&X_1 = x_{11}\\
&X_2 = x_{21} + x_{22} + x_{23} + x_{24}\\
&X_3 = x_{31} + x_{32} + x_{33} + x_{34}\\
&X_4 = x_{41} + x_{42} + x_{43}\\
&X_5 = x_{51} + x_{52} + x_{53} + x_{54}
\end{aligned}
$$

Thus, the evaluation model incorporated in the UNE 66180:2008 (2008) standard was based on a linear combination of variables (metrological management components), assuming that all those variables had the same degree of contribution to the overall

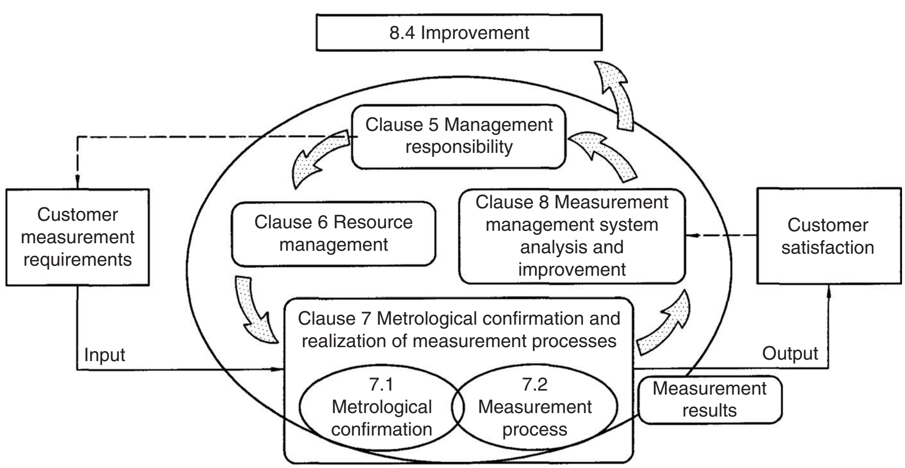

Figure 1.
Representation of a metrological management model based on the ISO 10012 standard

Chapter construct variable	Chapter	Component variable	Component
X_1	General requirements	x_{11}	General requirements (equivalent to chapter X_1)
X_2	Management responsibility	x_{21}	Metrological function
		x_{22}	Customer focus
		x_{23}	Reliability objectives
		x_{24}	Management review
X_3	Resources management	x_{31}	Human resources
		x_{32}	Information resources
		x_{33}	Material resources
		x_{34}	Outside suppliers
X_4	Metrological confirmation and measurement processes	x_{41}	Metrological confirmation
		x_{42}	Measurement process
		x_{43}	Measurement uncertainty and traceability
X_5	Analysis and improvement	x_{51}	General
		x_{52}	Auditing and monitoring
		x_{53}	Control of non-conformities
		x_{54}	Improvement

Table I. Interpretation of the different chapters and components of the metrological management model

MLMM system. This assumption can be found in many internationally acknowledged management evaluation models (Beltrán, 2004), both related to quality management systems (UNE 66174:2003, 2003) or to enterprise excellence (EFQM, 2010), regardless of the fact that in the latter case the model is also used as an external evaluation tool aimed at awarding excellence prizes. Table II shows the relation between different management systems and their evaluation tools.

Focussing on these two assumptions, this work seeks to further improve this evaluation model for metrological management systems, using the empirical data obtained from its application in a large number of Spanish companies to gain knowledge on its mechanisms. The objective was then twofold. On one hand, we analyzed the intra-variable relations of the model using structural equation modeling (SEM), thus seeking to validate the evaluation model itself, following the example of

	Quality management systems	Excellence models	Measurement management systems
Requisites	UNE-EN ISO 9001:2008 (2008)	Does not contain requisites	UNE-EN ISO 10012:2003 (2003)
Guidelines for performance improvement	UNE-EN ISO 9004:2009	Management criteria classified by agents and results of the EFQM model	UNE 66180:2008 (2008)
Auto-evaluation model	UNE 66174:2003 (2003)	REDER framework (results, focus, evaluation and revision) for auto-evaluation according to the EFQM model	

Table II. Relation between the main characteristics of some widespread evaluation models and the one suggested for the measurement management system

Curkovic *et al.* (2000). On the other hand, we used analytic hierarchy process (AHP) techniques to estimate weights for the different chapters and components of the evaluation model, in order to better represent the outcome of improvement strategies in companies.

2. Analysis of metrological management systems (ISO 10012) using SEM

The objective of SEM analyses is to find a model that fits to the empirical data sufficiently enough to serve as a useful representation of reality. The behavior of the observed variables could then be explained by the cause-and-effect relations estimated in the model. A SEM analysis normally covers three steps: model specification, model estimation and model evaluation (Coenders *et al.*, 2000).

2.1 Model specification

This stage corresponds to the formulation of the hypotheses required to explain the behavior of the observed variables. The analyst needs to identify the model's latent variables, and also to establish the cause-effect relations between the different latent variables, and between them and their indicators. The model specification consists of the formal description of these relations and their schematic representation in a diagram, where this formal description includes the identification of which model parameters will be fixed beforehand and which will be estimated using the empirical data. Normally, the corresponding coefficients are set to zero to establish the hypothesis that two variables are not related, whereas the model will be used to estimate those coefficients representing the relation between variables that are expected to be related (Hackl and Westlund, 2000). This is why the model contains the formal, and usually graphical, description of the hypotheses that the analyst wishes to confirm (or discard).

On the other hand, latent variables (those that cannot be directly measured, but can only be estimated from the observed variables) do not have predefined metrics, so the analyst also needs to establish a measurement scale for each one of them. This is usually accomplished by making the relation between the latent variable and one of its indicators equal to one. This will then be the reference indicator for that variable, providing an interpretable scale for it.

The basic hypothesis for this work was "the ISO 10012:2003 (2003) standard is based on the continuous improvement cycle formulated by Deming." The observed variables in the model correspond to the different components of the standard and could be measured directly when auditing companies. On the other hand, the chapters in the standard correspond to the latent variables, which cannot be directly quantified. Figure 2 shows the graphical representation of this basic hypothesis, as it was introduced in the software package AMOS 16.0. The latent variable "General Requisites" was not taken into account in the analysis, given that it depends on a single observable variable and due to the bad results generated by SEM models when incorporating this type of latent variables.

2.2 Model estimation

The estimation of the SEM model represented in Figure 2 required the collection of a large amount of empirical data through the evaluation of metrological management systems in actual companies in the Andalusian region, in the south of Spain.

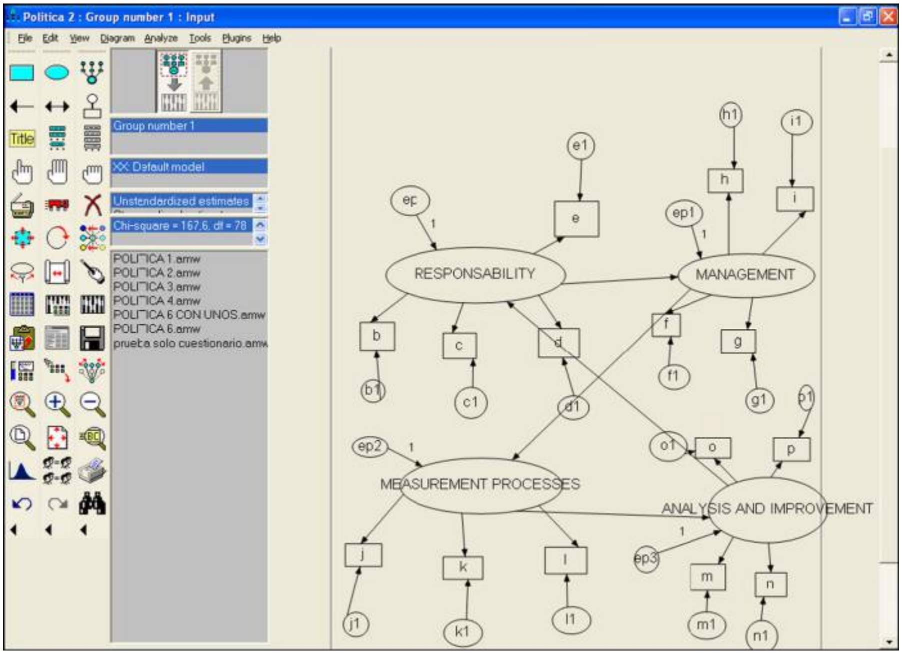

Figure 2.
Graphical representation of the basic hypothesis for the SEM model

Furthermore, candidate companies for the analysis had to fulfill two main requirements:

- Sampled companies were required to have previous management culture, resulting in certified (ISO 9001, EN 9100 ó ISO/TS 16949) or accredited (ISO 17025) quality management systems, which could also be completed with certified environmental management systems (ISO 14001) or other standardized management systems.
- Sampled companies were also expected to belong to activity sectors where metrology represents a key competitive factor. Even though metrology is a relevant factor in all the activity sectors where companies need to prove the reliability of a given product or service by measuring specified parameters, it is specially essential in those sectors where it is required to establish processes that improve the degree of compliance with the tolerances defined in the product's specifications.

The sample size for the analysis depended on the amount of data required by the SEM mathematical technique. We set an initial sample size of 300 companies, with the possibility of reducing it in case the analysis of the results produced by the gradual estimation of the SEM model allowed us to do so (dynamic sampling). The theoretical sampling error for 300 companies was estimated for continuous variables in normally distributed populations (which is the case of this analysis) following:

$$n = \frac{N z_{\alpha/2}^2 \sigma^2}{E^2 (N-1) z_{\alpha/2}^2 \sigma^2}$$

The estimated sampling error, for a 95.45 percent confidence level, was 5.8 percent for 150 companies, with errors around 10 percent resulting acceptable in this type of analyses (Martínez-Martín, 2003). The sampling method used, to select the companies to evaluate among those meeting the two requirements described above, was simple stratified random sampling, where the strata corresponded to the companies' activity sectors. The sampling had to be proportional to the number of certified companies in each activity sector (see Table III), thus following the probability proportional to size guidelines. Within each activity sector, the evaluated companies were selected randomly, thus guaranteeing proportional sampling depending on the number of certified companies in each sector.

Finally, once the participating companies had been selected, the data collection for the analysis was carried out using the web-based EVAMED tool (www.iat.es/simce/evamed), specifically designed. We used this tool to analyze the selected companies, evaluating them through the 155 questions contained in the UNE 66180:2008 (2008) standard (see Table IV). For each one of these questions, the company is assigned a score between 1 and 5, according to the criteria expressed in Table V.

Once the required data were collected, we estimated the coefficients or model parameters so that the model replicated as closely as possible the sample's variance and covariance matrices, given that the relations between parameters in any theoretical SEM model result in specific implications for the variances and covariances of the observed variables. The analysis applied the asymptotically distribution free (ADF) criterion, which does not require the normal distribution of the sample.

On the other hand, the univocal estimation of the model's parameters requires the model to be identified, which is achieved when every parameter can be expressed by at least one algebraic expression in terms of the sample's variances and covariances. A necessary, though not sufficient, condition for the model to be identified is to have a number of variances and covariances which is higher than the number of parameters to estimate, with the number of degrees of freedom in the model equal to the difference between both numbers. Nevertheless, the *ex ante* determination of whether the model is identified or not is not a trivial task, which makes it necessary to simulate the specified model, in order to verify whether all the parameters can be estimated, before starting the data collection.

2.3 Model evaluation

The usefulness of the model is determined by its capability to explain, or reproduce, the observed reality. This capability must be evaluated both for the model as a whole and for each one of the intra-variable relations contained in it. The ADF method used to estimate those relations requires at least $p(p+1)/2$ observations, where p is the

Table III. Sectorial distribution of certified management systems in Andalusia

Sector	Share of the total number of certifications (%)
Agro-industry	21
Metallic materials	19
Chemical	32
Aerospace	7
Electricity	7

Chapter	Component	Sub-component	Questions	No. of questions per component
X1: general requirements	x_{11}: general requirements	Process approach	1-4	11
		Identification of metrological requirements	5-11	
X2: management responsibility	x_{21}: metrological function		1-7	7
	x_{22}: customer focus		1-6	6
	x_{23}: reliability objectives		1-8	7
	x_{24}: management review		1-7	7
X3: resources management	x_{31}: human resources		1-7	7
	x_{32}: Information resources	Procedures and records	1-5	7
		Software	6-7	
	x_{33}: materials resources	Measurement equipment	1-8	10
		Enviromental conditions	9-10	
	x_{34}: outside suppliers		1-8	8
X4: metrological confirmation and measurement processes	x_{41}: metrological confirmation	Generalities	1-5	23
		Calibration	6-10	
		Metrological confirmation	11-14	
		Intervals of metrological confirmation	15-17	
		control of adjustments	18-19	
		Records of metrological confirmation process	20-23	
	x_{42}: measurement processes	Generalities	1-3	10
		Design of measurement processes	4-7	
		Operating the measurement processes	8-10	
	X_{43}: measurement uncertainty and traceability	Uncertainty measurement	1-4	5
		Traceability	5	
X5: analysis and improvement	x_{51}: generalities		1-6	6
	x_{61}: auditing and monitoring	Generalities	1-5	18
		Auditing	6-12	
		Monitoring	13-18	
	x_{62}: control of non-conformities	General	1-5	13
		Non-conformities processes	6-9	
		Non-conformities measurement equipments	10-13	
	x_{63}: analysis and improvement	Generalities	1-4	10
		Corrective action	5-7	
		Preventive action	8-10	
Total number of questions				155

Table IV.
Distribution of questions to evaluate metrological management systems according to the UNE 66180:2008 (2008) standard

Table V.
Evaluation criteria for each question in the metrological management model

Maturity level	Focus	Implementation	Results	Improvement
	Attributes of the maturity level[a]			
1.	There is evidence that the activity or process is being carried out There is some evidence that the activity or process is being carried out in a systematic way	The degree of implementation of the activity or process is below 25%	There is not significant evidence that the results of the activity or process are being measured The existing data show that the results of the activity or process are often unpredictable or not directly related to the focus	The improvement actions are based on immediate correction of the identified issues, without evidence of planned improvement activities
2.	There is clear evidence that the activity or process is being carried out in a systematic way There is some evidence that the activity or process is carried out in a justified and planned way	The degree of implementation of the activity or process is around 50%	There is some evidence that the results of the activity or process are being measured There is evidence that the results are a consequence of the company's policy	The improvement actions are based on the causal analysis of the identified incidences and in the planning of actions aimed to eliminate those causes
3.	There is clear evidence that the activity or process is carried out in a justified and planned way The inputs and outputs of the activity or process take into account other activities in the metrological management system, when applicable	The degree of implementation of the activity or process is around 75%	Clear evidence shows that the results of the activity or process are measured The activity or process presents some favorable results with respect to objectives or planned results	There is evidence of the adoption of measures to avoid potential incidences in the activity or process There is some evidence that the effectiveness of the improvement actions is being measured

(*continued*)

Table V.

Maturity level	Attributes of the maturity level[a] Focus	Implementation	Results	Improvement
4.	The activity or process is fully integrated in the metrological management system of the company The activity or process is coherent with the company's reliability policy	The activity or process is fully implemented	The activity or process presents favorable results with respect to objectives or planned results There is evidence that the results of the activity or process are favorable with respect to the previous period	There is evidence that the results of the activity or process and their comparison with internal objectives are used as a source of information for improvement There is evidence that the results of the evaluation of the metrological management system are used as a source of information for improvement There is evidence that the company measures the improvements achieved through the results of the activity or process
5.	The activity of process is integrated in the company's global management system (quality, environment, reliability and safety) The activity or process is coherent with the company's Global Policy and Strategy	The activity or process integrates the needs and expectations of all the stakeholders, including quality, environmental, reliability and safety measures	There is a sustained tendency for the results of the activity or process during at least three consecutive periods There is evidence of external comparisons, and they are favorable for most of the results of the activity or process	There is evidence that the improvement objectives for the activity or process are a consequence of the company's policy and strategy The improvement plans for the activity or process take into account the best practices available and the results of external comparisons

Note: [a]In order to reach a certain maturity level, the company must fulfill the attribute requisites for all the inferior levels number of variables, and our model consisted of 15 variables, which forced the number of evaluated companies to be at least equal to 120.

After comparing the model's results and consistency indexes with the observed data, we found close similarities, both in terms of the individual relations (all positive) and of the overall results. We were then able to confirm the initial hypothesis, obtaining the following values for the fitting indexes: RMSEA = 0.111, CFI = 0.819, CMIN/DF = 2.149. The estimated relations between the model's variables are shown in Table VI.

The confirmed model follows closely the sequence of metrological management systems based on ISO 10012, which in turn follow the PDCA continuous improvement cycle defined by Deming (ISO 9001:2008, 2008). In that cycle, the sequence is Plan (variables management responsibility and resource management), Do (variable metrological processes), Check (variable analysis and improvement, oriented toward analysis) and Act (variable analysis and improvement, oriented toward improvement), as shown in Figure 1.

The analysis of these results from the perspective of SEMs proves the continuous improvement behavior followed by metrological management systems. As a matter of fact, one of their basic principles is the fact that an adequate resource management should enhance the results obtained by the metrological operative processes, and this intra-variable relation obtains a coefficient value of 0.786 in the model, which means that increasing one unit the evaluation score for resource management in a company should result in an increase of 0.786 units in the evaluation score for metrological processes. Also, as expected, the evaluation score obtained for the analysis and improvement processes depends strongly on the efficient management of the metrological processes, which is confirmed by a direct and proportional relation between both variables in the model. The relation between analysis and improvement and management responsibility is also coherent, since a large portion (0.436 is a reasonable expectation) of the activities carried out in a company to analyze and improve processes directly trigger management actions, and thus represent direct inputs to the corresponding variable. Finally, and closing the cycle, the management responsibility processes should have a direct effect on the evaluation score obtained by the resource management processes, since they are activated by management responsibility, and this relation is also shown by the numerical results of the model.

This proves that the EVAMED model is consistent with the Deming sequence, and therefore appropriate for its application in process-oriented companies. This conclusion led us to incorporate similar evaluation procedures to other areas in the company, like logistics management (Muñuzuri *et al.*, 2013).

3. Estimation of a weighted model for metrological management using AHP

The quantitative model to evaluate metrological management in companies uses a set of variables which need to be quantified in the evaluation process. The final value of

Table VI.
Estimation of the model's intra-variable relations

Structural coefficient			Estimation
Management responsibility	→	Resource management	0.715
Resource management	→	Metrological processes	0.786
Metrological processes	→	Analysis and improvement	1.003
Analysis and improvement	→	Management responsibility	0.436

the MLMM obtained by each company is then the result of the direct aggregation of all those variables, thus considering all equally relevant in metrological management systems. This is not necessarily so, and it is reasonable to suppose that a more accurate version of the model would be:

$$
\begin{aligned}
& NMG = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 \\
& where \\
& X_1 = x_{11} \\
& X_2 = a_{21}x_{21} + a_{22}x_{22} + a_{23}x_{23} + a_{24}x_{24} \\
& X_3 = a_{31}x_{31} + a_{32}x_{32} + a_{33}x_{33} + a_{34}x_{34} \\
& X_4 = a_{41}x_{41} + a_{42}x_{42} + a_{43}x_{43} \\
& X_5 = a_{51}x_{51} + a_{52}x_{52} + a_{53}x_{53} + a_{54}x_{54}
\end{aligned}
$$

The fact that the a_i and a_{ij} coefficients may be different does not invalidate the model. Instead, it represents an opportunity for managers to apply more effort on those aspects of the model which are the most relevant, always keeping in mind that, as shown in the previous section, all the variables and aspects of the model are necessarily interrelated.

3.1 Technique choice

The AHP (Saaty, 1980) is a multicriteria evaluation method based on indirect assignment. Even though the main objective of multicriteria evaluation methods is to ponder different alternatives when faced by predefined choice situations, we have used these techniques to assign relative weights to the different variables of our mathematical model. From the existing multicriteria methods, we selected AHP, as it could be best adapted to the requirements of the analysis. AHP techniques provide an analytical tool and thus facilitate the task of the evaluating experts, given that:

- it enables the analyst to combine different expert panels, specific for the different analyzed areas;
- it allows for an easier comparison of the different aspects to evaluate; and
- it facilitates inductive analysis.

Finally, one of the side-effects of the application of AHP is the estimation of the consistency of the expert's opinions when evaluating different concepts through pair-wise comparison. This allows the analyst to take the appropriate actions when this consistency does not fall beyond a predefined threshold.

3.2 Application process

The first step, which was also fundamental for the adequate completion of the analysis, was the selection of the different expert panels. These experts acted as decision-making units, evaluating the one-to-one comparisons. We used five different expert panels in the analysis, composed of a total number of 28 experts (see Table VII), each one of them specialized in one or more specific areas of the model, namely:

- overall model;
- management responsibility;

Table VII.
Field of expertize and background for each one of the 28 experts participating in the AHP process

	Field of expertise		Background		
	Management systems	Metrological processes	University	Industry	Technological center
Expert 1	x	x			x
Expert 2	x				x
Expert 3	x				x
Expert 4		x	x		
Expert 5	x	x		x	
Expert 6	x	x		x	
Expert 7	x	x		x	
Expert 8		x		x	
Expert 9	x				x
Expert 10		x	x		
Expert 11		x		x	
Expert 12	x			x	
Expert 13		x	x		
Expert 14		x		x	
Expert 15		x		x	
Expert 16		x	x		
Expert 17		x		x	
Expert 18		x	x		
Expert 19		x	x		
Expert 20		x	x		
Expert 21		x	x		
Expert 22		x	x		
Expert 23	x	x			x
Expert 24		x		x	
Expert 25		x		x	
Expert 26	x	x		x	
Expert 27	x				x
Expert 28		x			x

- resource management;
- operative metrological processes; and
- analysis and improvement.

Each expert was then asked to fill the evaluation matrix for his/her area (an example of one of the filled evaluation matrices for the overall model is shown in Figure 3).

	General Requirements	Management responsibility	Resource Management	Measurement Processes	Analisys and improvement
General Requirements		3	3	1/3	3
Management responsibility	1/3		3	1/3	3
Resource Management	1/3	1/3		1/3	3
Measurement Processes	3	3	3		5
Analisys and improvement	1/3	1/3	1/3	1/5	

Figure 3.
Example of filled evaluation matrix for the overall model

This square matrix had as many rows and columns as aspects were to be compared, either chapters or elements of the model. The numbers to fill in the cells were to be taken from Saaty's numerical scale (Saaty, 1980), thus defining the correspondence between the qualitative opinions in the expert's mind and the corresponding numerical evaluations. As a consequence, typical in AHP applications, all the matrices were symmetrical.

Once all the individual evaluations were completed, we analyzed their consistency through the calculation of the respective consistency ratios (Saaty, 1980), which depend on the size of the comparison matrix (*n*), of a random index (*RI*) and of the maximum eigenvalue (λ_{max}):

$$CR = \frac{\lambda max - n}{(n-1)RI}$$

If the consistency ratio for a given expert was above a certain threshold value (following Reza Abdi and Labib, 2003, we used 0.11 as the threshold value in this analysis), the expert was asked to provide new evaluation values, in what constituted an approximate application of the Delphi procedure (Landeta, 1999). The matrices provided by those experts who after two attempts had not managed to provide consistent values were discarded, and the rest were used to calculate the model's weights. We then had a set of weights for each valid expert. Finally, each expert was in turn weighted depending on the proximity of his/her evaluations to the robust average of the overall panel (Aldian and Taylor, 2005), and the final aggregate weights were obtained. Figure 4 represents the development procedure followed in this work.

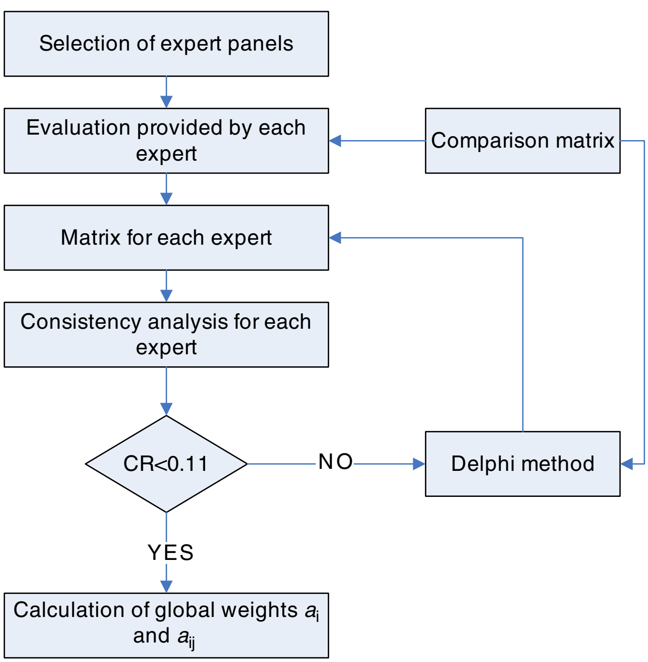

Figure 4.
Methodological sequence followed to calculate relative weights for the metrological management evaluation model

Following this procedure, relative weights were estimated both for the chapters and components of the model, which resulted as follows:

$$MLMM = 0.12X_1 + 0.13X_2 + 0.15X_3 + 0.45X_4 + 0.15X_5$$
$$with$$
$$X_1 = x_{11}$$
$$X_2 = 0.10x_{21} + 0.44x_{22} + 0.25x_{23} + 0.21x_{24}$$
$$X_3 = 0.44x_{31} + 0.17x_{32} + 0.28x_{33} + 0.11x_{34}$$
$$X_4 = 0.38x_{41} + 0.30x_{42} + 0.32x_{23}$$
$$X_5 = 0.16x_{51} + 0.43x_{52} + 0.20x_{53} + 0.21x_{54}$$

3.3 Result analysis

The result we obtained from the AHP analysis is an evaluation model for metrological management where the variables are not identically relevant any more, but have relative weights which signal their respective relevance in the model (and thus in the objectives of metrological management in a company). In the overall model, metrological operative processes were identified by the participating experts as the most relevant ones, and the ones with a higher influence (45 percent) in the MLMM in any given company. This was somehow expected, since this chapter represents the core of ISO 10012:2003 (2003). The other four chapters, on the other hand, obtained very similar relative weights.

Within the management processes, represented in the second restriction of the model, focus on the client clearly obtained the highest weight. This corresponds directly to the fact that it is one of the main basic principles in reliability management.

On the other hand, within resource management, the most valued variable is human resource management. This is why all the staff involved in metrological management systems should have updated and verifiable skills to carry out its assigned tasks. The variable material resources, representing the value of the necessary equipment to comply with metrological requirements, was also highly valued. Both variables accounted for 75 percent of the overall weight of the resource management chapter.

The operative metrological chapter was identified as the most important one inside the overall model equation. In this chapter, nevertheless, none of the three operative metrological processes considered in the model resulted more relevant than the others, which implies that companies should manage them with a similar intensity.

Finally, in the analysis and improvement chapter the highest rank is assigned to the audit and monitoring variable. This is possibly due to the relevance of monitoring, measuring and recording all the company's processes, resulting in the main information source to determine the adequacy and efficiency of its metrological management system.

Table VIII compares the results of applying the weighted and unweighted metrological management evaluation models to the 11 companies that were audited in Beltrán *et al.* (2010). We were surprised to find that both models resulted in very similar evaluations (which in a way validates the results of the original paper), but we believe that the weighted model provides a more accurate display of the relevance of the different components, and have thus replaced the unweighted model with the weighted one in the EVAMED tool.

Model component	AHP weight	Companies E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
X_1	0.12	2.4	2.3	1.8	2.0	1.7	2.1	1.9	1.8	2.1	2.3	3.0
X_2	0.13	2.2	2.3	1.6	2.6	2.0	2.1	2.1	1.8	2.2	2.3	3.1
x_{21}	0.1	2.8	3.3	1.5	2.7	1.9	3.2	2.1	1.9	3.0	2.0	3.6
x_{22}	0.44	2.7	2.2	2.1	2.9	1.4	1.9	2.4	2.1	2.6	2.5	3.6
x_{23}	0.25	1.4	2.0	1.1	2.6	2.5	1.4	1.4	1.5	1.5	2.1	2.2
x_{24}	0.21	1.7	2.4	1.4	2.1	2.5	2.7	2.3	1.5	1.7	2.3	3.0
X_3	0.15	2.8	2.5	2.1	2.5	2.1	3.1	3.0	1.9	3.1	3.3	2.7
x_{31}	0.44	3.2	2.3	1.9	2.1	1.9	3.1	2.7	2.0	3.2	3.5	2.7
x_{32}	0.17	2.4	2.4	2.7	3.3	2.5	3.4	3.5	1.4	3.1	3.7	2.1
x_{33}	0.28	2.5	2.9	1.7	2.6	2.2	2.9	3.1	2.1	2.9	2.9	2.8
x_{34}	0.11	2.7	2.5	2.6	2.8	2.2	3.1	3.0	2.2	3.0	3.3	3.2
X_4	0.45	2.5	2.2	1.7	2.1	2.3	2.9	2.7	1.8	2.7	2.7	2.3
x_{41}	0.38	2.6	2.1	1.3	1.6	2.3	2.7	2.7	2.1	3.0	3.6	3.1
x_{42}	0.3	2.6	2.7	1.8	2.4	2.0	2.5	2.1	1.7	1.6	2.2	2.0
x_{43}	0.32	2.3	1.9	2.0	2.3	2.6	3.4	3.2	1.5	3.5	2.2	1.7
X_5	0.15	2.9	2.5	2.0	2.7	1.9	2.4	2.8	2.1	2.0	2.5	2.8
x_{51}	0.16	2.2	2.4	2.1	2.1	1.8	2.0	1.6	1.6	1.2	2.0	2.3
x_{52}	0.43	2.7	2.6	2.5	2.9	2.1	2.5	3.0	2.4	1.9	2.6	3.2
x_{53}	0.2	3.2	2.6	1.2	2.7	2.0	3.0	3.0	2.3	2.5	2.5	2.7
x_{54}	0.21	3.6	2.5	1.6	2.8	1.5	2.1	3.0	1.7	2.2	2.5	2.4
Weighted MLMM		2.6	2.1	1.8	2.3	2.1	2.7	2.6	1.9	2.5	2.8	2.6
Unweighted MLMM		2.7	2.3	1.8	2.3	2.1	2.6	2.6	1.8	2.4	2.7	2.6

Table VIII. Comparison of results between the weighted and unweighted metrological management evaluation models

Conclusions

We have integrated two different analyses in this work, both based in the metrological management model outlined in the introduction of this paper and described in detail by Beltrán *et al.* (2010). These two analyses were focussed on the two basic hypotheses upon which the model is based, confirming one of them and discarding the other.

In the first analysis, we used SEMs to look at the intra-variable relations of the model. These relations confirmed that the model follows the Deming continuous improvement cycle, based on Planning (management responsibility and resource management), Doing (operative metrological processes), Verifying (analysis and improvement, oriented toward analysis) and Acting (analysis and improvement, oriented toward improvement). The confirmation of this fact was essential to validate the model, since companies base their metrological management on the ISO 10012:2003 (2003) standard, which is clearly based on the Deming cycle. Our SEM-based analysis proved that variations in our model were correlated with the expected results of the Deming cycle, which shows that the metrological management model can be fully integrated with the other process-oriented management standards applied in the company.

Second, we sought to perfect the design of improvement strategies for metrological management in companies, identifying the relative relevance of the different aspects involved. We used AHP techniques to obtain a weighted model to evaluate metrological management, and the fact that the different chapters and variables of the model obtained different weights discarded the hypothesis of equal contribution from all of them to the overall MLMM. This will enable us to reevaluate the MLMM for all the audited companies, and to evaluate new companies using this weighted model, thus providing better guidelines to assist companies in the improvement of their metrological management systems. Nevertheless, the weighted evaluations of the companies whose metrological management was audited showed very similar results to the unweighted ones, even though the contribution of the different model chapters to the overall results was significantly different.

The result of this work is the formulation of a robust model for the evaluation of the level of maturity of metrological management in companies, which is now integrated in the online tool EVAMED, available for the evaluation of the reliability of metrological processes. Furthermore, this evaluation model (UNE 66180:2008, 2008) is consistent with the metrological management model formulated in ISO 10012:2003 (2003), which in turn is consistent with the Deming cycle philosophy, as our analytical work also proved. With this evaluation model, companies can obtain a numerical score of their metrological management processes, which provides an evidence of their continuous improvement efforts toward guaranteeing the reliability of their measurements.

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Corresponding author
Dr Jesús Muñuzuri can be contacted at: munuzuri@esi.us.es