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GRAPH THEORY APPROACH TO QUANTIFY UNCERTAINTY OF PERFORMANCE MEASURES

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Abstract: *In this work, the performance measurement process is studied to quantify the uncertainty induced in the resulting performance measure (PM). To that end, the causes of uncertainty are identified, analysing the activities undertaken in the three following stages of the performance measurement process: design and implementation, data collection and record, and determination and analysis. A quantitative methodology based on graph theory and on the sources of uncertainty of the performance measurement process is used to calculate an uncertainty index to evaluate the level of uncertainty of a given PM or (key) performance indicator. An application example is presented. The quantification of PM uncertainty could contribute to better represent the risk associated with a given decision and also to improve the PM to increase its precision and reliability.*

Keywords: *Data Quality, Graph theory, Performance Measures, Risk determination, Uncertainty*

1. Introduction

Performance measurement process can be described as a set of steps involving designing, implementation, use and review of performance measures (PMs). Several authors argue that a PM should not be implemented in isolation and should instead be part of a performance measurement system (PMS). A PMS is a set of related PMs defined to assess an organization' progress in carrying out its mission. Many PMSs are available to companies, such as the Balanced Scorecard (Kaplan and Norton, 1996), or the Performance Prism (Neely *et al.*, 2002). PMs allow assessing processes' performance, comparing the performance of similar subsystems, or doing benchmarking exercises. The purpose of each PM must be clear (Basu, 2001) and must promote a company's strategy (van Schalkwyk, 1998). According to Macpherson (2001) the relevance of PMs is related to decisions they can support and that there are no bad PMs, only the bad use of them.

Before using a PM, some steps need to be performed: design and implementation. Subsequently other PMs must be reviewed to discard or change the ones that may no longer be needed. There are many works on the design and implementation of PMs (Sousa and Aspinwall, 2010) however, there are fewer works on the use and review of PMs. The "use" step can be described as the set of activities needed to collect the data and present results (Juran and Godfrey, 1999) or as a systematic process involving the following activities: data acquisition or

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measurement and data transmission (Lopes *et al.*, 2013).

It is expected that the resulting information from this process will be useful to make decisions (Juran and Godfrey, 1999). These decisions are made, typically, by different actors and with lower frequency than the above-mentioned activities. They can lead to ordinary control actions if the PM is outside its control limits (as in statistical process control (SPC)) or can support management actions. In both situations two types of errors can occur. Acting based on the value of a PM but its true value would not require action. In statistics (hypotheses testing) a similar error is called type I error or false positive and in SPC is called alpha risk, which represents the risk of pointing out a problem that does not exist. The second error consists on inaction based on the value of the PM when its true value would require action. In statistics a similar error is called type II error or false negative and in SPC is called beta risk, which represents the risk of not detecting a problem.

PMs can be considered a particular type of Data or Information and then they could have intrinsic errors if some attributes are not present. The literature refers (Batini *et al.*, 2009) some dimensions or attributes of Data/Information as: accuracy; completeness; timeliness; and consistency. This suggests that all data may lack some of these attributes, and there are several authors that suggest classifications of Information/Data Quality (Lee *et al.*, 2002). For example, Galway and Hanks (2011) classify data quality problems as operational, conceptual and organizational. There is an implied presumption that, were the data correct, the user could directly utilize them in making the necessary decision(s).

It can be argued that the discussion about the quality of data or information can be applied to PMs. To increase quality of PMs some of its attributes or requirements are identified in the literature (Macpherson, 2001; Ghalayini *et al.*, 1997; van Schalkwyk, 1998): relevant; credible; precise; valid; reliable and frequent.

It should be clear for the decision-maker the existence of uncertainty on data that produces the PM. This uncertainty may lead to increased risks in decisions, and it should be identified and represented to provide decision-makers with information on its magnitude. The quantification of PM uncertainty could contribute to better represent the risk associated with a given decision.

The study of the causes of PM uncertainty could also contribute to improve the process of designing, implementing, using and and reviewing the PMs. Particularly, it can represent a breakthrough on the reviewing step of existing PMs.

To contribute to the fields of data quality, performance measurement and benchmarking, the main objective of this work is to suggest a method to quantify uncertainty of PMs and to propose an Uncertainty Index associated with a given PM, which represents the level of uncertainty of a PM.

The paper is organised as follows. Section Two identifies the uncertainty sources or causes of PMs and its dependences. In Section Three a method is proposed to represent it through an uncertainty index. Section Four provides a numerical example and, finally, conclusions are drawn in Section Five.

2. Uncertainty sources of performance measures

2.1. Characterization of uncertainty sources

The set of activities associated with PM can be defined as a process, since they are repeatedly performed in a similar way. In the field of quality management, according to Juran and Godfrey (1999) those activities consist of: (i) understand the framework, (ii) plan the measurement, (iii) collect and store data, (iv) analyse, synthesize, formulate recommendations, present results and recommendations, and (v) make decision and take action.

A typical classification of the same activities in the field of performance measurement is: (a) design, (b) implementation; (c) use and (d) review (Braz *et al.*, 2011).

This work will explore in detail the factors, in the above activities, that can induce uncertainty in the resulting performance measure. These factors will be also designated by sources or causes of uncertainty. Because other classifications of activities of performance measurement can be proposed, and many classifications depend on the objectives of a given research, this work makes the analysis considering the following classification:

Stage 1. Design and Implementation (includes activities (i), (ii), (a) and (b) cited previously) – This stage consists in the understanding of stakeholders' requirements, organisational goals and the decisions actions space that can influence results. Organisational context and restrictions, such as capabilities and existing Performance Measures should affect the design of PMs resulting in a measurement plan. This plan can include a measurement protocol and should define all PM's relevant attributes according to best practices. It will also define the data analysis plan. Finally, to put these two plans into practice, some context restrictions may influence its implementation. This stage ends when the measurement and analysis plan are operational and ready to be used.

Stage 2. Data Collection and record (includes activities (iii) and (c)) – The Data collection consists of obtaining data and can be performed in different way, such as reading a value in a measurement device that may be installed in the production process or counting the number of occurrence of a particular event. In order to use the collected data to calculate a PM for a given period of time, data should be registered in (and, eventually, transmitted to) a computer or datasheet and be stored for latter analysis.

Stage 3. Determination and analysis (includes activities (iv) and some of (c)) – conduct planned analysis. The PM Determination consists of selecting recorded data for a specific period of time and applying a predefined expression for calculating the PM. Data analysis should be performed according to the plan, and should check if all the assumptions related to the PM and its context are still valid.

Two factors conducted to this classification: frequency of the activity and the actors involved.

In terms of activity frequency, design and implementation (stage 1) is made once, while collection and recording (stage 2) is the most frequent one. Determination and analysis (stage 3) has a frequency equal or minor than data collection and recording (stage 2).

Regarding the actors of these activities, typically, PMs are designed (stage 1) and/or authorized by top management, while data collection and recording (stage 2) is either an automated activity or it is done by operators. The determination and analysis (stage 3) is usually performed by someone with more responsibility than the previous actor and, in some cases, may be able to perform some decisions /actions based on the analysis outcome.

It is out of the scope of this work to study the decisions and actions based on the PMs. The outcome of this work is intended to be an input to activity (d) (the review stage), i.e. it will contribute to the improvement of PMs' quality. Table 1 synthesises the proposed stages to be analysed.

Table 1. Performance measure's stages characterisation

Stage	Description	Frequency	Typical Actors
1. Design and Implementation (D&I)	Understand the stakeholders' requirements, design PMs resulting in a measurement plan and implement the plan, considering the context.	Rare (once per PM)	Top Management
2. Data Collection and Record (C&R)	Collect and store data of PM according to plan.	High	Operators (or automated)
3. Determination and Analysis (D&A)	Conduct planned analysis	Medium	Technicians/ Middle management

Some of the activities in the stages can be made automatically (for example by a computer application), while others can be made manually (i.e. it may depend on human tasks). Generally, it could be a combination of both. All these activities can influence the results or values of any PM. Thus an unknown error or uncertainty is present in any PM. The following subsections present the factors on each of these three stages, which could contribute to the uncertainty of any given PM.

2.1.1. Design and implementation stage

Concerning the design and implementation stage, behaviour and competency of the people involved, the procedures or methodologies used to design and implement the PM, the context or environment conditions in view of the dimension to be measured, the type of policy adopted by the organization regarding human, knowledge and quality management as well as the organization culture, are factors that impact on the confidence of PM. Some attributes of each of these factors or uncertainty sources are presented in Table 2.

Table 2. Sources of uncertainty of the design and implementation Stage

Factor	Description
People (PE)	- **Experience** - **Knowledge acquiring and processing** (perceptions skills and knowledge and learning skills). - **Complacency** (professionalism, responsibility and interest regarding the work).
Procedure (PR)	- **Existence of a (standard) procedure** - **Descriptive/prescriptive procedure** - **Procedure, guidelines and laws are followed** - **Best practices are followed** (Benchmarking).
Context (CO)	- **Predictability** (dynamic/chaotic). - **Complexity** (dynamic/chaotic). - **Constraints** (economic, operational or technological).
Policy (PO)	- **Human resources management** (training). - **Knowledge management** - **Quality management** (definition of standards, procedures and responsibilities).
Organization culture (OC)	- **Management commitment/involvement** (providing necessary resources). - **Continuous improvement culture** (present problems avoided in the future).

2.1.2. Collection and record stage

In the collection and the record stage, beyond the organization culture and people factors that are also considered in this stage, the availability of an adequate and clear methodology for measurement and record, the appropriateness of the workplace environment, the accuracy, precision and ergonomics of the measurement equipment, the effectiveness of the record system, as well as management system maturity are factors that usually impact on PM confidence or uncertainty. These factors or sources of uncertainty are summarized in Table 3. Depending on the situation, some listed factors can be considered not significant, such as people factor when the collection and record systems are automated.

Table 3. Sources of uncertainty of collection and record stage

Factor	Description
People (PE)	- **Physical and mental fitness of operator** (emotional stability, concentration and memory, visual acuity, dexterity). - **Knowledge acquiring and processing of operator** (perceptions skills and knowledge, stress handling capacity, learning skills and experience). - **Complacency** (professionalism, responsibility and interrest regarding the work)
Measurement method (MM)	- **Measurement procedure** (availability of procedure comprehensively written). - **Supervision** (clarity of instructions of the supervisor).
Record method (RM)	- **Record procedure** (availability of procedure comprehensively written). - **Supervision** (clarity of instructions of the supervisor).
Workplace environment (WE)	- **Luminosity** - **Organization** - **Tidiness** - **Temperature**
Measurement equipment (ME)	- **Measurement equipment precision.** - **Measurement equipment accuracy** (equipment regularly calibrated). - **Measurement equipment design** (ergonomic design, easy to handle to perform measurement and values easy to read).
Data record system (DR)	- **Error-proneness** - **Error detection and proofing**
Management (MA)	- **Human resources management** (workload planning and training). - **Equipment management** (measurement equipment and data record system). - **Workplace management**. - **Quality management** (definition of standards, procedures and responsibilities).
Organization culture (OC)	- **Management commitment/involvement** (providing necessary resources). - **Continuous improvement culture** (recurrent problems avoided in the future).

2.1.3. Determination and analysis stage

In the last stage, people, management and organizational culture are also considered. Other significant uncertainty sources can be: the suitability of the determination and analysis method and of the tool used to perform the analysis, and the availability, accuracy and clearness of context information provided or acquired to perform the analysis. These sources are summarized in Table 4.

Table 4. Sources of uncertainty of determination and analysis stage

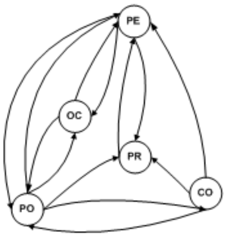
Factor	Description
People (PE)	- **Experience** - **Knowledge acquiring and processing** (perceptions skills and knowledge, stress handling capacity, learning skills and experience). - **Complacency** (professionalism, responsibility and interrest regarding the work)
Determination method (DM)	- **Determination procedure** (availability of procedure comprehensively written). - **Flexibility or adaptability of the method** (the method should change when there are changes in the system).
Analysis method (AM)	- **Determination procedure** (availability of procedure comprehensively written). - **Flexibility or adaptability of the method** (the method should change when there are changes in the system).
Tool or device (TO)	- **Software or Hardware operation** - **Presentation clarity** - **Flexibility**
Context Information (CI)	- **Information availability** - **Information accuracy** - **Information clarity**
Management (MA)	- **Human resources management** (training). - **Equipment management** (tool). - **Quality management** (definition of standards, procedures and responsibilities).
Organization culture (OC)	- **Management commitment/involvement** (providing necessary resources). - **Continuous improvement culture** (present problems avoided in the future).

If these sources were assumed independent and with the same effect in the uncertainty of the PM, then, its degree of achievement could be the basis to determine the uncertainty of a PM. However, these sources are related and therefore a different approach is proposed in the next section.

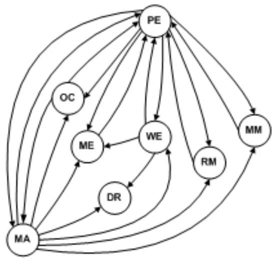
2.2. Identification of relationships among identified sources of uncertainty

The identified sources of uncertainty are related to each other, once each source can have an influence in the contribution to uncertainty of another source. For example, since Management (MA) takes care of all resources of the organization and decides about the methods to perform all the activities, it will influence positively or negatively the performance of: People (PE); Equipment (measurement equipment (ME) and data record system (DR)); measurement, registration and determination methods; and Work Environment (WE).

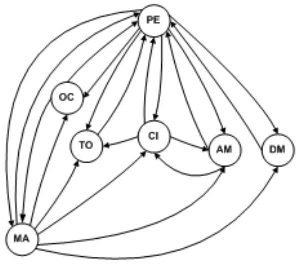
Similar relations can be deduced with other sources and may be depicted through a graph or digraph (graph with oriented edges). Figure 1 presents the digraph for each of the three stages: a) for the design and implementation stage, b) for the collection and record stage and c) for the determination and analysis stage. The nodes represent the causes or sources of uncertainty. Whenever a source of uncertainty affects the uncertainty contribution of another source, increasing the uncertainty of the PM, an arc will be present in a graph representation.



a)



b)



c)

Figure 1. Digraph of uncertainty sources and their dependencies (a) Digraph of the design and implementation stage, b) Digraph of the collection and record stage, c) Digraph of the determination and analysis stage)

2.3. Quantifying uncertainty using graph theory

In this work, graph theory is used to quantify the uncertainty in PMs. Therefore, the digraphs of Figure 1 are converted into three matrices (1) which will be designated by uncertainty sources matrices. The A_i elements of the matrices (represented in the graphs by a node) consist in the contribution of the *i* source for the uncertainty in the PM in the considered stage.

Since these contributions will be defined based on the judgment of people involved in the PM review, a scale based on qualitative information should be defined. Different approaches could be used: probability or fuzzy theories that will be able to deal with subjectivity or a Likert-type scale, to allow people involved expressing their degree of importance of the source. In this work, the contribution of the sources of uncertainty will be defined using a scale which starts in 1, which is the lowest value, assigned to a factor or source that is considered in the graph (factor that is considered as a source of uncertainty with a very low contribution to uncertainty). The value 5 is the highest value, which will be assigned to a factor that has a very high contribution to uncertainty.

The off-diagonal elements (a_{ij}) (represented in the graph by an arc between two nodes) consist in the relationship or interdependency between sources. The value assigned to the relationships will be decided by those involved in the performance measurement process. Their values will be defined in a scale from 1 to 5, assigning the 1 value when it is considered that no dependency exists, situation that is represented in the graph by the absence of an edge, 2 to 4 values when the dependency is weak (2), moderate (3) or strong (4) and 5 when the dependency is very strong.

$$S_n = \begin{bmatrix} A_1 & a_{12} & a_{13} & . & . & a_{1M} \\ a_{21} & A_2 & a_{23} & . & . & a_{2M} \\ a_{31} & a_{32} & A_3 & . & . & a_{3M} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{M1} & a_{M2} & a_{M3} & . & . & A_M \end{bmatrix} \quad (1)$$

The quantification of PMs uncertainty proposed in this paper will be performed through a methodology that uses the Permanent function (*per*) of the matrices. The permanent function is a mathematical expression used in combinatorial mathematical which is based in the A_i and a_{ij} values and correspond to the sum of several terms. The Permanent function is similar to the determinant of a M×M matrix considering all the terms as positive and hence, no information is lost (Rao, 2007).

3. Proposed methodology to quantify the uncertainty of performance measures

This section presents a methodology to develop an Uncertainty Index, which represents the uncertainty of a PM.

Taking into account the factors and relationships considered in each stage for a given PM, represented by S_n, the permanent function of each matrix is an indicator of the level of uncertainty of such PM in stage *n* (*n* = 1, 2, 3). Several authors have used this function in similar works (Rao, 2007; Darvish *et al.*, 2009; Aju Kumar and Gandhi, 2011). This value provides a means of representing not only the magnitude of an uncertainty source but also its effect on others sources. The higher the $per(S_n)$, the higher is the uncertainty of a PM.

This function can take values in different intervals for different PM. The maximum or minimum theoretical value can be used to create an easy to interpret index for each stage *n*, given by:

$$UI_n = \frac{per(S_n) - per(S_{n\min})}{per(S_{n\max}) - per(S_{n\min})} * 100 \quad (2)$$

The maximum value of the permanent function of the associated matrix $Per(S_{nmax})$ of a given PM is obtained when all the diagonal elements take the maximum value (the A_i are equal to 5) and the off-diagonal elements remain unchanged.

The minimum value for the permanent function of the global matrix $Per(Sn_{min})$ is obtained when the contribution of all the considered sources are equal to the minimum value (the A_i are equal to 1) and all the off-diagonal remain unchanged.

When $per(S_n) = per(S_{nmin})$, the UI is equal to zero and this represents an ideal PM. When $per(S_n) = per(S_{nmax})$, the UI_n is equal to 100%, which corresponds to the biggest uncertainty for a PM for a given context.

There are several alternatives to build a unique uncertainty index based on the three uncertainty indices previously defined. The average of the three indices (one possible alternative) would not be adequate since the uncertainty of one stage is not reduced if other stage has lower contribution to the uncertainty of the PM. It is proposed a simple method linked to the PM improvement goal (i.e. to reduce its associated uncertainty). The method consists of defining the PM UI as the maximum of the three UI_n previously calculated.

$$UI = Max(UI_n) \qquad (3)$$

The proposed methodology for evaluating the uncertainty associated with a given PM is exposed in Table 5. The information obtained from the utilization of this methodology may be used by top management to review the PM acting on the system to reduce the sources of uncertainty. The stage with highest UI_n should be assessed to ascertain improvements in the measurement process. After the implementation of improvements another iteration of the methodology could be made to ascertain the new value of the Uncertainty Indicator, starting at step 3.

After determining the UI (step six) it should be appended to the PM and its evolution monitored over time. Benchmarking exercises should include this index in data analysis.

Table 5. Proposed methodology to quantify the uncertainty of performance measures

Step	Description
1- Identifying uncertainty sources	For the given performance measurement process, the sources of uncertainty in each stage of the performance measurement process are identified, collecting and analysing information about the process. The digraphs of Figure 1 should be taken as reference.
2- Graphical representation of sources and their relationships for each stage	Three digraphs, one for each stage, are drawn considering the sources identified in the previous step and the relationships between these sources. These relationships are also identified analysing the process.
3- Developing uncertainty sources matrices for each graph	Fill in three matrices corresponding to each digraph: $S_{D\&I}$, $S_{C\&R}$ and $S_{D\&A}$. The matrices' dimensions are given by the number of uncertainty sources present in each stage. The diagonal elements (A_i) and the off-diagonal elements (a_{ij}) are quantified by people involved in the review process
4- Obtaining the uncertainty sources function of each matrices	For each matrices defined in the previous step, the permanent function per(S_n) is calculated.
5- Determining the uncertainty index (UI_n) for each stage	For each stage n, the maximum and minimum value of the Permanent function is calculated assigning the maximum value (9) and the minimum value (1), respectively, to the diagonal elements of the corresponding matrix, obtaining thereby the maximum value of the permanent function in each stage Per($S_{D\&Imax}$), Per($S_{C\&Rmax}$) and Per($S_{D\&Amax}$), and the minimum value Per($S_{D\&Imin}$), Per($S_{C\&Rmin}$) and Per($S_{D\&Amin}$). Based on Per($S_{D\&I}$), Per($S_{C\&R}$) and Per($S_{D\&A}$), the uncertainty index is calculated for each stage n, following the expression (3)
6- Determining the uncertainty index (UI) for the Performance Measure	UI= max (UI_n). Based on the UI_n (step 5) the worst situation (maximum uncertainty at a given stage/activity) should be focussed as the target for improvement.

If there is no consensus on a given value (step 3), sensitivity analysis should be performed to provide information on the robustness of the proposed index.

4. Application example

The application example concerns the manufacturing of Printed Circuit Boards

(PCBs) to be used in car multimedia systems by a multinational company. In the production lines of PCBs, an automated optical inspection (AOI) system is used to control and assess the quality of the reflow soldering process. PCBs are autonomously scanned by a camera to identify a variety of soldering defects such as open circuits or short circuits. These defects are measured by the volume of solder paste placed on a given PCB position and compared with pre-defined specifications.

To reduce defects detected at the final quality control test, aligned with the company continuous improvement culture, it was decided to use a performance indicator to be calculated at the end of the reflow soldering process: number of soldering defects per million opportunities (DPMO).

A quality team was commissioned to define the performance measure and the methods of collection, record, determination and analysis. The same team implemented the PM. Since the equipment, AOI, is not able to measure all the positions of soldering deposition during the cycle time, only usual critical positions are analyzed. The PCB fixation mechanism and its position when optical inspection is made is a critical factor to the quality of the measurements.

In each PCB, AOI signals and registers the number of soldering defects in the critical inspected positions in a database. The number of inspected positions is also recorded for each PCB in the same database. Daily DPMO is calculated for each shift of the company production lines. The DPMO values are controlled daily by the line manager. Weekly, in the quality team meeting the obtained values in each line and shift are compared to each other and with the established target, and possible tendencies are checked.

In one of these meetings, the analysis of the performance measure uncertainty was undertaken following the methodology proposed in this paper and the matrices ((3), (4) and (5)) for each performance measure stage were defined by consensus.

$$S_{D\&I} = \begin{array}{c} \\ PE \\ OC \\ PO \\ PR \\ CO \end{array} \begin{array}{c} \begin{array}{ccccc} PE & OC & PO & PR & CO \end{array} \\ \begin{bmatrix} 2 & 4 & 2 & 4 & 1 \\ 4 & 1 & 3 & 1 & 1 \\ 3 & 2 & 1 & 3 & 3 \\ 2 & 1 & 1 & 3 & 1 \\ 3 & 1 & 4 & 5 & 4 \end{bmatrix} \end{array} \qquad (4)$$

$$S_{C\&R} = \begin{array}{c} \\ OC \\ MA \\ ME \\ WE \\ DR \end{array} \begin{array}{c} \begin{array}{ccccc} OC & MA & ME & WE & DR \end{array} \\ \begin{bmatrix} 1 & 5 & 1 & 1 & 1 \\ 3 & 4 & 3 & 5 & 4 \\ 1 & 1 & 5 & 1 & 1 \\ 1 & 1 & 2 & 4 & 2 \\ 1 & 1 & 1 & 1 & 2 \end{bmatrix} \end{array} \qquad (5)$$

$$S_{D\&A} = \begin{array}{c} \\ PO \\ OC \\ MA \\ TO \\ CI \\ AM \\ DM \end{array} \begin{array}{c} \begin{array}{ccccccc} PO & OC & MA & TO & CI & AM & DM \end{array} \\ \begin{bmatrix} 1 & 4 & 3 & 2 & 3 & 2 & 2 \\ 4 & 1 & 4 & 1 & 1 & 1 & 1 \\ 3 & 2 & 2 & 4 & 5 & 2 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 1 \\ 3 & 1 & 1 & 3 & 2 & 4 & 1 \\ 3 & 1 & 1 & 1 & 3 & 2 & 1 \\ 2 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \end{array} \qquad (6)$$

Based on the matrices (4), (5), (6) and equation (2), the uncertainty index was calculated for each stage according to Table 6.

Table 6. Results of Uncertainty Indices for each performance measurement stage

Permanent function/Stage n	D&I	C&R	D&A
$Per(S_n)$	8 024	4 088	452 728
$Per(S_{nmax})$	26 370	12 870	2 495 280
$Per(S_{nmin})$	4 602	1 078	237 976
UI_n	**15.7%**	**25.5%**	**9.5%**

The UI of this performance measure is 25,5%. As it was expected, the Collection and Record stage was the one with higher uncertainty mainly due to the PCB fixation mechanism. The third stage has the lowest uncertainty index, despite having several factors that could contribute to PM uncertainty, since these factors are being well managed.

Results interpretation suggests that this performance indicator could be improved if the Collection and Record stage is enhanced. In these conditions the highest uncertainty sources to be analysed for potential improvement are Management (A_2), Measurement Equipment (A_3) and Workplace Environment (A_4).

The quality team in cooperation with the AOI manufacturer developed and implemented modifications on the fixation mechanism and associated measurement set-up, resulting in an improved precision and accuracy of measurements.
After putting in place this process improvement the quality team reassessed element A_3 (of $S_{C\&R}$) from A_3=5 to A'_3= 2, resulting in a new matrix $S'_{C\&R}$. The per($S'_{C\&R}$) is 2 555 and the UI'_2 is 12,5%. The new value of PM uncertainty (UI') is now, 15,7%, resulting in a lower level of uncertainty for the PM. This improved PM has the main source of uncertainty defined by the uncertainty of D&I stage. A further iteration could be made to ascertain the feasibility of changing the Design & Implementation stage to achieve a potential improvement of UI' from 15,7% to 12,5% (imposed by the improved C&R stage).

5. Conclusions

The process of performance measurement was analysed in order to identify and define the sources of uncertainty that may affect the value of PMs. Three stages were analysed and controllable factors that company can influence were identified, which provides detailed knowledge about a given performance indicator. Besides these relevant sources of uncertainty the method considers their interdependences in the quantification of uncertainty of a given stage. For each stage of performance measurement, the permanent function of the matrix associated with the graph of these sources is used to determine the value of the uncertainty index of any PM.

One of the biggest contributions of this work is to present managers with a tool to assess the uncertainty of any PM. In addition, the method deployment allows focusing on the improvement of such PM, because it assesses the sources of uncertainty, allowing the computation of improvements in the Uncertainty Index if an enhancement in a controllable factor is decided.

This work is part of a project that aims to develop a framework to reduce the uncertainty of performance measurement systems. Results could provide a breakthrough on the method of revising the Performance Measurement System by increasing Data Quality. This issue is also relevant in Benchmarking.

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