XI Congreso Galego de Estatística e Investigación de Operacións
A Coruña, 24-25-26 de outubro de 2013

QUANTIFICATION OF UNCERTAINTY OF PERFORMANCE MEASURES USING GRAPH THEORY

Isabel S. Lopes[1], Sérgio D. Sousa[2] e Eusébio Nunes[3]

[1,2,3] Centro Algoritmi, University of Minho

ABSTRACT

In this paper, the graph theory is used to quantify the uncertainty generated in performance measures during the process of performance measurement. A graph is developed considering all the sources of uncertainty present in this process and their relationship. The permanent function of the matrix associated with the graph is used as the basis for determining an uncertainty index.

Keywords: Data Quality, Graph Theory, Performance Measures, Uncertainty.

1. INTRODUCTION

Performance measurement can be described as a set of steps involving designing, implementation, use and review of performance measures. Performance measures (PMs) must be designed and implemented before using them. There are many works on the design and implementation of PMs (Sousa and Aspinwall, 2010), however, the above mentioned steps are not performed with the same frequency, suggesting that a different attention should be made to them. For example, designing or implementing PMs is not typically done on a daily basis, but its use may be a company's daily activity. The "use" step can be described as the 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 measurement, data transmission and performance measure determination.

It is expected that the resulting information from this process will be useful to make decisions. Juran and Godfrey (1999) argue that "the choice of what to measure and the analysis, synthesis, and presentation of the information are just as important as the act of measurement itself" and emphasise the system to which the measurement process belongs. The larger measurement systems also embrace the decisions that are made and the framework in which the process operates. These decisions are made, typically, by different actors and with lower frequency than the above-mentioned activities.

To design a Performance Measurement System it is crucial to understand who will make the decisions (and how) and who will take actions (Juran and Godfrey, 1999), i.e. the purpose of each PM must be clear (Basu, 2001), and must promote a company's strategy (Schalkwyk, 1998). Before determining what to measure and how to measure it, the overall framework in which the Performance Measurement System operates should be understood (Juran and Godfrey, 1999). It can be concluded that the relevance of PMs is related to decisions they can support and that there are no bad PMs, only the bad use of them (Macpherson, 2001).

PMs can be considered a particular type of Data or Information and the literature refers some dimensions or attributes of Data/Information as (Batino et al., 2009): accuracy; completeness; timeliness; and consistency. This suggests that all data may lack some of these attributes, and there are examples of authors that suggest several classifications of Information/Data Quality (Lee et al., 2002), for example, Galway and Hanks (2011) classify data quality problems as operational, conceptual and organizational. Associated with operational data problems 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 quality of data or information can be applied to PMs. It should be clear to the decision-maker the existence of uncertainty on data that produces the PM. The quantification of data uncertainty could contribute to better represent the risk associated with a given decision. The study of the causes of data uncertainty could also contribute to improve the process of designing and reviewing the PMs.

To increase quality of PMs some of its attributes or requirements are identified in the literature (Macpherson, 2001), (Schalkwyk, 1998), (Ghalayini et al., 1997): relevant; credible; precise; valid; reliable and frequent. Other authors also refer that good PMs should have the following characteristics:

• data collection and methods for calculating the PMs must be clearly defined (Globerson, 1985);

• presentation of PMs must be simple (Tenner and DeToro, 1997);

• PMs must be flexible (Ghalayini et al., 1997), including being tied to desired results (Franco and Bourne, 2003);

• more extensive use should be made of subjective data (Schalkwyk, 1998); and

• ratio-based performance criteria are preferred to absolute numbers (Globerson, 1985).

However, the designing of PMs may not comply with all of these requirements and, even if they are all fulfilled at the design stage, during its implementation or use the system on which the PMs are integrated may change (Sousa et al. 2013).

To contribute to the field of Performance Measurement and to the field of Data Quality, this work studies the causes of uncertainty on the process of using PMs. A quantitative methodology based on graph theory is used to calculate an indicator for uncertainty evaluation of a given PM or (key) performance indicator.

2. THE PERFORMANCE MEASUREMENT PROCESS

The process of performance measurement (use step) involves three different activities: measurement, data record/transmission and performance measure determination (fig. 1).

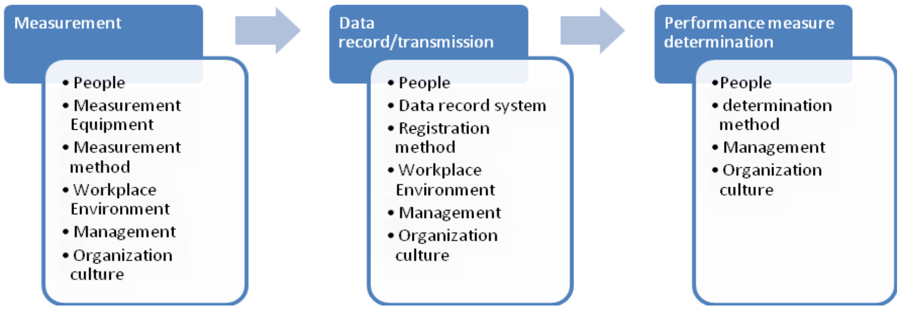

Figure 1: The process of performance measurement

The Measurement Activity 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 data collected in the previous activity to calculate a PM for a given period of time, data should be registered in a computer or datasheet. The Data Record/Transmission Activity can be made in different ways: data is automatically registered when the measurement is performed; or the data is recorded by someone who reads the value and writes it in a computer system or datasheet.

The PM Determination Activity consists of selecting recorded data for a specific period of time and applying a predefined expression for calculating the performance measure. This task can be made automatically by a computer application or can be made manually.

In this process, several factors can induce uncertainty. These factors that are considered as the sources or causes of uncertainty are presented in figure 1 associated with each activity whose results they influence, and are explained in the next section.

3. FACTORS INFLUENCING THE PERFORMANCE MEASUREMENT PROCESS

1. People (PE)

The People factor can induce uncertainty in all three activities: measurement, data record/transmission and performance measurement activities. However, if the data acquisition is automatic, people will not be involved and this factor would not contribute to uncertainty.

The personnel can induce uncertainty deliberately or unintentionally. Measurement is frequently a repetitive task which requires concentration and memory, visual acuity and dexterity. In several situations, experience has also a significant impact in the result of the measurement activity. For instance, the identification of defects in footwear production involves analysing some attributes in order to verify if they are complying with specifications. The experience of the people involved in this process is relevant to identify all the attributes that are not in accordance with requirements and to avoid concluding that the attribute is not in conformity when, in fact, it is.

The personal characteristics of the people involved, such as knowledge, stress handling capacity and learning skills, helps in the avoidance of errors in adverse or dynamic situation.

Recording data is also a repetitive task that can be influenced mainly by the capacity of concentration of people involved. The capacity of concentration, knowledge and experience are also important factors for the activity of PM determination.

2. Measurement method (MM)

A procedure for measurement could be available or not. In certain cases, it is not necessary but in other cases, it is. The procedure method, when required, should be comprehensively written to avoid misunderstanding and should be easy to read to facilitate knowledge acquisition.

The operator may follow the instructions of the supervisor that could be clearly expressed or not. Due to a faulty communication process, the measurement method may be performed erroneously.

3. Registration method (RM)

As the measurement method, a registration method not clearly explained could be a source of uncertainty in the results. If data is introduced in a digital support, errors can occur. When data is computed automatically, there is a small possibility of detecting these errors.

4. Workplace environment (WE)

Workplace environment can affect the results in both automatic and manual data acquisition. Environment factors such as the luminosity, tidiness, workplace organization and temperature could impair the measurement and registration activities made by the operator. In an automatic process, factors such as dirtiness and temperature may, in some situation, have an important effect in the equipment used.

5. Management (MA)

Appropriate training should be given to people involved in the measurement, data registration and performance measure determination activities, in order to assure that they have the adequate knowledge and skills to perform the activities correctly.

A good management of measurement equipment and data record system should also be made in order to assure its correct functioning when required. It involves performing adequate maintenance actions and calibrations periodically. Once the workplace affects the measurement and registration activities, the organization should take care of defining and assuring the adequate workplace environment.

If the organization has a management system implemented, following for instance the ISO 9001 standard, it is expectable that it defines standards, procedures and responsibilities. In this case, if it is considered necessary, procedures will be certainly available for measurement, registration and PM determination. The organization will also manage adequately their resources such as human resources and equipment.

6. Organization culture (OC)

Management should be committed with the performance measurement system and all its indicators in order to provide the necessary resources such as training, human resources, adequate equipment and record system (software and hardware, for example).

If a culture of continuous improvement is in place in the organization, it is expected that problems that have occurred in the past are avoided in the future through the implementation of improvement actions. Therefore, it is expected that the uncertainty induced in the results would be less in this case.

7. Data record system (DR)

If the data record system works in a digital support, the software or hardware of the technology used can induce uncertainty when performing in a non-regular way (error in data transmission, error in registration). For instance, if there is a power failure, the transmission or registration process can be missed without being noticed.

8. Measurement equipment (ME)

The measurement equipment can introduce error on data directly or indirectly. It induces errors directly through its precision and accuracy. While precision is intrinsic of the equipment and cannot be changed without a technical change in equipment, the accuracy can be improved by regular calibrations.

The measurement equipment design characteristics such as ergonomics, usability and easily to read are important factors in the reduction or avoidance of errors introduced by people that use the equipment.

9. Determination method (DM)

A PM should reflect adequately the reality that it measures. An organization should define the expression and the necessary data for its calculation.

The determination method can be applied erroneously even if there is a procedure for its calculation. However, if this procedure exists and it is followed properly, then the uncertainty introduced by this factor will be insignificant, considering a static environment. Once the reality that is measured is generally dynamic, after been defined, the PM and the determination procedure must be reviewed periodically in order to adapt it to new situations.

4. RELATIONSHIP BETWEEN THE IDENTIFIED FACTORS

The identified factors or sources of uncertainty are related to each other, once each factor can have an influence in the contribution to uncertainty of another factor.

The Organization Culture (OC) will affect the performance of the people. If the culture promotes team work, the involvement of people, rewarding, recognition and training, then people will be more motivated. The organization culture will also affect the way the organization is managed.

Once Management (MA) takes care of all resources of the organization and decides about the methods to perform all the activities, a good or bad management will influence positively or negatively the performance of its resources and methods, such as:

- People (PE);
- Equipments (Measurement equipment (ME) and data record system (DR));
- Measurement, registration and determination methods;
- Work Environment (WE).

On the other hand, the WE can affect the performance of people and of the equipments used, such as the measurement equipment and the data record system. For instance, a WE with high temperature or high humidity can damage the equipment or affect its accuracy or precision.

A good performance concerning the uncertainty contribution of the People factor (PE) can induce a good performance in the contribution of the factors related to:

- Equipments, since people has adequate dexterity and skills to handle and use the equipments despite the equipment been easy or not easy to be manipulated;
- Work environment, since its influence in the work performed by the worker will be lower;
- Methods (measurement, registration and determination), since methods are easily understood and applied with or without well written procedures.

The method used will affect, in its turn, the people factor. For instance, if the method of registration involves several steps and the memorization of data, then it is expected that some errors will be introduced by the operator.

Whenever a factor or an uncertainty source affects the uncertainty contribution of another factor, increasing the uncertainty of the PM, an edge will be present in a graph representation. Hence, the resulted graph of the considered process is represented in figure 2.

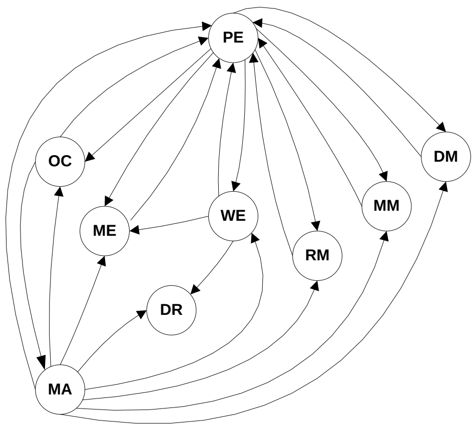

Figure 2: Graph of uncertainty sources and their dependencies

5. THE GRAPH THEORETICAL APPROACH

Graph theoretical methodology has been used by many authors to model and analyse several systems and problems in different fields of science and technology (Kumar and Gandhi, 2011). A graph/digraph is designed in order to represent the system or problem and, based on this digraph, a matrix is built assigning values to the nodes and edges. The representation of the graph/digraph by a matrix offers ease in computer handling (Tilak et. al, 2010). The permanent function of the matrix is used to obtain an index which is used to evaluate the system or problem.

Some authors have proposed methods based on graph theory for different selection processes and ranking. Rao (2006a) proposed a method to evaluate and rank flexible manufacturing systems using graph theory in order to select a suitable manufacturing system from among a large number of available alternatives. The graph is developed considering factors that influence the selection and their relative importance. Rao (2006b) proposed a similar method to select materials for a given engineering component. A method for the selection and comparison of robots was developed by Rao and Padmanabhan (2006). Graph theory was also used for ranking contractor considering that selection criteria are dependent to each other unlike most of the methods that have been developed to perform this selection (Darvish et al., 2009).

Some others authors used graph theory to produce an index that quantify and help to evaluate a system. Tilak et al. (2010) defined a methodology for finding the feasibility of transition to flexible manufacturing systems for any industry defining the enablers which facilitate this transition process. Wagner and Neshat (2010) developed an approach to quantify and hence mitigate supply chain vulnerability. Kumar and Gandhi (2011) proposed a methodology to quantify human error in carrying out maintenance of equipment. The contributing factors in error occurrence and their relations are identified in order to build graphs which originate matrices for which permanent function is determined.

In this work, the graph theory is used to quantify the uncertainty in PMs. Therefore, the graph in figure 2 is converted into a matrix which will be designated by the uncertainty sources matrix (1). The A_i elements of the matrix (represented in the graph by a node) consist in the contribution of the *i* source for the uncertainty in the performance measure. A scale should be used to assign value to these elements. In the literature, different scales are used. The off-diagonal elements (a_{ij}) (represented in the graph by an edge between two nodes) consist in the relationship or interdependency between sources. The value assigned to each source and their relationships will be decided according to expert judgment and to those involved in the performance measurement process.

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

The Permanent function is a mathematical expression used in combinatorial mathematics that, based in the A_i and a_{ij} values, determines a result that will be used to determine an uncertainty index. This function is the sum of several terms and is nothing but the determinant of a M×M matrix considering all the terms as positive and hence, no information is lost (Rao R. V., 2007).

The general expression for the permanent function of an M×M matrix is given as:

$$
\begin{aligned}
Per(S) = \prod_{i=1}^{M} A_i &+ \sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{ji}) A_k A_L \dots A_M \\
&+ \sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{jk} a_{ki} + a_{ik} a_{kj} a_{ji}) A_l A_m \dots A_M \\
&+ \left\{ \sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{ji})(a_{kl} a_{lk}) A_m A_n \dots A_M \right. \\
&+ \left. \left[\sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{jk} a_{kl} a_{li} + a_{il} a_{lk} a_{kj} a_{ji}) A_m A_n \dots A_M \right] \right\} \\
&+ \left(\sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{ji})(a_{kl} a_{lm} a_{mk} + a_{km} a_{ml} a_{lk}) A_n A_o \dots A_M \right. \\
&+ \left. \sum_i \sum_j \sum_k \dots \sum_M (a_{ij} a_{jk} a_{kl} a_{lm} a_{mi} + a_{im} a_{ml} a_{lk} a_{kj} a_{ji}) A_n A_o \dots A_M \right) + ..
\end{aligned}
\tag{2}
$$

6. THE PROPOSED METHODOLOGY

For evaluating the uncertainty associated with a given performance measure, the following methodology is proposed.

1. Identifying uncertainty sources - For the given performance measurement process, the sources of uncertainty are identified collecting and analysing information about the process. The graph of figure 2 should be taken as reference.

2. Graph representation of sources and their relationships - The graph is drawn considering the sources identified in the previous step and the relationships between this sources that are also identified analysing the process.

3. Developing uncertainty sources matrix of the graph - The value of the diagonal elements (A_i) will be defined by experts in a scale from 1 to 10 (1 for a minimum uncertainty induced by the source and 10 for the maximum) and the off-diagonal elements (a_{ij}) will be defined in a scale from 1 to 5 (1 for a weak relationship and 5 for the strongest).

4. Obtaining the uncertainty sources function of the matrix - Based on the matrix defined in the previous step the permanent function per(S) is calculated.

5. Determining the uncertainty index (UI) - Taking into account the factors and relationships considered in the studying case (graph defined in step 2), the maximum value for the permanent function of the associated matrix is obtained when all the diagonal elements take the maximum value of the considered scale (10) and all the non-zero off-diagonal elements take also its maximum value (5). This matrix will be designated by S_{max}. Similarly, the minimum value for the permanent function is obtained when the contribution of all the considered sources are equal to 0 (the A_i are equal to zero) and all the non-zero off-diagonal elements take their minimum values (1), taking into account the factors considered in the studying case. This matrix will be designated by S_{min}. Then, the index is determined as indicated in the following expression:

$$
UI = \frac{per(S) - per(S_{\min})}{per(S_{\max}) - per(S_{\min})} * 100 \tag{3}
$$

The obtained value is a percentage, where 100% corresponds to the maximum uncertainty that could be obtained for the PM with the considered sources (identified in step 1) and their relationships, and 0% corresponds to an ideal situation where no uncertainty is introduced by the process.

7. APPLICATION EXAMPLE

For testing this methodology, a PM used to evaluate an assembly line of Surface Mounted Technology was considered. In this productive process, the components called Surface Mounted Devices are mounted and soldered to the Printed Circuit Board (PCB) through the reflow process. Measurement equipment based on Automatic Optical Inspection inspects PCBs, counts the number of defects and performs quality records. Then, the PM DPMO is calculated as follows:

$$DPMO = \frac{\text{number of defects}}{\text{total number of opportunities}} \times 1.000.000 \quad (4)$$

Although the equation (4) is simple, it is very important to know what is considered as the total number of defects and opportunities, otherwise mistakes may be made in interpretation, resulting in different analyzes and results of the PM. The assessment of the number of defects, despite being performed automatically, is not without uncertainty.

The application of the methodology presented in section 6 to this concrete situation will allow assessing the level of uncertainty in the PM considered. All steps of the methodology deserve a depth discussion among the experts who know this process of automated inspection. The results that have been reached in each step are the expression of the consensus reached in this discussion. Each factor or source of uncertainty of the PM and the strength of relationships between factors are analysed in detail. Thus, as a result of applying steps 1 and 2, the following graph was obtained:

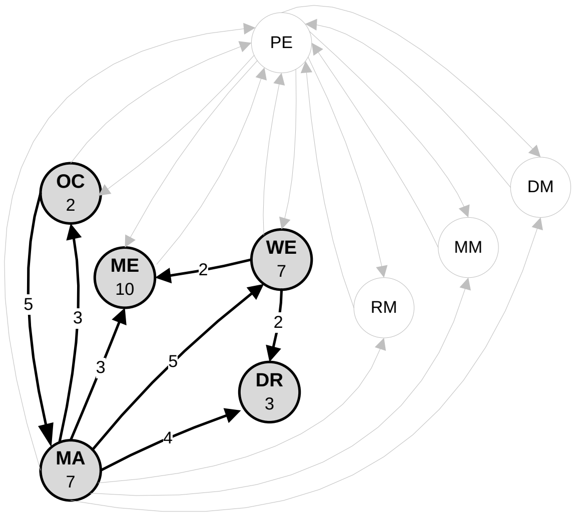

Figure 3: Graph of the case study

Then, the corresponding matrix is given by:

$$S = \begin{array}{c} \\ \textbf{OC} \\ \textbf{MA} \\ \textbf{ME} \\ \textbf{WE} \\ \textbf{DR} \end{array} \begin{array}{c} \begin{array}{ccccc} \textbf{OC} & \textbf{MA} & \textbf{ME} & \textbf{WE} & \textbf{DR} \end{array} \\ \begin{bmatrix} 2 & 5 & 0 & 0 & 0 \\ 3 & 7 & 3 & 5 & 4 \\ 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 2 & 7 & 2 \\ 0 & 0 & 0 & 0 & 3 \end{bmatrix} \end{array} \quad (5)$$

The permanent function obtained for this matrix (5) is 6090. For determining the best value of the permanent function that can be obtained for this performance measurement process, the permanent function of the S_{min} was calculated and gives 0. Similarly, the worst value was also determined calculating the per(S_{max}) and gives 115 000. Applying expression 3, the uncertainty index value is 5,3% for the considered PM.

8. CONCLUSIONS

In this work, the process of performance measurement was analysed in order to identify and define the sources of uncertainty that may be present in any process. Nine sources of uncertainty were considered relevant and their interdependences was analysed. The permanent function of the matrix associated with the graph of these sources can be used to determine the value of the uncertainty index of any PM.

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.

ACKNOWLEDGEMENTS

This work was financed with FEDER Funds by Programa Operacional Fatores de Competitividade – COMPETE and by National Funds by FCT –Fundação para a Ciência e Tecnologia, Project: FCOMP-01-0124-FEDER-022674.

REFERENCES

Basu, R. (2001) “New criteria of performance management”. Measuring Business Excellence. 5(4):pp. 7-12.

Batini, C., C. Cappiello, Chiara Francalanci and Andrea Maurino (2009) "Methodologies for data quality assessment and improvement" J ACM Comput. Surv. 41(3): 1-52.

Darvish, M, M. Yasaei and A. Saeedi (2009) “Application of graph theory and matrix methods to contractor ranking.” International Journal of Project Management 27: 610-619.

Franco, M. and M. Bourne (2003) "Factors that play a role in "managing through measures"." Management Decision 41(8): 698-710.

Galway, L. A. and C. H. Hanks (2011) "Classifying Data Quality Problems." IAIDQ's Information and Data Quality Newsletter 7(4): 1-3.

Ghalayini, A., J. Noble and T. Crowe, (1997) "An integrated dynamic performance measurement system for improving manufacturing competitiveness." International Journal of Production Economics 48: 207-225.

Globerson, S. (1985) "Issues in developing a performance criteria system for an organisation." International Journal of Production Research 23(4): 639-46.

Juran, J.M. and A.B. Godfrey (1999) “Juran's Quality Handbook”. 5th ed.: McGraw-Hill.

Kumar, V. A. and O. Gandhi (2011) “Quantification of human error in maintenance using graph theory and matrix approach.” Quality and Reliability Engineering International 27:1145-1172.

Lee, Y. W., D. M. Strong, Beverly K. Kahn and Richard Y. Wang, (2002) "AIMQ: a methodology for information quality assessment." Information and Management 40(2): 133-146.

Macpherson, M. (2001) "Performance measurement in not-for-profit and public-sector organisations." Measuring Business Excellence 5(2): 13-17.

Rao R. V. (2006a) “A decision-making framework model for evaluating flexible manufacturing systems using digraph and matrix methods.”International Journal of Advanced Manufacturing Technology 30: 1101-1110.

Rao R. V. (2006b) “A material selection model using graph theory and matrix approach.” Materials Science and Engineering A 431: 248-255.

Rao R. V. (2007) “Decision making in the manufacturing environment: using graph theory and fuzzy multiple attribute decision making methods”. London: Springer.

Rao R. V. And K. K. Padmanabhan (2006) “Selection, identification and comparison of industrial robots using digraph and matrix methods.” Robotics and Computer-Integrated Manufacturing 22: 373-383.

Schalkwyk, J. (1998) "Total quality management and the performance measurement barrier." The TQM Magazine 10(2): 124-131.

Sousa, S. D; Nunes, E. P. and Lopes, I.S. (2013) “Uncertainty Components in Performance Measures”, IAENG Transactions on Engineering Technologies - Special Issue of the World Congress on Engineering 2012, Yang, Gi-Chul et al. (eds), Springer, pp. 753-765.

Sousa, S.D. and Aspinwall, E. (2010) “Development of a performance measurement framework for SMEs”, Total Quality Management & Business Excellence, vol. 21: 5, 2010, pp.475-501.

Tenner, A. and I. DeToro (1997). “Process Redesign”. Harlow, Addison-Wesley.

Tilak, R, R. Shankar and M. Suhaib (2010) “GTA-based framework for evaluating the feasibility of transition FMS.” Journal of Manufacturing Technology Management 21(2): 160-187.

Wagner S. M. And N. Neshat (2010) “Assessing the vulnerability of supply chains using graph theory.” International Journal of Production Economics 126: 121-129.