Proceedings of ICAD2004
The Third International Conference on Axiomatic Design
Seoul – June 21-24, 2004
ICAD-2004-42

A RATIONAL WAY TO SELECT A MEASURING SYSTEM FOR MECHANICAL PARTS INSPECTION

António Gonçalves-Coelho.
agc@fct.unl.pt
UNIDEMI,
Department of Mechanical and Industrial Engineering,
Faculty of Science and Technology,
The New University of Lisbon
Quinta da Torre, 2829-516 Caparica,
PORTUGAL

António Freire Mourão.
ajfm@fct.unl.pt
UNIDEMI,
Department of Mechanical and Industrial Engineering,
Faculty of Science and Technology,
The New University of Lisbon
Quinta da Torre, 2829-516 Caparica,
PORTUGAL

Helena Guitiss Navas.
hvgn@fct.unl.pt
UNIDEMI,
Department of Mechanical and Industrial Engineering,
Faculty of Science and Technology,
The New University of Lisbon
Quinta da Torre, 2829-516 Caparica,
PORTUGAL

ABSTRACT

The selection of a measuring system for dimensional and geometrical tolerances of mechanical parts is crucial for the final definition of a manufacturing process and its detailed programme. The symbols and indications of adjustments, surface roughness, dimensional and geometrical tolerances in the final drawings of mechanical parts determine the measuring techniques and resources. There is not only one measuring system at all. Its appropriateness depends on particular details of the mechanical part, its production rate, its manufacturing process, human and technical means, costs, time limit, and specific contract conditions. Axiomatic Design allows comparing the information content of each measuring scheme, and this methodology can be a scientific basis for a rational selection. The present paper contains a studied real case using this methodology.

Keywords: design, decision-making, axioms, metrology, flexibility.

1 INTRODUCTION

Mechanical parts are produced from blank or stock materials through a definite set of technological operations, and their dimensional and geometrical accuracy are key points for the assembly phase and for the product performance. Thus, measuring is an important issue in the quality evaluation of mechanical parts.

Broadly speaking, the selection of a measuring system depends on its measuring range, resolution and accuracy, and on some other attributes that are closely related either to the workpieces that are to be measured or to the measuring system itself. However, there is an important feature that is seldom considered, at least in a quantitative form: the *flexibility* of the measuring system relative to the specific tasks that are to be performed.

The word flexibility has different meanings for different people, and sometimes even for the same person depends on the context. Therefore, a clarification is needed: in the scope of this work, we will define flexibility as the property that allows a system to respond to modifications of its initial FRs after it has been fielded, i.e. in operation, in a timely and cost-effective way [Saleh *et al.*, 2001]. The inverse of flexibility is *suitability*, which one can define as the property that allows a system to respond to its initial FRs in a timely and cost-effective way.

Accordingly, flexibility and suitability are very important when workpieces of different shapes and/or sizes are to be measured, which is a current condition in batch production.

This paper addresses a case where flexibility is at a premium, a situation that suggests the use of a Coordinate Measuring Machine (CMM). In fact, some of the advantages of using CMMs over conventional gaging techniques are flexibility, reduced set-up time, improved accuracy, reduced operator influence, and improved productivity [Wick and Veilleux, 1987].

Therefore, a selection method based on flexibility and suitability will be presented here.

2 EVALUATING THE FLEXIBILITY

From the previous section, one can ascertain that the top-level FR, the flexibility, can be decomposed in $FR_{1.1}$= "inspection time per component" and $FR_{1.2}$= "cost-effectiveness", as shown in Fig. 1.

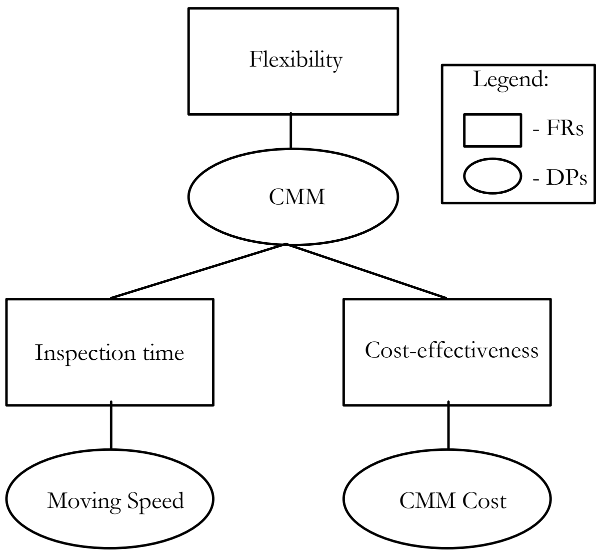

Figure 1. Decomposition of Flexibility.

The following sub-sections illustrate how both the inspection time per workpiece and the cost-effectiveness can be estimated, and how they can be combined to assess flexibility.

2.1 INSPECTION TIME PER COMPONENT

Suppose that the time required to inspect a given workpiece using a specific CMM, t_0, can be determined through a test measurement. Suppose also that the typical CMM's head moving speed is v_0.

As the inspection time depends essentially on the moving speed of the CMM's head, then the estimated measuring time, t, which one can achieve using another CMM is roughly given by

$$t = t_0 \frac{v_0}{v}, \quad (1)$$

where v is the head moving speed of the latter CMM.

2.2 COST-EFFECTIVENESS

Any industrial equipment serving a company is said to be cost-effective if his total costs conform to the company's budget. Thus, the cost-effectiveness can be defined as

$$\eta_C = \frac{B}{C}, \quad (2)$$

where B is the available budget and C are the CMM total costs. This means that $\eta_C \geq 1$ when $C \leq B$, i.e., when the budget is large enough to support the expenditure.

The total costs due to the ownership and operation of a CMM are mainly due to

a) Annual amortization
b) Maintenance, calibration and consumables
c) Floor space and power costs
d) Labor and overhead costs

Items a) and b) were found to be proportional to the CMM's purchase price.

2.3 DESIGN EQUATION

The complete design equation for the system shown Fig. 1 is

$$\begin{Bmatrix} Flexibility \\ Inspection\ Time \\ Cost-effectiveness \end{Bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{bmatrix} \begin{Bmatrix} CMM \\ Moving\ Speed \\ CMM\ Cost \end{Bmatrix} \quad (3)$$

Eq. (3) shows that this is a uncoupled design, for which the information content is the sum of the information content relative to each one of the three FRs, as proposed by Suh [1990] and made clear by Frey and Hirschi [2002].

The top-level FR, flexibility, is qualitative by nature. Therefore, it is worth to conclude that its information content is an unknown constant. Consequently, it represents a simple shift of the information account's origin. Therefore, it can be ignored for computation purpose, and Eq. (3) becomes:

$$\begin{Bmatrix} Inspection\ Time \\ Cost-effectiveness \end{Bmatrix} = \begin{bmatrix} \times & 0 \\ 0 & \times \end{bmatrix} \begin{Bmatrix} Moving\ Speed \\ CMM\ Cost \end{Bmatrix} \quad (4)$$

2.4 FLEXIBILITY AND SUITABILITY

From Eq. (4), one can see that the information content due to flexibility is given by

$$I_{Flexibility} = I_{Inspection\ Time} + I_{Cost-effectiveness} \quad (5)$$

where

$$I_{Inspection\ Time} = \log_2 \frac{Inspection\ Time\ System\ Range}{Inspection\ Time\ Common\ Range} \quad (6)$$

and

$$I_{Cost-effectiveness} = \log_2 \frac{Cost-effectiveness\ System\ Range}{Cost-effectiveness\ Common\ Range} \quad (7)$$

According to its definition, the suitability is given by

$$S = \frac{1}{I_{flexibility}} \quad (8)$$

It will be shown that the information content and the suitability computed in this way can be used as metrics to assess the CMM's flexibility and suitability for a given task.

3 A CASE STUDY

A measuring system had to be selected for a company to inspect several distinct types of workpieces. This called for flexibility and the option for a CMM was made.

Four different typical workpieces were selected for inspection, and the technical specifications of the eligible CMMs were prescribed from the workpieces' dimensional and geometrical characteristics.

Two candidate CMMs were selected according to both their technical specifications and the company's budget. These two CMMs were named CMM1 and CMM2.

Inspection tests were made using a vendor's CMM to estimate the inspection time per workpiece for the selected parts. Eq. (1) was used for the candidate CMMs, and the data obtained in this way is shown in Table 1.

Table 1. Estimated inspection time/wkpc.

Workpiece	Estimated inspection time (h)	
	CMM1	CMM2
Type A	0.033	0.029
Type B	0.042	0.036
Type C	0.050	0.043
Type D	0.067	0.057

The total annual costs were estimated according to sub-section 2.2, using the candidate CMMs' price tags. Following the company's historic data, a margin of ±10 percent was considered to accommodate the variations of the labor costs and overheads. These costs are shown in Table 2, and it is worth to note that they represent more than 74% of the total annual costs for any one of both the candidate machines.

Table 2. Estimated annual costs.

	Estimated annual costs (EUR)	
	Minimum	Maximum
CMM1	53160	62120
CMM2	56020	64980

The annual budget associated to the CMM ownership and operation was 60,000 EUR. Therefore, the limit values of the cost-effectiveness for the candidate CMMs could be estimated applying Eq. (2) to the values of Table 2. The achieved values are shown in Table 3.

Table 3. Cost-effectiveness system range limits.

	Estimated cost-effectiveness	
	Minimum	Maximum
CMM1	0.996	1.129
CMM2	0.923	1.071

The largest possible Inspection Time/wkpc ranges for CMM1 and CMM2 can be found in Table 1. For each CMM, the lower and the upper limit is the time required to inspect workpieces Type A and Type D, respectively, as shown in Fig. 2.

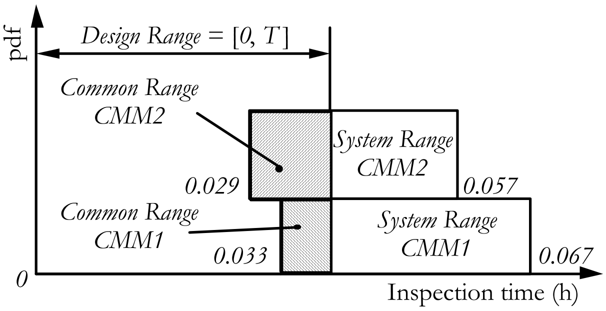

Figure 2. Ranges for Inspection Time/wkpc.

The upper limit, T, was considered variable. This enables us to assess the effects of changing the batch mix composition. Therefore, T is the weighted average inspection time per workpiece for a batch mix composed by different kinds of workpieces, so that the upper limit of the design range can sweep from 0.029 h to 0.067 h. A comparable procedure was adopted for the cost-effectiveness, although with unchanging limits for the design range. The data of Table 3 was used and the corresponding results are depicted in Fig. 3.

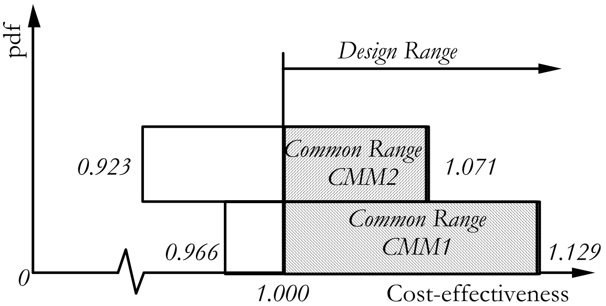

Figure 3. Ranges for Cost-effectiveness.

The information content was computed in turn, using Eqs. (5), (6) and (7). The attained results are shown in Fig. 4.

4 DISCUSSION

Suppose that one want to inspect everyday one of the two batch mixes which compositions are shown in Table 4.

Table 4. Composition of the batch mixes.

Workpieces	Number of Workpieces	
	Batch mix 1	Batch mix 2
Type A	125	0
Type B	75	50
Type C	50	75
Type D	0	125
TOTAL	**250**	**250**

The weight-averaged inspection time/workpiece for each batch mix was calculated according to Table 1, and the results that were obtained are recorded in Table 5.

Table 5. Weight-averaged inspection time/wkpc (h).

	Batch Mix 1	Batch Mix 2
CMM1	0.039	0.057
CMM2	0.034	0.049

The mean inspection costs/workpiece were also calculated and the results are displayed in Table 6.

Table 6. Mean inspection costs/wkpc (EUR).

	Batch Mix 1	Batch Mix 2
CMM1	0.981	1.092
CMM2	1.030	1.030

Table 7 contains the values for the cost-effectiveness as computed for both batch mixes.

Table 7. CMM's cost-effectiveness.

	Batch Mix 1	Batch Mix 2
CMM1	1.041	0.935
CMM2	0.992	0.992

From Table 5 and 7, one can see that both CMM1 and CMM2 are operating inside the system range for both Inspection Time and Cost-effectiveness, as depicted in Figs. 2 and 3. This means that both CMM1 and CMM2 can accomplish the FRs.

From Table 5, one can see that CMM2 performs the inspection of any of the batch mixes in less than the 12.8 h of an entire workday. CMM2 is always below the current workday duration (12.8 h) for both batch mixes. This does not happen to CMM1, which needs extra labor hours to process Batch Mix 2. From Table 6, one can conclude that Batch Mix 1 has better costs/wkpc when processed by CMM1, while CMM2 produces better results for Batch Mix 2. However, Table 7 shows that the cost-effectiveness of CMM1 is higher when it processes Batch Mix 1, and that CMM2 have a better cost-effectiveness when inspecting Batch Mix 2. From Table 5 and 7, one can see that both CMM1 and CMM2 are operating inside the system range for both Inspection Time and Cost-effectiveness, which are depicted in Figs. 2 and 3. This means that both CMM1 and CMM2 can accomplish the FRs.

Therefore, one may conclude is that CMM1 is better to inspect Batch Mix 1 and CMM2 is better to process Batch Mix 2.

Figs. 4, and 5, which are based in the CMMs' information content, as computed according to section 2 above, allow for a quicker insight to the problem.

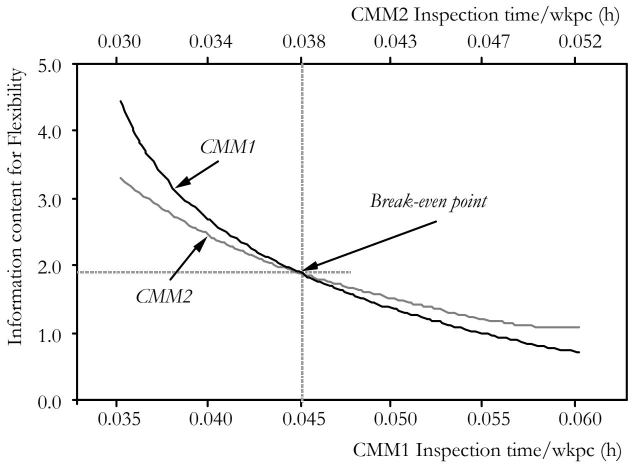

Figure 4. Information content of CMM1 and CMM2.

For Batch Mix 1 we have a weight-averaged inspection time/wkpc of 0.039 h on CMM1 (or 0.049 h on CMM2). According to the rule "the less information the better" and the point corresponding to 0.034 h is to the left of the break-even point, one can conclude that CMM2 is more flexible than CMM1. Similarly, Fig. 5 shows that CMM1 is more suitable than CMM2 to perform the task because in what concerns to suitability its information content is lesser.

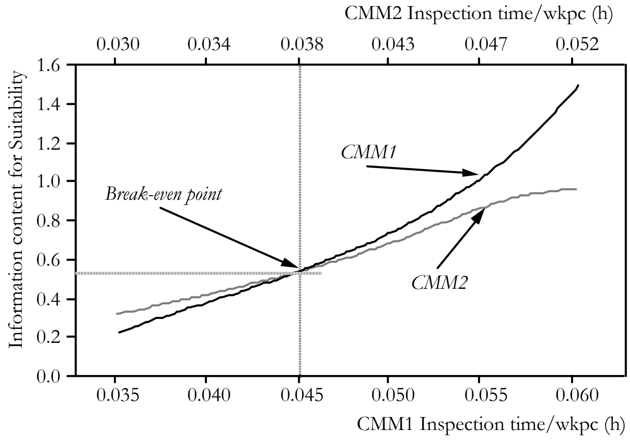

Figure 5. Suitability of CMM1 and CMM2.

As for Batch Mix 2, it can be inspected on CMM1 with a weight-averaged inspection time/wkpc of 0.057 h (or 0.049 h on CMM2). Inasmuch as 0.057 h is to the right of the break-even point, for the same reason from Figs. 4 and 5 one can conclude that now CMM1 is more flexible and CMM2 is more suitable.

5 CONCLUSION

A new approach for the selection of a CMM based in specific metrics for flexibility and for suitability was presented here, as well of a case study where the new method was used, which conclusions are in consonance to the ones that were obtained through a traditional and harder to use procedure.

The main conclusions of our discussion are:

For a given budget, the following rules hold:

1) For any CMM, the more is the information content, the less is the machine's flexibility.
2) For each specific inspection time/wkpc, the more flexible CMM is the one which information content is smaller.
3) Flexibility and suitability are antagonists.

Therefore, the information content provides appropriate metrics to appraise the flexibility and the suitability of CMMs, and the present rules hold for any other type of equipment.

6 ACKNOWLEDGMENTS

The present authors would like to thank the Faculty of Science and Technology of The New University of Lisbon (UNL) and the Portuguese Foundation for Science and Technology (FCT). Their support is helping to make possible our research work.

7 REFERENCES

[1] Frey, D.D., Hirschi, N.W., "The Effects of Coupling on Parameter Design", 2nd International Conference on Axiomatic Design, *ICAD2002*, Cambridge, Mass., June 10-11, 2002

[2] Saleh, J.H., Hastings, D.E., Newman, D.J., "Extracting the Essence of Flexibility in System Design", 3rd NASA/DoD Workshop on Evolvable Hardware, Long Beach, CA, 12-14 July, 2001.

[3] Suh N.P., *The Principles of Design*, New York: Oxford University Press, 1990. ISBN 0-19-504345-6

[4] Wick, C., Veilleux, R.F. (eds.), *Tool and Manufacturing Handbook, Vol. 4: Quality Control and Assembly*, SME, 1987. ISBN 0-87263-177-X