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Inspection Allocation Planning for a Multiple Quality Characteristic Advanced Manufacturing System

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Producing products with multiple quality characteristics is always one of the concerns for an advanced manufacturing system. To assure product quality, finite automatic inspection systems should be used. Inspection planning to allocate inspection stations should then be performed to manage the limited inspection resource.

Except for finite inspection station classes, in this work, the limited number of inspection stations, of each inspection station class, is considered for solving the inspection allocation problem in a multiple quality characteristic advanced manufacturing system. Since the product variety in batch production or job shop production increases to satisfy the changing requirements of the various customers, the tolerances specified will vary from time to time. This inspection allocation problem is solved using a unit cost model in which the manufacturing capability, inspection capability, and tolerance specified are concurrently considered for a multiple quality characteristic product. The situation of unbalanced tolerance design is also considered. The inspection allocation problem can then be solved according to customer requirements.

Since determining the optimal inspection allocation plan seems to be impractical, as the problem size becomes large, two decision criteria (i.e. sequence order of workstation and tolerance interval) are employed separately to develop two different heuristic solution methods in this work. The performance of each method is measured in comparison with the enumeration method that generates the optimal solution. The result shows that a feasible inspection allocation plan can be determined efficiently.

Keywords: Inspection allocation; Inspection resource constraint; Multiple quality characteristics

1. Introduction

Since producing products with multiple quality characteristics is always one of the concerns of a supplier, an advanced manufacturing system (AMS) which integrates successive automatic manufacturing stages (i.e. processes or workstations) to fabricate products. Automatic inspection stations (AIS) can be employed to assure product quality. With only a finite inspection resource available, an inspection allocation problem occurs in a multistage manufacturing system. Lee and Unnikrishnan pointed out this could occur in an electronic manufacturing industry that performs precision testing on package circuits or chips [1], and also in other industries, especially small and medium-sized industries, where precision inspection is needed and only limited inspection resources are available [2].

Depending on the varying inspection capabilities and applications, inspection stations can be categorised into several classes. Each inspection station class consists of inspection stations that have the same inspection usage and capability. To solve the inspection allocation problem, we must consider:

1. At which workstation should an inspection activity be conducted.
2. Which kind of inspection station class should be used if an inspection activity is needed [1–4].

The solutions involve determining whether and what kind of inspection station class should be allocated immediately following each workstation in a multistage manufacturing system.

There could be a finite number of inspection station classes available which are suitable for monitoring one or more workstations. Lee and Unnikrishnan solved the inspection allocation problem with this kind of inspection resource constraint [1]. However, another kind of inspection resource constraint should be considered in the case of limited financial resources and other situations. For example, the number of inspection stations of each inspection station class could be more than one and finite, i.e. four or five, and only two are available for a multistage manufacturing system. This could be because the others are servicing other manufacturing systems or have been sent for calibration, etc. The problem of a limited number of inspection stations of each inspection station class had been further considered [2].

Except for the inspection resource constraints, most of the work on the inspection allocation problem considers inspection error to establish and solve relative objective functions [1,3,4]. It had been concluded that inspection error varies even when

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applying the same inspection station to monitor various workstations that have different manufacturing capabilities. It also becomes different even when applying the same inspection station to monitor the same workstation when the tolerance is changed. Therefore, manufacturing capability, inspection capability, and tolerance have been integrated to evaluate and improve the inspection performance [5,6]. It can be inferred that the performance of an AMS can also be concurrently affected by the manufacturing capability, inspection capability, and tolerance, so work should no longer end with evaluating a stand-alone workstation or inspection station. The integration concept should be applied to solve the inspection allocation problem for an AMS that integrates several workstations and inspection stations.

Since the product variety in batch production or job shop production will be increased to satisfy the changing requirements of various customers, the tolerances specified will vary from time to time. It is impractical to assume that the inspection error of a CAI system is constant or has a specified probability distribution, determined from previous observations or experience, for all possible tolerances that were not specified previously. Therefore, an inspection error model that deals with inspection capability, manufacturing capability, and tolerance was interpreted and applied [2]. The inspection allocation problem can then be solved by adjusting the inspection error when tolerances are rapidly changed for customer requirements. However, this deals only with an AMS that fabricates a single quality characteristic product, and also, only a bilateral tolerance design is considered. It is necessary to further extend the work to solve the inspection allocation problem for an AMS that fabricates multiple quality characteristic products.

The objective of this paper is to solve the inspection allocation problem in an AMS that fabricates multiple quality characteristic products of assured product quality and relative costs. Based on the finite inspection resource constraints, a unit cost model is established to reflect the real situation of rapid change in customer requirements. The situation of unbalanced tolerance design is also considered. Since determining the optimal inspection plan seems to be impractical, as the problem size becomes large, two decision criteria (i.e. sequence order of workstation and tolerance interval) are employed separately to develop two different heuristic methods. The performance of each method is measured in comparison with the enumeration method that generates the optimal solution. The result shows that a feasible inspection allocation plan can be determined efficiently. A feasible manufacturing plan can then be evaluated by concurrently solving the inspection allocation problem.

2. System and Model Analysis

The assumption that both the manufacturing capability and the inspection capability are normally distributed is applied. It is common practice when using statistical methods (i.e. statistical quality control and process capability study) to solve real manufacturing problems, and the same for studying inspection capability [2,5–9]. However, the probability density function in the following models should be modified to take account of the actual validated distribution, if necessary.

2.1 System Description

There are several types of multistage manufacturing system, such as, serial, non-serial, and a re-entrant hybrid of serial or non-serial types. However, each kind of manufacturing system should be individually solved for the different characteristics and limitations. One serial multistage manufacturing system that fabricates products with multiple quality characteristics is studied. As shown in Fig. 1, the characteristics and limitations under consideration are as follows:

1. The manufacturing system integrates several successive workstations (i.e. n) to fabricate parts serially in batches. No, or only one, inspection system can be assigned after each workstation to perform 100% inspection.
2. Each workstation is responsible for manufacturing to a specific quality characteristic and has its own manufacturing capability that is normally distributed. The probability of producing a non-conforming quality characteristic depends not only on the manufacturing capability, but also the bilateral or unbalanced lower/upper specification limits.
3. There are finite inspection station classes available for this manufacturing system. Depending on the usage and the capability, each inspection station class could be suitable for performing inspection operations for one or more workstations. Each inspection station class has its own specific capability that is normally distributed.
4. The number of available inspection stations in each class is finite. Each inspection station is assigned once and cannot be re-assigned to monitor other workstations in the middle of the production of a batch. The inspection time for each inspection station can be represented by the inspection cost.
5. There exist two kinds of inspection error when applying any inspection station. Type I error, α, occurs when a conforming part is rejected. Type II error, β, occurs when a non-conforming part is accepted. The inspection error of an inspection station is not a constant or a specified probability. This variation depends not only on the inspection capability and manufacturing capability, but also on the specified tolerance [2].
6. A part will be discarded if its kth quality characteristic is measured and said to be less than the lower specification limit. A part will be correctly reworked if its kth quality characteristic is measured and is found to be larger than the upper specification limit.
7. A product sold to a customer is said to be in conformance when there exist no non-conforming quality characteristics. A product sold to a customer is said to be in non-conformance when there exist one or more non-conforming quality characteristics.

2.2 Notation

Based on the manufacturing system described above, the following shows the necessary notations:

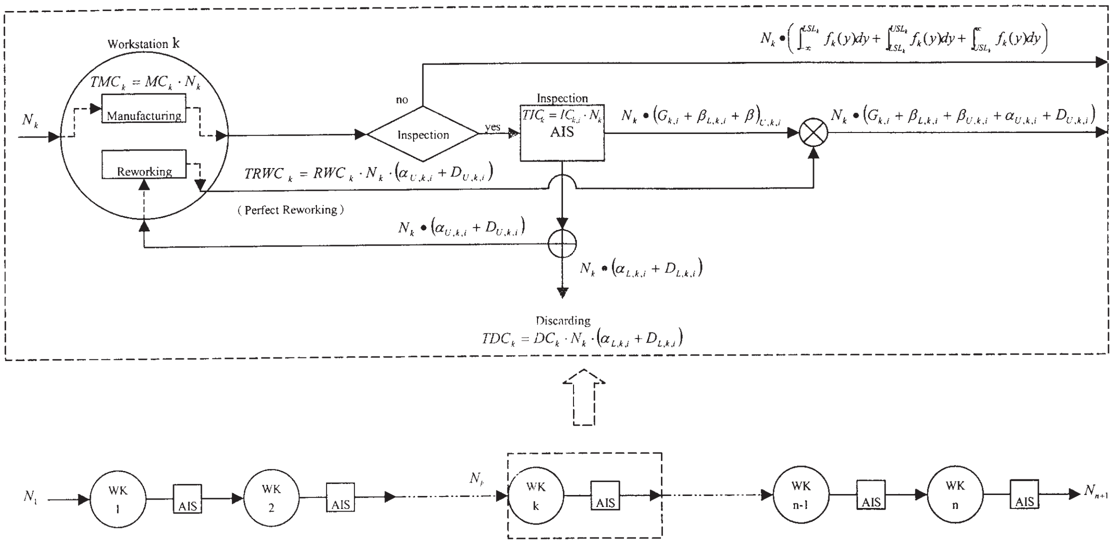

Fig. 1. Workflow and cost analysis for a multiple quality characteristic advanced manufacturing system.

k — the kth quality characteristic fabricated on workstation k in the manufacturing system, $k = 1, \ldots, n$

f_k — manufacturing capability of workstation k

m_k — the target value of the kth quality characteristic

LSL_k — lower specification limit for quality characteristic k (i.e. $m_k - K_{Lk}\sigma_k$)

USL_k — upper specification limit for quality characteristic k (i.e. $m_k + K_{Uk}\sigma_k$)

i — inspection station class i available for the manufacturing system, $i = 1, \ldots, r$

g_i — inspection capability of inspection station class i

NI_i — available number of inspection stations class i for the manufacturing system

N_k — number of parts entering workstation k for manufacturing quality characteristic k

$G_{k,i}$ — expected probability that conforming units are correctly classified as good units by inspection station class i after the workstation k process

$D_{L,k,i}$ — expected probability that non-conforming units with quality characteristics less than the LSL_k are correctly classified as bad units by inspection station class i after the workstation k process

$D_{U,k,i}$ — expected probability that non-conforming units with quality characteristics larger than the USL_k are correctly classified as bad units by inspection station class i after the workstation k process

$\alpha_{L,k,i}$ — expected type I error that conforming units are incorrectly classified as bad units with quality characteristics less than the LSL_k by inspection station class i after the workstation k process

$\alpha_{U,k,i}$ — expected type I error that conforming units are incorrectly classified as bad units with quality characteristics larger than the USL_k by inspection station class i after the workstation k process

$\beta_{L,k,i}$ — expected type II error that non-conforming units with quality characteristics less than the LSL_k are incorrectly classified as good units by inspection station class i after the workstation k process

$\beta_{U,k,i}$ — expected type II error that non-conforming units with quality characteristics larger than the USL_k are incorrectly classified as good units by inspection station class i after the workstation k process

MC_k — unit manufacturing cost of quality characteristic k

TMC_k — expected total manufacturing cost of quality characteristic k

$IC_{k,i}$ — unit inspection cost of inspection station class i for quality characteristic k

$TIC_{k,i}$ — expected total inspection cost of inspection station class i for quality characteristic k

RWC_k — unit rework cost of quality characteristic k

$TRWC_k$ — expected total rework cost of quality characteristic k

DC_k — unit discard cost of quality characteristic k

TDC_k — expected total discard cost of quality characteristic k

UC — expected unit cost of a product that is sold to a customer

2.3 Manufacturing Capability and Inspection Capability

Generally, designers determine the upper and lower specification limits (USL/LSL) to ensure the correct functional ability of products. The tolerance of each quality characteristic can be expressed as $[m_k - K_{Lk}\sigma_k,\ m_k + K_{Uk}\sigma_k]$ for an unbalanced tolerance design. The specification limits are then directly applied for inspecting and monitoring the manufacturing quality. Either a bilateral tolerance or a unilateral tolerance are special cases of unbalanced tolerance. Bilateral tolerance is the case when $K_{Lk} = K_{Uk}$. Unilateral tolerance is the case when $K_{Lk} = 0$ or $K_{Uk} = 0$, that is, the related concept of both bilateral and unilateral tolerances can be derived from the solution of the unbalanced tolerance application [6]. The situation of unbalanced tolerance design is considered.

Let the manufacturing capability of workstation k be normally distributed as $f_k(y) \sim N(\mu_k, \sigma_k^2)$, where y is the true dimension of the quality characteristic manufactured in the workstation. The quality characteristic could be $y < LSl_k$, $LSL_k \leq y \leq USL_k$, or $y > USL_k$. Table 1 shows the possible manufacturing quality results from the manufacturing capability when no inspection capability is considered.

Two kinds of measurement error occur when applying an inspection station to monitor the manufacturing quality. Type I error, α, occurs when a good part is rejected. Type II error, β, occurs when a bad part is accepted. Type I/II errors will not occur concurrently when measuring a part. Let the inspection capability of an inspection system be normally distributed as $g(x/y) \sim N(\bar{x}, \sigma_i^2)$, where $\bar{x}$ represents the mean value of the measurement data on a quality characteristic with a true dimension y. Table 1 also shows all possible situations when concurrently considering the manufacturing capability and inspection capability [2,5,6].

2.4 Work Flow Analysis

According to Table 1, Fig. 1 shows the possible situations of a batch of parts entering a multistage manufacturing system. Depending on whether an automatic inspection station is located after a workstation, the expected number of parts entering into a workstation can be determined. Let $\sum_{i=1}^{r} V_{k,i} = 1$ represent the situation when there is an inspection station of the ith inspection class applied for monitoring workstation k, otherwise, $\sum_{i=1}^{r} V_{k,i} = 0$. The number of parts entering workstation k, where $2 \leq k \leq n$, can then be expressed as [2]:

$$N_k = N_{k-1}\left[\left(\sum_{i=1}^{r} V_{k-1,i}\right)(G_{k-1,i} + \alpha_{U,k-1,i} + D_{U,k-1,i} + \beta_{L,k-1,i} + \beta_{U,k-1,i}) + \left(1 - \sum_{i=1}^{r} V_{k-1,i}\right)\right] \quad (1)$$

To establish the unit cost model, the expected number of products that are sold to customers should be established. Equation (1) can be expressed in terms of N_1 as:

$$N_k = N_1 \prod_{j=1}^{k-1}\left[\left(\sum_{i=1}^{r} V_{j,i}\right)(G_{j,i} + \alpha_{U,j,i} + D_{U,j,i} + \beta_{L,j,i} + \beta_{U,j,i}) + \left(1 - \sum_{i=1}^{r} V_{j,i}\right)\right] \quad (2)$$

The expected number of parts in a batch that is sold to customers can be derived from the value of N_{n+1}:

Table 1. Analysis of manufacturing capability and inspection capability.

Measurement True dimension	$x < LSL_k$	$LSL_k \leq x \leq USL_k$	$x > USL_k$	Manufacturing capability
$y < LSL_k$	$D_{L,k,i}$	$\beta_{L,k,i}$	–	$\int_{-\infty}^{LSL_k} f_k(y)dy$
$LSL_k \leq y \leq USL_k$	$\alpha_{L,k,i}$	$G_{k,i}$	$\alpha_{U,k,i}$	$\int_{LSL_k}^{USL_k} f_k(y)dy$
$y > USL_k$	–	$\beta_{U,k,i}$	$D_{U,k,i}$	$\int_{USL_k}^{\infty} f_k(y)dy$

$$G_{k,i} = P(LSL_k \leq x \leq USL_k, LSL_k \leq y \leq USL_k) = \int_{LSL_k}^{USL_k} f_k(y) \int_{LSL_l}^{USL_k} g_i(x|y)dxdy$$

$$D_{L,k,i} = P(x < LSL_k, y < LSL_k) = \int_{-\infty}^{LSL_k} f_k(y) \int_{-\infty}^{LSL_k} g_i(x|y)dxdy$$

$$D_{U,k,i} = P(x > USL_k, y > USL_k) = \int_{USL_k}^{\infty} f_k(y) \int_{USL_k}^{\infty} g_i(x|y)dxdy$$

$$\alpha_{L,k,i} = P(x < LSL_k, LSL_k \leq y \leq USL_k) = \int_{LSL_k}^{USL_k} f_k(y) \int_{-\infty}^{LSL_k} g_i(x|y)dxdy$$

$$\alpha_{U,k,i} = P(x > USL_k, LSL_k \leq y \leq USL_k) = \int_{LSL_k}^{USL_k} f_k(y) \int_{USL_k}^{\infty} g_i(x|y)dxdy$$

$$\beta_{L,k,i} = P(LSL_k \leq x \leq USL_k, y < LSL_k) = \int_{-\infty}^{LSL_k} f_k(y) \int_{LSL_k}^{USL_k} g_i(x|y)dxdy$$

$$\beta_{U,k,i} = P(LSL_k \leq x \leq USL_k, y > USL_k) = \int_{USL_k}^{\infty} f_k(y) \int_{LSL_k}^{USL_k} g_i(x|y)dxdy$$

$$G_{k,i} + D_{L,k,i} + D_{U,k,i} + \alpha_{L,k,i} + \alpha_{U,k,i} + \beta_{L,k,i} + \beta_{U,k,i} = 1$$

$$\int_{-\infty}^{LSL_k} f_k(y)dy + \int_{LSL_k}^{USL_k} f_k(y)dy + \int_{USL_k}^{\infty} f_k(y)dy = 1$$

$$N_{n+1} = N_1 \prod_{j=1}^{n} \left[\left(\sum_{i=1}^{r} V_{j,i} \right) (G_{j,i} + \alpha_{U,j,i} + D_{U,j,i} + \beta_{L,j,i} + \beta_{U,j,i}) + \left(1 - \sum_{i=1}^{r} V_{j,i} \right) \right] \quad (3)$$

For a multiple quality characteristic product, a product sold to a customer is said to be in conformance when there exists no non-conforming quality characteristic, and a product sold to a customer is said to be in non-conformance when there exist one or more non-conforming quality characteristics. Therefore, the expected number of conformance products with multiple quality characteristics manufactured by the AMS can be expressed as:

$$N_{good} = N_1 \prod_{j=1}^{n} \left[\left(\sum_{i=1}^{r} V_{j,i} \right) (G_{j,i} + \alpha_{U,j,i} + D_{U,j,i}) + \left(1 - \sum_{i=1}^{r} V_{j,i} \right) \int_{LSL_j}^{USL_j} f_j(y)\mathrm{d}y \right] \quad (4)$$

The relative cost due to the manufacturing capability and inspection capability should be further analysed for establishing the unit cost model.

2.5 Cost Model Analysis

The possible costs concerned in this work include the costs of manufacturing, inspection, reworking, and discarding. Each kind of cost should be analysed for each quality characteristic of a product.

Manufacturing and Inspection Cost

As shown in Fig. 1, manufacturing cost occurs in every workstation and depends on N_k. That is, the manufacturing cost model can be expressed as:

$$TMC_k = MC_k\, N_k \quad (5)$$

The inspection cost depends not only on N_k, but also on whether an inspection station is applied. That is, the inspection cost model can be expressed as:

$$TIC_k = \left(\sum_{i=1}^{r} V_{k,i} \right) IC_{k,i}\, N_k \quad (6)$$

Reworking and Discarding Cost

As shown in Fig. 1, the rework cost occurs in workstation k only when the kth quality characteristic of a part is measured and is found to be larger than USL_k. That is, the rework cost model can be expressed as:

$$TRWC_k = \left(\sum_{i=1}^{r} V_{k,i} \right) RWC_k\, N_k\, (\alpha_{U,k,i} + D_{U,k,i}) \quad (7)$$

Discard cost occurs in workstation k only when the kth quality characteristic of a part is measured and said to be less than LSL_k. That is, the discard cost model can be expressed as:

$$TDC_k = \left(\sum_{i=1}^{r} V_{k,i} \right) DC_k\, N_k\, (\alpha_{L,k,i} + D_{L,k,i}) \quad (8)$$

As stated in Eqs (4)–(8), the unit cost model of a conformance product with multiple quality characteristics that is sold to a customer can be expressed as:

$$\text{Min } UC = \sum_{k=1}^{n} (TMC_k + TIC_k + TRWC_k + TDC_k)/N_{good} \quad (9)$$

subject to:

$$\sum_{i=1}^{r} V_{k,i} \leq 1 \quad (10)$$

$$\sum_{k=1}^{n} V_{k,i} \leq NI_i \quad (11)$$

Eqs (10) and (11) show the inspection resource limitations. Equation (10) represents the situation where none or only one inspection station can be assigned after each workstation. Equation (11) represents the situation where limited inspection stations are available for each inspection station class.

3. Decision Criteria and Heuristic Methods

The inspection allocation problem can be solved since the objective function has been established. Early work used optimal techniques, i.e. dynamic programming approaches and nonlinear integer programming to solve their own objective functions [10,11]. However, these optimisation techniques become impractical when the problem becomes large. It has been proposed that a heuristic approach is more attractive to practitioners [1,2]. Therefore, two decision criteria were employed to develop two different heuristic methods to solve the objective function in Eq. (9). Their performances are compared with the enumeration method (EM) that generates the optimal solution.

Based on identifying a non-conforming product as early as possible to reduce unnecessary successive costs, the sequence order of a workstation is the criteria for developing the sequence order method (SOM). That is, the earlier a workstation is placed in a manufacturing stage, the higher the priority for it to be monitored by a suitable inspection station.

Consequently, the higher the defective rate of workstation k, the more necessary it is to assign an inspection station for monitoring that workstation. A non-conforming product can then be screened out before entering the next workstation, to reduce the unnecessary successive costs. However, the defective rate is affected not only by the manufacturing capability of a workstation, but also by the tolerance specified. That is, the defective rate will vary when tolerances are changed by customer requirements even when applying the same workstation and inspection station. Therefore, the tolerance interval specified for a workstation is the criteria for developing the tolerance interval method (TIM). Figure 2 shows the procedure for both SOM and TIM.

4. Case Study and Discussion

To measure the performance of the two heuristic methods, they were written in VBA and run using Microsoft Excel. A

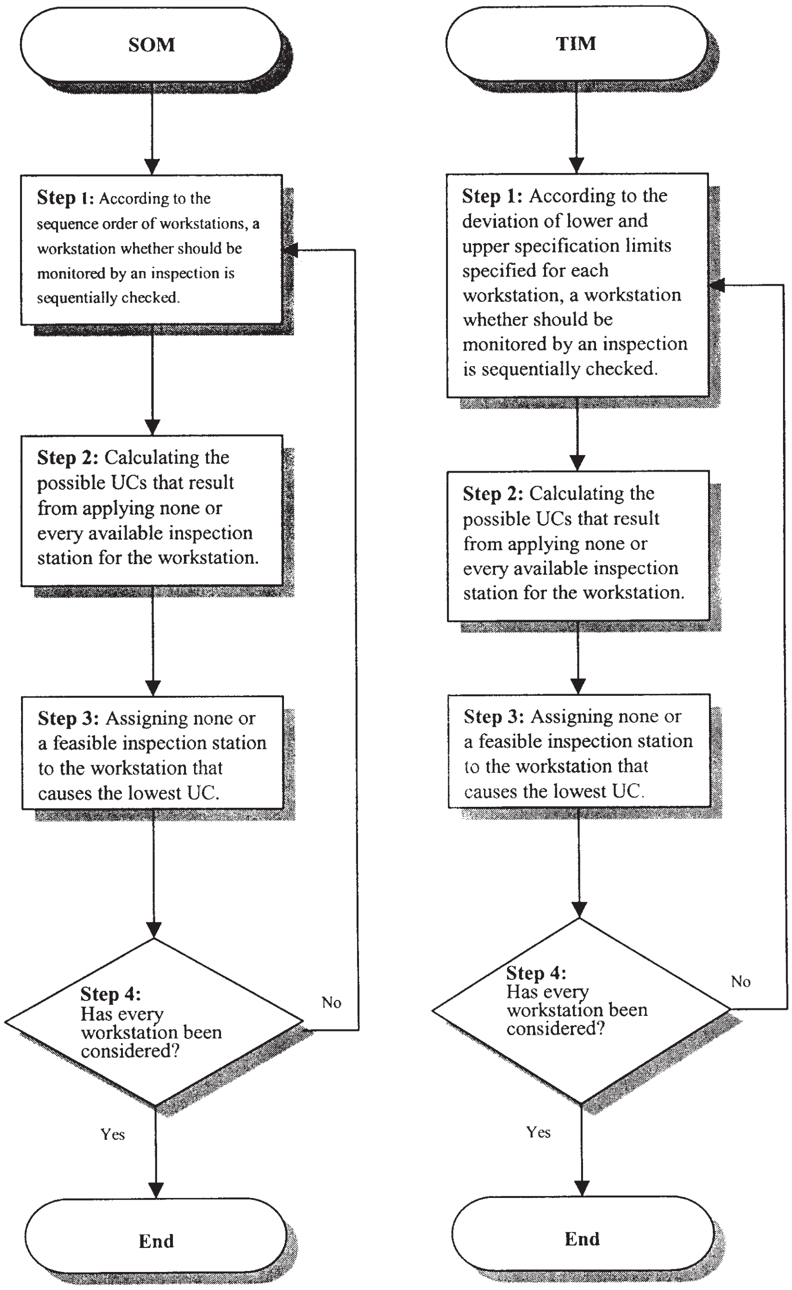

Fig. 2. Flowchart of the SOM and TIM.

computer with Intel Pentium II 400 CPU and 192MB RAM was used. As expressed in Section 2.5, there are many parameters that affect the unit cost model, such as, manufacturing capability, inspection capability, tolerance, and the relative costs. A multistage manufacturing system with five successive workstations and three inspection station classes was applied to study cases with different parameters. The batch size was set to be 1000 for each case. However, it still takes time to run the EM with all possible parameter combinations, therefore, just 20 cases were generated randomly and run to evaluate the overall performance of the heuristic methods. The inspection usage and resource constraint expressed in Eq. (11) for each case are generated randomly. Table 2 shows 5 partial cases of 20. As shown in Table 3, other parameter values of 20 cases were randomly generated using a uniform random number generator. Since most gauge capability studies were conducted to see if σ_i^2 is small relative to σ_k^2, the precision-to-tolerance (P/T) ratio, $6\sigma_i/USL_k - LSL_k$ is applied and required to be at least less than 0.1. Therefore, the value of σ_i is generated to ensure that the P/T ratio is between 0.001 and 0.06.

Table 3 shows that the SOM cannot produce the optimal solution as can the TIM, however, the cost deviation is only

Table 2. Partial cases of inspection usages and resource constraints.

Case	k / i	1	2	3	4	5	NI_i	$IC_{k,i}$
	1	*	–	*	–	*	2	6
1	2	*	*	–	*	*	3	2
	3	–	*	*	*	*	2	4
	1	–	*	*	*	*	3	2
2	2	*	–	*	*	–	1	2
	3	*	*	*	*	*	2	8
	1	*	*	*	–	*	1	1
3	2	*	*	*	*	–	1	2
	3	*	*	–	*	*	2	3
	1	*	*	–	*	*	1	3
4	2	*	*	*	*	–	2	1
	3	*	–	*	*	*	1	4
	1	*	*	*	–	*	2	2
5	2	*	*	*	*	*	2	1
	3	*	–		*	*	1	2

*, inspection class i can be applied to monitor workstation k.

Table 3. Average performance of heuristic methods.

Cost deviation $\left(\frac{B}{A} - 1\right)\%$		A			Time efficiency $\left(1 - \frac{A}{C}\right)\%$	
		EM	TIM	SOM		
	EM		92.35%	92.43%	EM	
B	TIM	0.11%		1.11%	TIM	C
	SOM	0.13%	0.02%		SOM	

Parameter		Range	Deviation
σ_k		0.1–0.6	0.1
$[LSL_k,\ USL_k]$		2.0–3.0σ_k	0.1
σ_i	$P/T = 6\sigma_i/USL - LSL \Rightarrow$	0.001–0.06	0.001
MC_k		20–180	10
RWC_k		20–180	10
DC_k		20–200	10

0.02%. Consequently, the time efficiency of the TIM is not as good as that of the SOM, however, the deviation is only 1.11%. The expected unit cost of the inspection allocation plan determined by either the SOM or the TIM is, however, close to that of the optimal inspection allocation plan determined by the EM. The heuristic methods also have better processing time efficiency than the EM. Either SOM or TIM has an acceptable performance for the expected unit cost and the processing time in comparison with the EM. According to the study of the 20 cases, the TIM is suitable when there are large differences among tolerances specified for each workstation. Otherwise, the SOM should be applied, rather than applying the TIM, for time efficiency.

5. Conclusion

It is important to conduct inspection planning during process planning for a multistage manufacturing system. Except for the available finite inspection station classes, availability of only a limited number of inspection stations of each inspection station class should be considered further to solve the inspection allocation problem. Accompanied by the unit cost models in which the manufacturing capability, inspection capability, and unbalanced tolerance specified are concurrently considered, the inspection allocation problem can then be solved by taking into account the real situation of the rapid changing of customer requirements. It is necessary to extend the work further to solve the inspection allocation problem for an AMS that fabricates multiple quality characteristic products. A feasible manufacturing plan can then be further determined and confirmed during process planning by solving the inspection allocation problem concurrently .

Two heuristic methods are introduced for the large size inspection allocation problem. Both can have an acceptable performance, not only in processing time, but also for the feasible inspection plan determined. TIM is recommended when there are large differences among tolerances specified for each workstation; otherwise, SOM should be applied rather than TIM, for time efficiency.

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