Improving shop floor control: an entropy model approach

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New manufacturing theories and techniques such as just-in-time and total quality management advocate the use of small lots in production and subsequently reduction of setup times. This yields better quality, lower response time, less operating expenses and less work-in-process. The implementation of the small-lot concept often encounters opposition from production people who feel that increasing the number of lots (an apparently inevitable result of reducing their size) implies a need for more information and more information technology.

By means of a normative model, based on information theory and the entropy measurement, this paper proves that the move toward smaller lots implies less information needs. The model also shows the relationship between improvement activities, such as setup and time per part reduction, and the information needs.

1. Introduction

The past two decades have witnessed the emergence of new management philosophies and techniques which, when implemented, completely change manufacturing paradigms and practices. These management methods—just-in-time (JIT), total quality management (TQM) and the theory of constraints (TOC) have made a significant contribution to production, and their implementation has been known to turn losing businesses into profitable ones (see, for example, Schonberger 1986, Deming 1986, Goldratt 1988, Ronen and Starr 1990, Drucker 1990).

Because of high setup costs, past production management theories favoured large-lot production. Now, in line with the new production management theories, more and more firms are producing in smaller lots. However, these theories and the new production management techniques that have emerged from them, have not been accompanied by a proper information management methodology.

This article will review the implications of a move from large- to small-lot production on the firm's information system. Intuitively, small-lot production should require a stronger information system than large-lot production, because of the larger number of lots to be managed. This intuition causes production and information system managers to resist the shift to small-lot production, or at least, to request that the existing information system be upgraded to help them cope with the perceived additional workload. It is the intention of this article to show that a transition to small-lot production brings with it, if correctly managed, a decrease in information needs, and not an increase as might be expected. The study copes with this problem by analysing it in two ways:

(1) by using the entropy measurement to measure the quantity of information;
(2) by constructing a model to evaluate the information needs, and analysing the ways to reduce them.

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The next section briefly summarizes the benefits of small-lot manufacturing and the associated information paradox. Section 3 presents entropy as a measurement of information. Section 4 develops the entropy model to analyse the quantity of information required in small-lot manufacturing. Section 5 presents the conclusions to be drawn.

2. Small-lot production

Contrary to the classic Western approach, which favours large-lot production (see, for example, Schonberger 1982), an important component of all the new production theories is the reduction of lot size. The classic Western approach favoured large-lot production because of the economies of scale that are apparently to be derived thereby. The source of these economies of scale are several:

(1) the larger the lot size, the fewer the number of lots and thus the greater the savings to be achieved in machine setup, purchasing and lot handling costs;
(2) control is simpler when the number of lots is small.

The advantages of the small-lot approach may be summarized as follows.

(1) There is less lead time per lot. As the size of the lots gets smaller, the time they spend on the floor shortens accordingly.
(2) Because of the shorter lead times, adaptation to market demands is rapid.
(3) Less work is in process, and operating expenses are reduced accordingly.
(4) There is a reduction in production defectives. Unused stock deteriorates for many reasons: spoilage, corrosion, loss of solderability in printed circuits, obsolescence of electronic components, mechanical failures, humidity, etc. Thus a reduction in lead times reduces the defect rate.
(5) Process quality improves. Shorter lead times and a reduction of work-in-process enable the firm to locate production problems more rapidly and correct them. Suzaki (1987, chapter 1) graphically describes inventory as the sea covering sand banks. As stocks are reduced along with lot sizes, problems are uncovered and can be tackled.
(6) Worker involvement increases and worker motivation improves. The increased involvement of workers is part of the general just-in-time approach (see Schonberger 1982, 1986).

Integration of the JIT, TQM and TOC methods brings us to a general formulation on lot sizes: 'Work in small-, appropriately- and smart-sized lots.' If the production process is not bottlenecked, small lots are advantageous, in accordance with the argument detailed above. In today's Western industry, lot sizes are such that in most cases any reduction is certain to improve the firm's performance. If the lot passes through a production constraint (a bottleneck, or a scarce resource) its size should be carefully calculated as a function of production loss. In these cases a team should be appointed to shorten setup times. The term appropriately-sized lots means meeting market demands in the relevant time framework (week, month, etc., as determined by management). Smart-sized lots take into account relevant company considerations (e.g. avoid rules of thumb like 'no more than 3 printed circuits per lot', while one needs to assemble four circuits per product).

3. Entropy as a measure of information quantity

One of the means of measuring the quantity of information is Shannon's (1948) entropy function. Shannon borrowed the notion of entropy from thermodynamic science and suggested using it in the communication and information theory which he developed. He suggested using entropy as a measure of the amount of information passed from a transmitter to a receiver, and as an index of the uncertainty level of a stochastic process. Shannon defined the function and used it to measure the capacity of a communications channel, and to develop efficient codes for coding information (see Ahituv and Neumann 1990, chapter 3).

The definition of the entropy function is as follows:

Given a group of events $E=\{e_1,\ldots,e_n\}$, and the *a priori* probabilities of the events' occurrence

$$P=\{p_1,\ldots,p_n\}$$

where

$$p_i \geqslant 0 \quad \text{and} \quad \sum_{i=1}^{n} p_i = 1$$

the entropy function of E is defined as follows:

$$H=-\sum_{i=1}^{n} p_i * \log(p_i)$$

where $0*\ln(0)=0$.

Characteristics of the entropy function

(1) The function H is continuous in P_i.
(2) If $p_i=1/n$ for all i, then H is monotonically increasing in n.
(3) If a given state is broken up into two sub-states, the original H is the weighted sum of the two new H's. For example, Fig. 1 shows two probability trees with identical results. According to the rule,

$$H(1/2, 1/3, 1/6) = H(1/2, 1/2) + 1/2 * H(2/3, 1/3)$$

(4) $0 \leqslant H \leqslant \ln(n)$.
(5) If there is certainty, $H=0$.
(6) H achieves its maximum when uncertainty is maximal, i.e. $p_i=1/n$ for all i.
(7) Any *a priori* knowledge about an event, or about the conditional probabilities of subsequent events, reduces H, i.e. it reduces uncertainty.

Notes

(1) It is common to use 2 as the base for logarithms in entropy calculations. This option gives entropy the dimension of a binary digit (bit).
(2) Many researchers ask 'What does entropy really measure?'. Arrow (1986) claims entropy measures the value of information, if and only if the decision-maker's utility function is logarithmic.
(3) For other applications of the use of the entropy function as a measure of information, the reader is referred to Lev (1969) and Mitroff and Mason (1974).

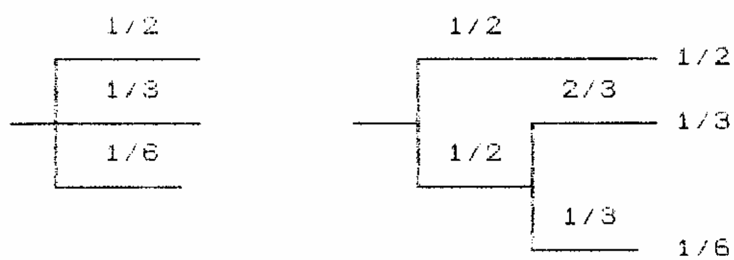

Figure 1. Breakdown of probabilities (Shannon 1948).

4. Information requirements of small-lot production

4.1. *Information paradox of small-lot manufacturing*

Production managers considering a move to small-lot production, usually react by requesting an upgrading of their information system. This includes upgrading data gathering on the floor and installing new software to process the data. There is usually a need to increase the computer's data processing capability as well. The reaction occurs at two stages:

(1) as an argument against the change, when it is being considered;
(2) as a request to upgrade the information system, after the decision has been taken.

The rationale for the above request is as follows:

(1) Lot size is inversely proportional to the number of lots.
(2) The amount of information is directly proportional to the number of lots: $II = C1 * NL$.

(1) and (2) imply:

(3) The amount of information needed is inversely proportional to the size of the lot: $II = C2 * (1/LS)$, where II = number of information items needed, NL = number of lots, LS = lot size, and C1 and C2 are constants.

4.2. *Entropy model*

4.2.1. *Description*

Let us review the assembly line's information requirements by calculating its entropy. In this model entropy measures the level of information needed in order to ascertain the location of a lot along the assembly line, when the probability of its being at any one station is known.

We will check the entropy of a production line, and see how it varies when the lot size of a certain product is changed, while the total production level remains constant.

The higher the entropy of a system, the higher its level of uncertainty, and the more information is required to understand what is happening in it.

The analysis will be as follows:

(1) calculate the entropy of a single lot;
(2) calculate the amount of information required concerning the production line.

The calculation involves a line with S stations in series.

4.2.2. *Entropy of a production line*

The requirement is to produce a given quantity P of products. The line is serial, containing S stations. Let us take a time unit T_T, greater than or equal to the time it takes to produce the required amount, and relate it to the frequency of the lot being at any one station. Figure 2 contains a schematic representation of the line.

Let the production time of a lot in any station i be T_i. Then the probability of its being at that station (PR) is given by

$$PR_i = T_i / T_T$$

The lot's lead time is given by

$$T_L = \sum_{i=1}^{s} T_i$$

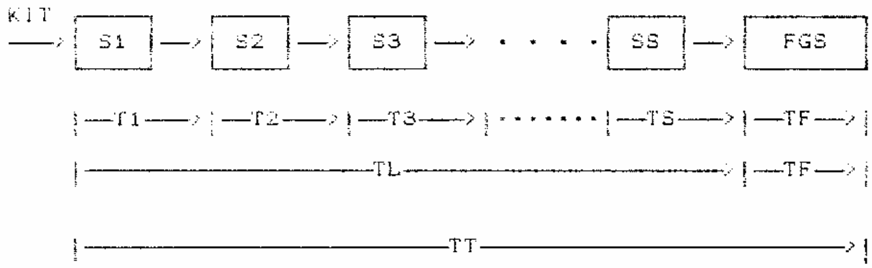

Figure 2. Times in the entropy model.

The probability of its being anywhere along the line is

$$PR_L = T_L/T_T = \sum_{i=1}^{s} T_i/T_T$$

The rest of the time the lot is in the finished goods deposit, or it is already with the customer. This time is given by

$$T_F = T_T - T_L = T_T - \sum_{i=1}^{s} T_i$$

Note: This can also be the time spent by the lot before production, i.e. as raw material, without affecting the model.

The probability of the lot being in the finished goods deposit is given by

$$PR_F = T_F/T_T = \left(T_T - \sum_{i=1}^{s} T_i\right) \Big/ T_T$$

The lot's entropy is

$$H(B) = -\sum_{i=1}^{s} (PR_i * \log(PR_i)) - PR_F * \log(PR_F)$$

We will now check the amount of data which needs to be transmitted from the line (the system's entropy).

We claim that it is necessary to transmit data only from lots located in the assembly line itself. In other words, information about lots in the finished goods deposit is not needed to manage the line and is therefore irrelevant. Hence, to obtain the amount of data required from the line (the system's entropy), we need only multiply a single lot's entropy by the number of lots and by the relative frequency of its being in the line.

The system's entropy $H(S)$ will be given by:

$$H(S) = B * PR_l * H(B) = B * \left(\sum_{i=1}^{s} T_i/T_T\right) * H(B)$$

For a production line with S identical stations, let: P = number of items, S = number of stations, B = number of lots, N = number of items per lot, T = lead time of item in one station. Thus, $N * B = P$.

Since the stations are identical, the lead time of a lot in one station is $T_i = N * T$ for all i. The total lead time is given by

$$T_L = \sum_{i=1}^{s} T_i = S * N * T$$

Without loss of generality, assume the time reference unit T_T to be a multiple of the longest lead time. This is the time it would take to produce the whole amount if it were to be produced in one lot:

$$T_T = C*(T_L)_{B=1} = C*(T_L)_{P=N} = P*T*S*C$$

The meaning of the constant C is as follows: when the entire amount is produced in a single lot, C is the ratio between the gross time (process lead time plus time spent in finished goods deposit) and the net time (process lead time only). Hence $C \geqslant 1$.

The probability of a lot being in the ith station is:

$$PR_i = T_i/T_T = N*T/T_T = N*T/(P*T*S*C) = N/(P*S*C)$$

The probability of its being anywhere along the line is:

$$PR_L = \sum_{i=1}^{s} PR_i = S*PR_i = S*N/(P*S*C) = N/(P*C)$$

The time spent by the lot in the finished goods deposit is:

$$T_F = T_T - T_L = T_T - \sum_{i=1}^{S} T_i = P*T*S*C - S*N*T = S*T*(P*C-N)$$

The probability of its being in the finished goods deposit is:

$$PR_F = T_F/T_T = S*T*(P*C-N)/(S*T*P*C) = (P*C-N)/(P*C)$$

The lot's entropy as a function of its size is:

$$\begin{aligned} H(B) &= -\sum_{i=1}^{S} (PR_i*\log(PR_i)) - PR_F*\log(PR_F) \\ &= -S*(PR_i*\log(PR_i)) - PR_F*\log(PR_F) \\ &= -S*\frac{N*T}{P*T*S*C}*\log\frac{N*T}{P*T*S*C} - \frac{(P*C-N)}{P*C}*\log\frac{(P*C-N)}{P*C} \\ &= -\frac{N}{P*C}*\log\frac{N}{P*S*C} - \frac{P*C-N}{P*C}*\log\frac{P*C-N}{P*C} \end{aligned}$$

Substituting $B = P/N$ we get the lot's entropy as a function of the number of lots:

$$H(B) = -\frac{1}{C*B}*\log\frac{1}{B*S*C} - \frac{B*C-1}{B*C}*\log\frac{B*C-1}{B*C}$$

The system's entropy as a function of the number of lots will be:

$$H(S) = B*PR_L*H(B) = B*(N/(P*C))*H(B)$$

Since $B = P/N$ we obtain

$$\begin{aligned} H(S) &= B*(N/(P*C))*H(B) = (1/C)*H(B) \\ &= -\frac{1}{C^2*B}*\log\frac{1}{B*S*C} - \frac{B*C-1}{C^2*B}*\log\frac{B*C-1}{B*C} \end{aligned}$$

The system's entropy as a function of the lot size will be given by:

$$H(S) = -\frac{N}{C^2*P}*\log\frac{N}{P*S*C} - \left(\frac{1}{C} - \frac{N}{P*C^2}\right)*\log\left(1 - \frac{N}{P*C}\right)$$

Let us now check the system's entropy as a function of the number of lots. The entropy of the previously defined line (serial, with all production times equal) is a function of the number of lots, the number of stations and the time reference chosen (this comes across in the constant C).

Theorem 1. For $B \geq 2$ and $S \geq 2$, entropy as a function of the number of lots is monotonically decreasing. This means that an increase in the number of lots (or a decrease in the size of lots) reduced entropy.

Theorem 2. As the number of lots tends to infinity, entropy tends to zero (see Ronen and Karp 1991 for the proof of both theorems).

4.2.3. *Evaluation of the function for a line with ten stations*

For purposes of illustration, the entropy for an assembly line of 10 stations was computed as a function of the number of lots ($C=1$).

Figures 3 and 4 show entropy as a function of the number of lots and their size. The continuous line represents entropy, and the points denote the two members which make up the function.

4.3. *A model for the review of the line's information items*

To counter the widespread belief that a reduction in lot sizes requires bigger computer resources, due to the rise in the number of information items, we now present a model which reviews the information required to manage a production line. Analysis of the model will demonstrate how it is possible to cut back on information items through the right management approach, based on the theories and techniques presented in section 2.

This analysis will reinforce the conclusions reached in the previous section.

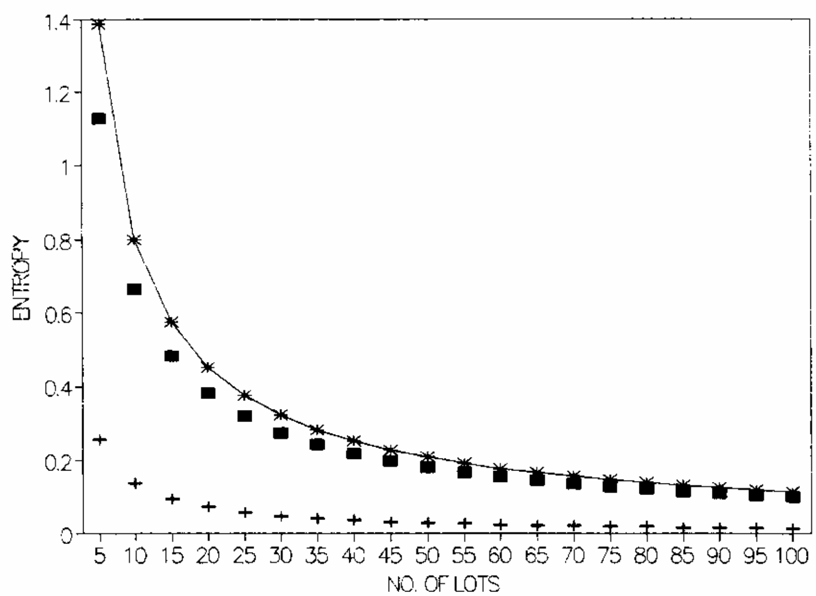

Figure 3. Entropy versus number of lots.

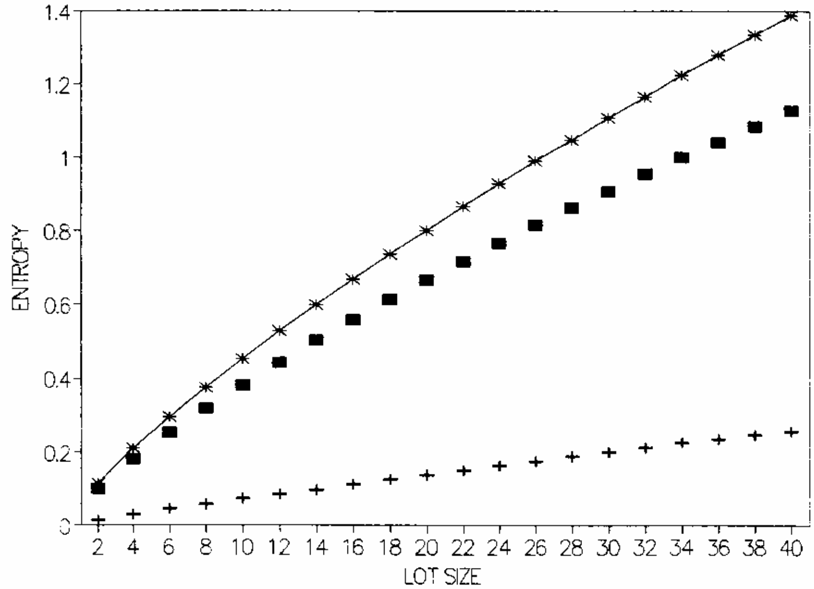

Figure 4. Entropy versus lot size.

4.3.1. *The model*

Basic assumptions

Let us review which data the assembly line manager requires in order to control the flow of lots along the line. The manager needs information in order to:

(1) supervise the production process;
(2) plan supplies to customers and honour marketing commitments;
(3) locate problems along the line and initiate corrective action;
(4) maintain product quality;
(5) effect changes in the products within the assembly line, if needed.

Let us review the messages sent to and from the line. The following model will quantify these messages.

The basic data for the model are:

NS the number of stations
NP the total number of parts
TPP the average time per part in each station
SUT the average setup time in each station

The decision variable is

LS the lot size

The model's output includes

NL number of lots
TS average lot time per station
LT lead time (total lot production time)
II information items needed

and the model's coefficients are

a, *b*1, *b*, *c*

Calculation of the model

Equalities which follow immediately from the above definitions are:

number of lots

$$NL = NP/LS$$

average lot time in station j

$$TS_j = SUT_j + TPP_j * LS$$

and the lead time

$$LT = \sum_{j=1}^{NS} TS_j$$

We make the following claims:

(1) Information items sent to and from a production station deal with the lot itself and with the parts in it. Hence, for a fixed production time the number of information items sent to and from station j and dealing with lot i will be a linear function of the lot size: $II(i, j) = a + b1 * LS$.

(2) The longer a lot is in a station, the more information items it will spawn. Hence, the number of information items dealing with parts in a lot will be a linear function of the time spent by the lot in the station (the coefficient $b1$ will be a linear function of the time per station):

$$b1 = b + c * TS$$

Hence

$$II(i, j) = a + b1 * LS = a + LS(b + c * TS_j) = a + b * LS + c * TS_j * LS$$

Comments

During the processing of a lot in a station, information items are needed which deal with:

(1) the lot *per se*;

(2) part or all of the parts in the lot.

The reasons information is required about parts in a lot are:

(1) quality problems (information about defective parts only. A good part need not originate any information items);

(2) missing parts;

(3) time related problems, such as:

  (*a*) the failure rate—the longer the product remains in the assembly line, the higher the failure rate;

  (*b*) the number of changes to be made on products in the line—this number gets bigger the longer the lot stays in the line.

The number of information items (messages) sent from station j is given by:

$$II(j) = \sum_{i=1}^{NL} (a + b * LS + c * TS_j * LS) = a * NL + b * NP + c * NP * TS_j$$

A lot's production time in a station is made up of the parts' lead time and the station setup time:

$$TS = SUT + TPP * LS$$

Hence

$$II(j) = a*NL + b*NP + c*NP*TS_j$$
$$= a*NL + b*NP + c*NP*(SUT_j + TPP_j*LS)$$
$$= a*NL + b*NP + c*NP*SUT_j + c*NP*TPP_j*LS$$

The number of lots is inversely related to the lot size:

$$NL = NP/LS$$

Hence

$$II(j) = a*NL + b*NP + c*NP*SUT_j + c*NP*TPP_j*LS$$
$$= a*NP/LS + b*NP + c*NP*SUT_j + c*NP*TPP_j*LS$$
$$= NP*(a/LS + b + c*SUT_j + c*TPP_j*LS)$$

The number of information messages (items) from the entire line is the sum of all station information items:

$$II(S) = \sum_{j=1}^{NS} II(j) = NP*\sum_{j=1}^{NS}(a/LS + b + c*SUT_j + c*TPP_j*LS)$$

Significance of the results

The number of information items originating in a station is represented by a function consisting of four members. Two of them (the second and third) are independent of lot size. The first is inversely related to lot size, and the fourth is directly related to it. Since the first member deals with the entire lot, and is linearly related to the number of lots, it is inversely linear in relation to lot size. The fourth member follows from lead time. The shorter it is, the less time the parts spend in the assembly line, and hence the less is the amount of information about them required.

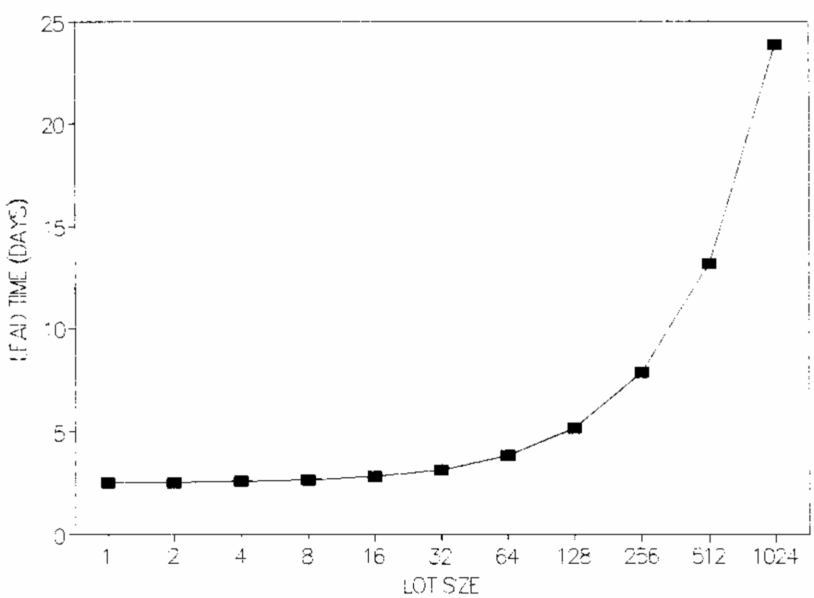

Figure 5. Lead time versus lot size.

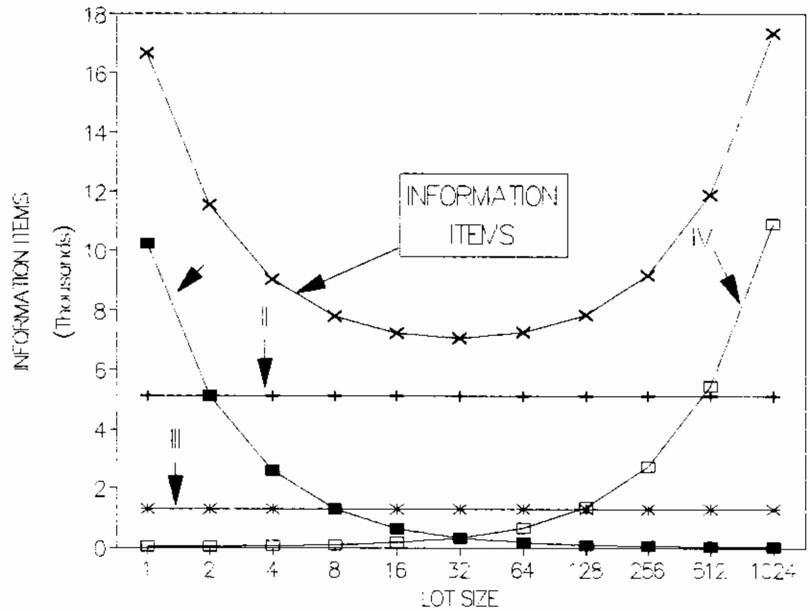

Figure 6. Information items versus lot size.

Example

Figure 5 shows required lead time as a function of lot size in a production line whose specifications are detailed below.

Figure 6 shows the number of information items needed in the same line, as well as the function's four members. The production line specifications are:

number of stations $NS = 10$
number of parts $NP = 1024$
average time per part in each station $TPP = 1$ min
average setup time in each station $SUT = 120$ min (2 hours)
Coefficients: $a = 1$, $b = 0{\cdot}5$, $c = 0{\cdot}5$ (II/day) ($= 0{\cdot}001$ II/min) (a workday equals 480 min).

It can be seen that when the number of lots is small, lead time is quite long and hence the fourth member, which relates to the parts' stay in the line, is dominant. Any reduction in lot size brings about a reduction in the volume of information. As the number of lots increases the first member, dealing with the lot itself, becomes dominant, and then a reduction in lot size might increase the volume of information.

4.3.2. *Ways to cut back on information items*

In order to reduce the number of information items sent to and from the line, we must deal with the function's factors as well as its coefficients.

Setup times

Reducing setup times is an important element of the new production management theories. Now we see that it can influence information systems as well.

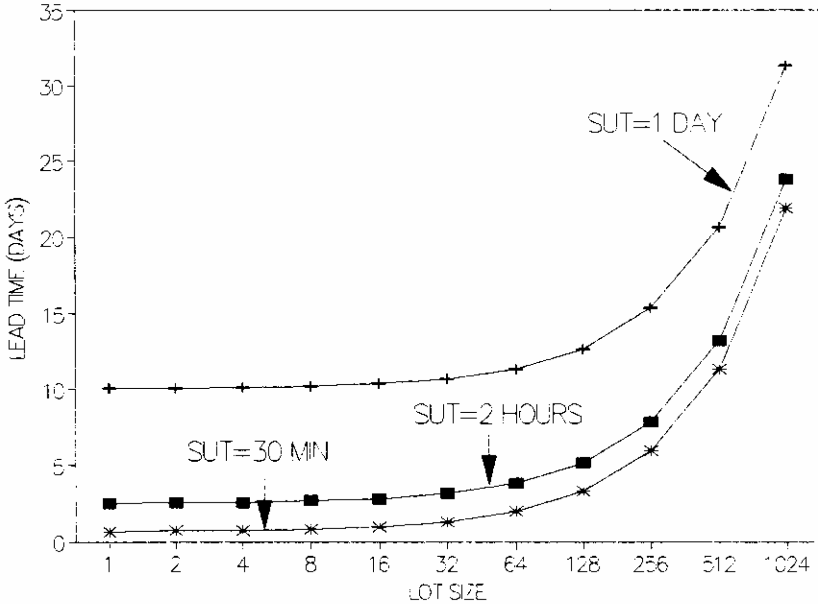

Figure 7. Lead time versus lot size.

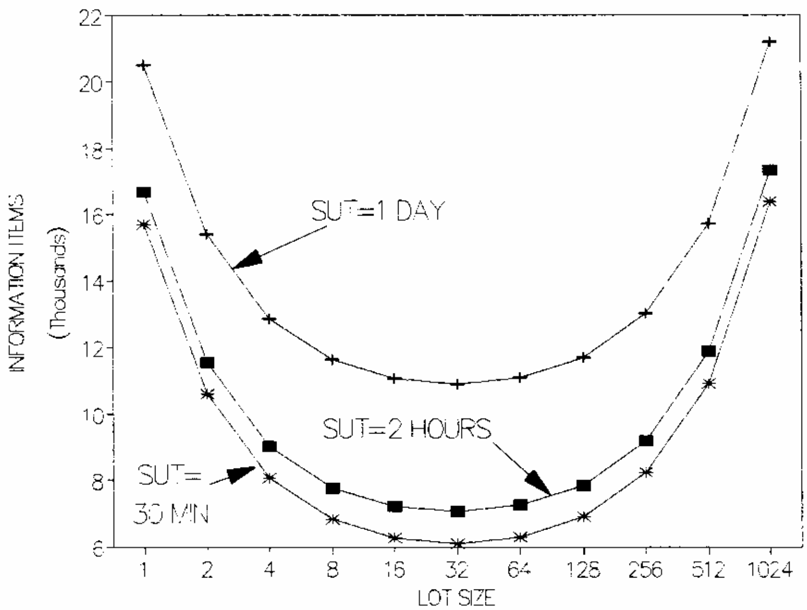

Figure 8. Information items versus lot size.

Figure 7 shows changes in lead times as a function of lot size. The line data are as before, but there are three setup times:

(1) $SUT = 480$ min (1 workday);
(2) $SUT = 120$ min (2 hours);
(3) $SUT = 30$ min.

Figure 8 shows information items for these data.

Lead time

Several steps can be taken in order to reduce lead time.

(1) *Reduce time-per part.* Figure 9 shows changes in lead times as a function of lot size, when the time per part (TPP) in a station is assigned different values:

(*a*) $TPP = 2$ min;
(*b*) $TPP = 1$ min;
(*c*) $TPP = 0{\cdot}5$ min.

Figure 10 shows information items for the same data.

(2) *Reduce waiting times.* In our model, waiting times are included in lead times, and their reduction will immediately reduce lead times and thereby reduce the number of information items.

(3) *Improve assembly line maintenance.* This will make for a smoother flow of parts along the line. Improved maintenance can be achieved by the total preventive maintenance (TPM) approach.

(4) *Work with complete kits.* This will also make for a faster flow of parts along the assembly line.

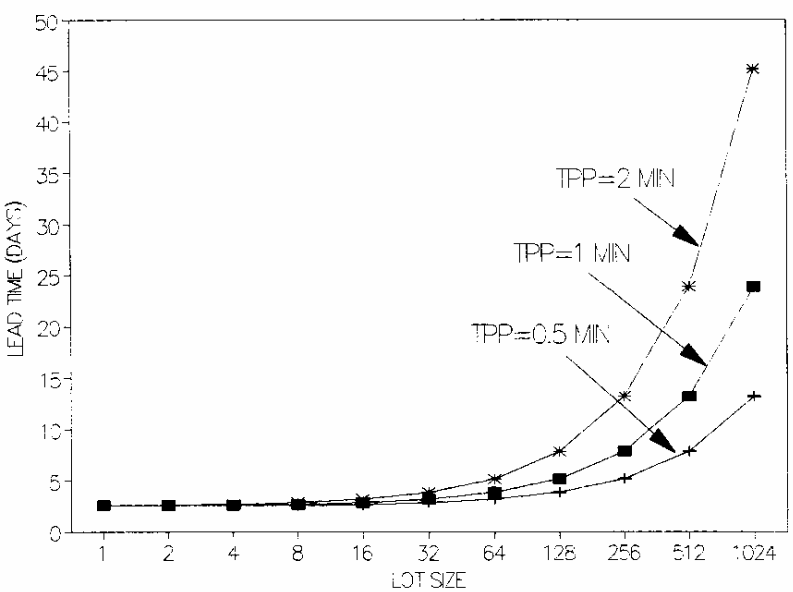

Figure 9. Lead time versus lot size.

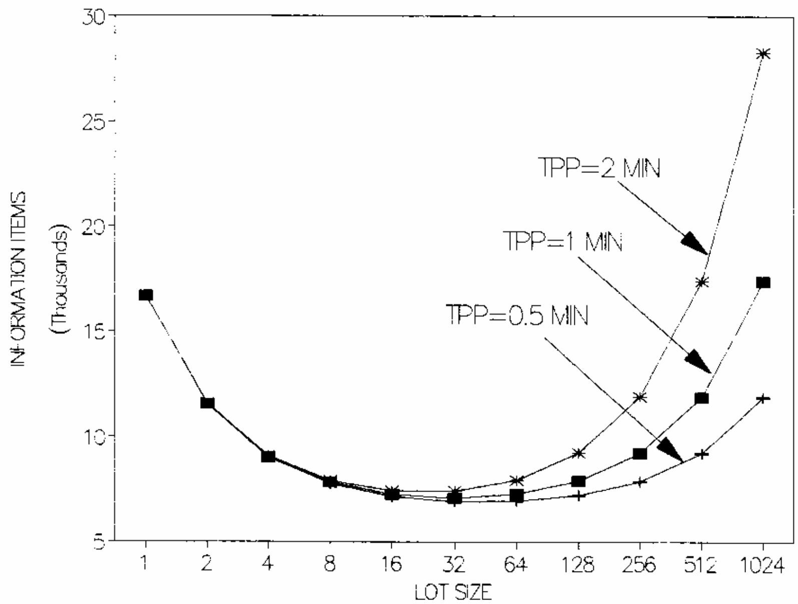

Figure 10. Information items versus lot size.

Reduce information requirements dealing with lots (reduction of coefficient 'a')

Information requirements dealing with the lot *per se* can be changed in a number of ways.

(1) *When a lot's stay in a station drops below a certain threshold, the manager does not need information about its move to another station.* This claim will be illustrated in the following extreme example: In a line comprising ten stations, lead time is 1 month. In order to obtain information about a lot's flow along the line, 11 different messages are needed (moving from station to station, or exiting the line). Suppose we manage to reduce a lot's lead time to 1 day. The manager does not now need perfect information about every lot's location at any one time. He will be happy just knowing the lot is in the finished products deposit, or, even better, that it has been marketed.

Indeed, if perfect information about every lot's location at any one time were to be directed to him, the manager might drown in a sea of data. Thus we see that lower lead times may change the line manager's information requirements. A manager might be satisfied with periodic information about the lots' location along the line. The implications for our model are that the coefficient '*a*' may be reduced.

Note: This study deals with the manager's information needs, but the above claim has further implications. The manager himself may, as lead time is reduced, be able to spend less time supervising the assembly line and turn his attention to other tasks, or cut back the number of supervisory staff along the line.

(2) *Coefficient 'a' can be reduced by managing through buffers.* The idea is not to sample all stations, but sample buffers instead (see Schragenheim and Ronen 1991).

Reduce information requirements dealing with parts in a lot (reduction of coefficient 'b')

Information about parts in a lot is uncalled for. Where production flows smoothly and without problems, managing lots should suffice, and there should be no need to manage parts of a lot. The rationale for managing parts has to do with quality problems and missing items. Hence, in order to reduce the number of information items dealing with parts of a lot, we can

(1) improve product quality;
(2) perform preventive maintenance;
(3) make sure kits are complete, in order to avoid having to deal with materials.

Reduce information requirements caused by the lot's stay in the line (reduction of coefficient 'c')

(1) The improvement in the quality of purchased components may reduce time-related component failures, thus reducing information requirements caused by the lot's stay in the assembly line.

(2) Good planning, and blocking insignificant demands for modifications, will reduce the number of changes and with it the coefficient 'c'.

4.3.3. *Implications*

The entropy model clearly shows that information requirements may be reduced by reducing lot size. This gain is not, however, an automatic outcome of reducing lot size; it can only be achieved in conjunction with management methods such as TQM, JIT or TOC.

A production line manager interested in reducing lot size might be well-advised not to make the attempt unless he means to accompany it with additional engineering and managerial measures. Such measures include:

(1) reduction in setup times;
(2) reduction in lead times;
(3) improvement in product quality;
(4) changes in the approach to information gathering.†

If these changes accompany a reduction in lot size, the manager will attain a reduction in information requirements.

In a wider perspective, one may view information requirements as an indicator of managerial difficulties, and of the manager's ability to control the assembly line. Hence, in addition to its other advantages, the small-lot managing method can help, as part of a general managerial theory, to increase the manager's control of the line.

5. Conclusions

We have reviewed the implications of a transition to small-lot production on the firm's information system. The widely held belief is that production in smaller lots requires a stronger information system, since there are more lots to manage. This view causes resistance to change, and impedes its adoption by manufacturing firms. This article disproves the belief in two different ways:

(1) It presents the design of an entropy model which checks the assembly line's information requirements as a function of lot size. We show that a reduction in

† A large mechanical firm reduced lot sizes without taking these four accompanying steps. After 6 months, work reverted to its previous mode, with lot sizes doubled again, due to management's inability to control the process.

lot size reduces entropy, i.e. it reduces uncertainty. This means that less information is needed to manage the assembly line.

(2) It presents the design of a model which reviews information needs, and indicates methods to reduce them. These methods all derive from the new production management theories.

In conclusion, whenever the shift to small-sized lots is accompanied by a compatible managing method, the amount of information required to manage production lines is reduced.

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