Quality Issues impacting Production Planning

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Abstract: Among the various problems affecting production processes, the unpredictability of quality factors is one of the main issues which concern manufacturing enterprises. In make-to-order or in perishable good production systems, the gap between expected and real output quality increases product cost mainly in two different ways: through the costs of extra production or reworks due to the presence of non-compliant items and through the costs originating from inefficient planning and the need of unscheduled machine changeovers. While the first are relatively easy to compute, even ex-ante, the latter are much more difficult to estimate because they depend on several planning variables such as lot size, sequencing, deliveries due dates, etc. This paper specifically addresses this problem in a make-to-order multi-product customized production system; here, the enterprise diversifies each production lot due to the fact that each order is based on the customer specific requirements and it is unique (in example, packaging or textiles and apparel industry). In these contexts, using a rule-of-thumb in overestimating the input size may cause high costs because all the excess production will generate little or no revenues on top of contributing to increasing wastes in general. On the other hand, the underestimation of the lots size is associated to the eventual need of launching a new, typically very small production order, thus a single product will bear twice the changeover costs. With little markups, it may happen that these extra costs can reduce profit to zero. Aim of this paper is to provide a critical analysis of the literature state-of-art while introducing some elements that can help the definition of lot-sizing policies considering poor quality costs.

Keywords: production planning; make-to-order; lot-sizing; quality problems;

1. Introduction

Among the various different production planning issues that an industrial company daily needs to cope with, when the production system yield rate is not deterministic and the quality rate is variable, the lot-sizing problem represents a critical problem, particularly in multiproduct make-to-order environment where the orders must be completely fulfilled and stock-outs are not admissible.

The effect of quality rate variability interfere with a correct production/purchasing lot-sizing causing costs increase: these obviously depend on the value of the processed material, on the processing costs and on the time wasted in setup or changeover procedures on the machines; on top of these, costs increase mainly depends on the production rules and the criteria that need to be followed in case a production lot has encountered a quality problem that has returned a number of compliant finite product which is lower than needed, i.e. the customer order cannot be correctly satisfied. In this sense, three cases can be identified:

- it is possible to amend the problem reworking non-compliant products, without the need of new raw materials or components input;
- it is possible to amend the problem reworking non-compliant products, however new inputs are needed;
- non compliant finite products cannot be reworked and must be disposed; thus, to complete the demanded lot, new production orders must be launched and one or more production phases must be repeated.

While in the first case quality issues do not impact on the materials gross requirements, in the third case – being the presence of scraps – it is necessary to appropriately overestimate the production/purchasing lot size. The latter case is the most interesting, specifically when the ratio between compliant and non-compliant product is highly variable. Indeed, an inadequate overestimation of materials input leads to the need of bearing extra costs for additional production runs and to the risk of a delayed delivery of the ordered product, with the associated consequences in terms of corporate image. On the contrary, an excess over-sizing of the material lot entails a cost increase in terms of passive interests for the circulating capital in form of work-in-progress along with the associated consequences in terms of mark-up reduction.

The problem gets more complex if two more scenario characteristics are taken into account. The first is associated to the number of typologies of finite products treated in the production system: this is related to the need of performing a higher or lower number of setup and changeovers in all the different phases of the process, every time a new order is launched. The second scenario characteristic is associated to the possibility to keep in stock half-finished o finite products. Indeed, stock is an effective mean to decouple production planning from the demand dynamics, meanwhile allows balancing processes variability through a compensation effect on the ordered/produced volumes. Production planning of standard components or modular products is obviously much easier to handle thanks to the effect of the so-called square-root-law (Schiraldi, 2007).

On the contrary, let's analyze a multi-product scenario in which neither half-finished products storage is admissible nor reworks: this condition is common in customized production (e.g. packaging) where each received order is unique and has specific characteristics which are only valuable for a certain customer. A setup is performed every single lot and, in case non-compliant product may overcome a given threshold, a new production order must be launched. Here, stock management is not the solution and lot-sizing errors can lead to unbearable costs for the production system.

2. Lot-Sizing and Costs of Poor Quality

The defective capability of a production system to ensure the output conformity represents a disturbing element for the production planning processes; it constitutes the sources for a number of inefficiencies which can be included in the "Costs of Poor Quality" (Gryna, 1999). The classification of COPQ envisages:

- *Internal Failure Costs:* costs that affect the production and supply phases of a company and are related to inefficiencies in the internal process, due to errors detected before the product is delivered to the customer*;*
- *External Failure Costs:* costs due to noncompliance with customer specifications, due to errors that are discovered after the product is delivered to the customer;
- *Appraisal Costs:* costs incurred to determine whether a product fulfills the requirements for the quality expectations;
- *Prevention Costs:* costs incurred to prevent the emergence of internal failure costs and external failure costs, due to all the operations and procedures that aim to (asymptotically) reduce the probability of producing nonconforming product.

Specifically, in addition to components analyzed by Gryna, in the above mentioned contexts it must be considered an extra production cost, due to more processing cycles needed to meet the order quantity if the compliant units are not enough. These are mainly represented by changeover costs and more generally by equipment needed to restart the production run, which in dedicated productions are not negligible. For example, it must be noted that, for many industrial companies in the packaging sector - where product price is very low and contribution margins are narrow - this means face a serious risk for the order profitability.

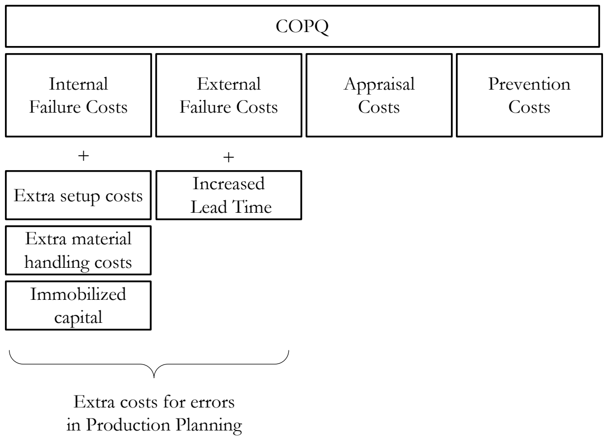

Figure 1 – Components of COPQ

A potential cost item is also related to the extension of production lead time span occurring when other production cycles are necessary to complete a specific order. The increased time span can trigger, besides damaging company's image, far more concrete and quantifiable penalties that might arise for failing to meet a delivery date.

In order to prevent the onset of above described costs, companies could be forced to oversize production lots.

3. Literature review

Literature review shows that the various contributions on this topic can be divided in accordance to two main aspects.

The first aspect concerns the configuration of the production process - which is described as it is divided into phases, each one followed by a quality control that inspects 100% of processed units and eventually discards non-compliances, without any kind of rework. Thus, on this basis we can distinguish Single Stage scenarios (SS) or Multiple Stage scenarios (MS), depending on whether one or more than one quality controls phases are present in the production process.

The second aspect concerns with the possible re-actions on the case in which, after the final quality control, the number of compliant finite products is lower than needed. Thus, on this basis we can distinguish Single Production Run scenarios (SR) and Multi Production Run scenarios (MR), where a Production Run indicates a production cycle from the first processing phase to the last quality control.

In SR scenarios it is not possible to complete eventual lack of compliant finite products through the launch of another production order; indeed, lot sizing policy takes into account costs of shortage of compliant finite products, i.e. penalties or damages of corporate image. The aim is therefore to define the lot size maximizing the expected profit on each order and only considering the cost of the first production run.

On the contrary, in MR scenario it is possible to iterate production runs if this is necessary to complete the ordered quantity of finite products. Thus, in this case the customer demand must be rigidly met and no stock-out is admissible. The trade-off between the costs of new production run orders and the costs of failure in meeting the demand has been analyzed since the 50s (Bowman, 1955), (Llewellyn, 1959), (Levitan, 1960), (Giffler, 1960), (Goode & Saltzman., 1961), and the SR problem was initially approached. Indeed, the MR problem formulation results to be much more complex because of the need of taking into account the dynamic nature of the scenario through a Multiple Lot-Sizing Production to Order (MLPO) approach (Klein, 1966), (Sepehri, Silver, & New, 1986), (Pentico, 1988), (Zhang & Guu, 1996), (Anily, Beja, & Mendel, 2002), (Grosfeld-Nir & Gerchak, 2004). This paper is thus focused on the modeling of the MS/MR (Multiple Stage / Multiple Run) problem.

4. A modeling framework proposal

A modeling approach may start from the definition of the following elements:

- stochastic model that represents the generation of non compliant units;
- structure of production costs;
- choice of the solution approach.

Firstly, the stochastic law that describes the phenomenon of generating a random number of defective units produced by a single process stage must be defined. Obviously, the number of compliant units can be measured only after the quality control test, following the last operation of a stage. In literature, a number of ways to model the randomness of the production process is found (Pentico, 1994):

1. the randomness is related to the whole lot and not to single units, i.e. the compliance is "all-or-nothing". For example, all the units are processed in a single batch and a single percentage representing the probability that the process is successful is estimated;
2. the generation of compliant units is represented by a Bernoulli process and thus the number of compliant products after a single processing stage can be represented by the binomial distribution B(p, N) where p is the estimated probability that a processing operation is successful while N is the number of units that are processed in that stage. In this model the process is assumed to be stationary and each unit generation processes is independent (no autocorrelation). The advantage of this model is due to its simplicity as there is the only need to estimate the parameter p. Thus, it is an appropriate approach to represent processes that are stable and under statistical control;
3. the probability of having a certain percentage of compliant units is estimated and is assumed independent from the size of the lot. Thus, a continuous random variable in the interval [0, 1] is defined. This model should only be used when the number of units in the lots is large and it does not vary considerably from one order to another. It is best applied to scenarios in which the production system has limited capacity to adapt to changes in a stochastic environment or to changes in production parameters.
4. the interrupted geometric model with parameter p is applied (Zhang & Guu, 1998); this is the probability that a single processing is successful and it is used to describe the situation where a process runs out of statistical control and then start generating defective output. This model may be appropriately used for the case of a machining tool that gets gradually deteriorated and progressively increase the percentage of unacceptable processing. Similarly, there are cases where compliant units are produced only after some time from production start, i.e. this may happen after a setup/changeover operation in some specific manufacturing processes.

The second element that should be evaluated concerns the definition of the scenario variables and the associated costs:

S — the number of stages of the production system (in MS scenarios, S>1);

U_i — the number of compliant units from stage i that are inputted in the following stage i-1;

$P(U_i | U_{i+1})$ — the probability of obtaining U_i compliant units after the stage i , given that the units in input were U_{i+1};

K_i — the cost of launching a production run in the single stage i;

C_i — the variable unit cost for a production run in the single stage i;

D — the demand in terms of number of units required to be compliant in a single production order;

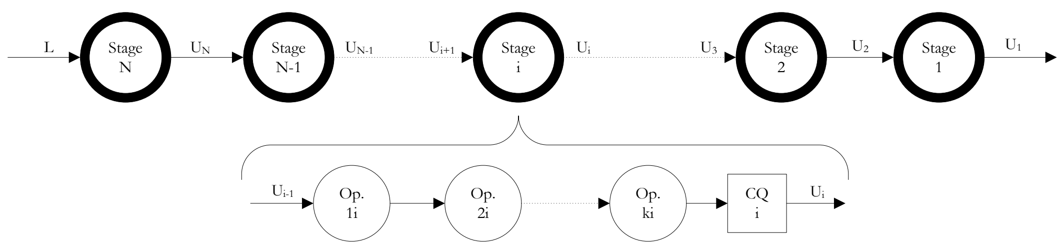

Figure 2 - A multi-stage production system

L the decision variable of the problem, which expresses the size of the production batch i.e. the number of units to be inputted in the first stage of the process at the first run.

Lastly, the solution approach to the problem needs to be chosen: different formulations of the MLPO problem are presented in literature. An effective approach may be founded on dynamic programming, as it has been proposed by Pentico in 1994 for an n-stage system:

$$f_n(\mathrm{D},\mathrm{L}) = \min_{\mathrm{L} \geq \mathrm{D}} \{\mathrm{C_n}(\mathrm{L})\} =$$

$$= \min_{\mathrm{L} \geq \mathrm{D}} \left\{ \mathrm{K_n} + \mathrm{c_n L} + \sum_{\mathrm{U_n}=0}^{\mathrm{L}} \mathrm{C_{n-1}}(\mathrm{U_n}) \mathrm{p_n}(\mathrm{U_n}|\mathrm{L}) \right\}$$

where $f_n(D, L)$ is the minimum cost to fulfill an order of D units in a batch of L units while $C_{n-1}(U_n)$ is the expected production cost for stage n-1 in order to satisfy a demand of D compliant products, given an input of U_n units. Here any storage costs or salvage value for units in excess is considered.

Being effective, dynamic programming approach cannot however be defined efficient: the computational complexity is surely high and the problem is solvable only for little values of D (Sepehri, Silver, & New, 1986). As an alternative, heuristics able to reach good solutions starting from the estimation of the marginal production cost have been developed. In this sense, the Sepehri, Silver e New (1986) algorithm has been proved to reach solutions quite near to the optimal one.

5. Directions for future research

This paper is focused on the impact of process quality variability on production planning in specific MTO scenarios, dealing with the costs that a company has to bear due to the uncertainty of the production yield rate. In these scenarios, finding the optimal production/purchasing lot-size is a difficult problem, which becomes untreatable, increasing the value of the demand. However, up to now, the developed heuristics are only applicable with certain stochastic models and in low complexity production systems. Moreover, their assessment has been performed on a limited number of scenarios and the problems formulations usually do not consider the aim of reducing production lead time. Thus, based on the modeling framework presented in this paper, a simulation model which can cope with real random and dynamic scenarios should be developed in order to better perform heuristics algorithms tests.

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