MANUFACTURING COSTS IN CONVENTIONAL AND LEAN MANUFACTURING

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Summary: The work analyses the relationship between the size of a production lot and the number of machine changeovers through the lens of an analysis of viability (an analysis of the total production costs). The problem is looked into from the perspective of two distinct production management philosophies: the classic (conventional) production theory, based on the (economically) optimal lot size on the one hand and lean manufacturing, based on the EPEI index, on the other. The relationship between the results produced by the two approaches is illustrated in sample calculations. The findings have practical implications for the practitioners and theoreticians of production management and production engineering.

Keywords: lot size, changeovers, conventional production, lean manufacturing, EPEI.

1. Introduction

Any production manager is faced with three fundamental questions: what to produce (what product range?), how much to produce (what production plan and lot size to choose?) and when to produce? Another question, one which completes the picture, is: how to produce (what manufacturing technology to apply)?

The "how much" question is one of the fundamental dilemmas of people involved in the management of production. On the one hand, manufacturers tend to produce as big lots as possible. This allows them to benefit from the economies of scale: the unit cost of production is lowered, but this involves much work in process (WIP) inventory. On the other hand, WIP inventory can be reduced by manufacturing a product more frequently, but in this case the costs go up as the costs of preparing production (changeover costs) are disproportionately higher than the costs of production (direct labour costs). Production managers try to balance the two contradictory tendencies by specifying lot size by finding compromise.

2. Specifying lot size

The issues involved in determining the size of lots and scheduling them to minimise costs and production time is called the Economic Lot Scheduling Problem (ELSP) [1]. A decision concerning lot size is a fundamental choice in logistics and any failure to consciously take it in actual production is mainly a consequence of insufficient knowledge of the possibilities, conditions and consequences of applying particular methods. This decision depends on economic factors and organisational factors (conditions within the enterprise and material properties). When deciding on the size of a lot, we also make a decision to create some inventory [2, p. 195]. There is much room for discretion in specifying lot size and the frequency of manufacturing [2, pp. 198-204] [3, pp. 193-222] [4, pp. 187-199].

The determination of lot size may be done in either of two ways. In both cases, the following restrictions apply: the size of the production of a given product range (demand), the production capacity of the company and supplier's potential to deliver (the previous process). In the first method, the aim we want to achieve is to maximise the lots of each product range (to an economically viable level). The effect will be the extensification of the number of changeovers in the production of each product family. In the other method, the procedure is completely the opposite. In the manufacturing process, we try to intensify the number of changeovers for each range, the result being a determined lot size for a given product range (minimised size). The first approach seems closer to the classic theory and practice of production management. The other corresponds to the more recent manufacturing techniques (lean manufacturing/production).

2.1. Classic approach to determining the optimal lot size

When specifying lot size using conventional methods, we look for the balancing point for production costs (K_{PR}) and production launch costs (K_{UP}), which can be illustrated as follows:

$$K_{PR} = K_{UP} \tag{1}$$

Production costs (K_{PR}) are determined by the following:

– the optimal lot size (n_{opt}) looked for,
– the total unit production time (T_j), and
– labour costs (K_j) expressed as the average hourly cost of manufacturing a product.

Manufacturing costs are calculated as follows:

$$K_{PR} = n_{opt} \cdot T_j \cdot K_j \tag{2}$$

Production launch costs (K_{UP}) include the following:

– the total time of the preparation and completion of a product (T_{pz}), and
– labour costs (K_{tpz}) expressed as the average hourly cost of preparing a machine for the production of an object.

The costs of production launch are calculated using the following formula:

$$K_{UP} = T_{pz} \cdot K_{t_{pz}} \tag{3}$$

The values K_j and K_{tpz} are distinguished form one another because of the differences in the qualifications of workers. K_j is the costs of the labour of the operator working on the machine during production. K_{tpz} includes the costs of the labour of the worker doing the changeover (a more valued job position). Therefore, K_{tpz} is usually higher than K_j.

In the following mathematical transformations [5, pp. 57-58]:

$$n_{opt} \cdot T_j \cdot K_j = T_{pz} \cdot K_{t_{pz}} \tag{4}$$

$$n_{opt} = \frac{T_{pz} \cdot K_{t_{pz}}}{T_j \cdot K_j} \tag{5}$$

and assuming that:

$$\frac{K_{t_{pz}}}{K_j} = \frac{1}{q} \tag{6}$$

where q is the coefficient of the proportionality of the costs of launching production to the costs of production, we have come up with the final formula for the size of the optimal lot:

$$n_{opt} = \frac{T_{pz}}{T_j \cdot q} \tag{7}$$

Figure 1 is a graphic representation of the problem.

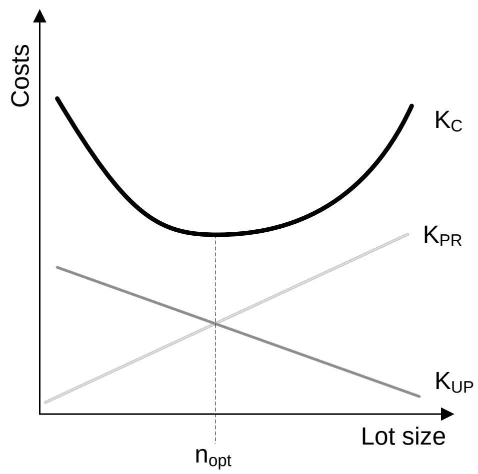

Fig. 1. The relationship between production costs and launch costs
Source: own study

In the literature of the subject, we can find examples of further modifications to the optimal lot size specified using the analytical method (Formula 7) or the graphic method (Fig. 1) [6, pp. 44-47]. The range in which the so-called economic production lot size can be shaped is the following [7, p. 65]:

$$n_{ek} = \langle 0{,}7 \div 1{,}5 \rangle n_{opt} \tag{8}$$

In the area of the optimal lot value, the curve of the total production costs (K_c) in Fig. 1, for a wide range of lot sizes, changes only to a minor extent. In this area, lot size may be altered significantly, which is useful for adjusting the course of manufacturing and leads to only a relatively small increase in the total costs of production.

2.2. Specifying lot size in lean manufacturing

The fundamental principle of lean manufacturing (lean production) is to rely on the customer demand: only as much is produced as ordered by the buyer. In lean manufacturing, lot size is determined using the value of the EPEI index. EPEI (Every Part Every Interval, e.g. week, day, shift, hour) reflects the cycle of the change of a product range on a machine. If the production of all items assigned to a machine takes 2 days, EPEI amounts 2 days. This means that lot size should correspond to the customer's two-day demand for the product family. EPEI reflects how often a process can produce items from among all those produced (the entire product range). In a wider interpretation of EPEI, it can be said that it reflects the flexibility of the production process (the pace of WIP inventory replenishment; the rotation aspect).

The EPEI index for an object (a machine or a uniform machine group) is determined as follows [8, pp. 176-177]:

$$EPEI = \frac{a}{p} \tag{9}$$

where:
a – number of products in the range (the measure of product diversity),
p – number of changeovers of the machinery

The relation counter contains all products from a range manufactured on one machine or a group of machines. It is necessary to look into the documentation concerning all the products manufactured by the company.

The number of changeovers (the denominator) is determined using the following formula:

$$p = \frac{F_d - F_p}{t_{pz}} = \frac{T_p}{t_{pz}} \tag{10}$$

where:
F_d – available time
F_p – production load
T_p – time available for machinery changeover,
t_{pz} – average machinery changeover time.

The value of EPEI is determined directly by two parameters: the number of items assigned to a machine and the number of possible changeovers. The former, determined by the production technology, is rigid and difficult to modify. The latter leaves much room for manoeuvre.

The EPEI for a production process should be assumed to be the highest EPEI of any machine present in the process. A high EPEI means low flexibility (limited time for changeovers, low number of changeovers). The machine with the maximal EPEI will be the bottleneck of the production process.

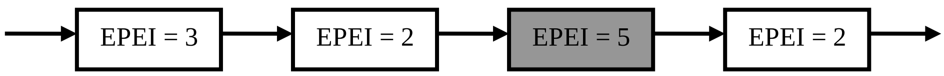

Fig. 2. The calculation of EPEI for a production process (conceptual)
Source: own study

The remaining machines, with better flexibility, can be changed over at least as many times as the bottleneck. However, more frequent changeovers make no sense as flow is anyway determined by the pace of production at the machine with the greatest EPEI (the bottleneck). Therefore, the flexibility of a production process is as high as the lowest flexibility of a machine in the production process [8, pp. 179-182].

3. Lot size optimisation

3.1. Initial assumptions

We compare two approaches to the determination of production lots and, consequently, the number of changeovers. The first is the classic approach based on the determination of the optimal lot size on the basis of the sum of changeover times and the sum of total unit production time. The other approach draws on the lean manufacturing solution based on the EPEI index. The adopted optimisation criterion is the total production cost defined as the sum of the costs of launching and running production.

$$K_C = K_{UP} + K_{PR} \tag{11}$$

where:
K_{UP}- the cost of launching production
K_{PR}- the cost of production

To make our analysis less complicated, we decided to introduce a number of simplifications. We assume that the unit production costs related to the consumption of energy, plant and equipment, and labour remain constant whatever the way production is divided into lots, so they are not a set of variables affecting the selection of the lot determination solution. Another simplification concerns the changeover on a machine or a group of machines. Whatever the manner of dividing production into lots, the unit cost of changeover remains the same. The cost of changeover is understood as the sum of the costs involved in the work of the changeover operator, interruptions of work on the machine and the use of necessary energy, tools, etc. Additionally, we assume that the cost of changeover applies to any machine, whatever the sequence of items it produces. This simplification applies also to the unit price of the processed material. It is assumed that this value does not increase in each consecutive operation and is constant throughout the technological process. Also, in both methods of determining lot size, the specified inventory replenishment cost will be identical and constant in the analysed period of time. For the purposes of the article, we ignore the issue of streams. It is thus assumed that the production system includes solely individual machines. We are going to develop this analysis in a future work and supplement it with the aspects we left out here, which will undoubtedly make it more attractive from the point of view of practitioners.

The above simplifications allowed us to make the optimisation problem more specific. As mentioned above, the optimisation criterion is the minimisation of the total costs of launching and carrying out production. Based on the assumptions and simplifications, changeover costs should be understood as the costs of all completed changeovers for the purposes of a given product range production program. The costs of production are the costs of maintaining WIP inventory alone. We assume that the size of WIP inventory is a consequence of maintaining one lot on each machine (as required by the production technology).

In the following two subsections, we presented mathematical formulas allowing for the calculation of the above cost categories in the conditions of the classic theory (based on optimal lot size) and the lean manufacturing philosophy (based on EPEI).

3.2. Optimisation in the classic theory

The classic theory is based on the determination the optimal lot size. The optimal lot size calculated separately for each product range allows us to determine the how often the production of a lot is repeated in the period for which the production program has been defined. The total cost of launching a selected item for the purposes of manufacturing it as part of a program is therefore equal to the following:

$$K_{UP_{ai_{KT}}} = \frac{P_{ai}}{nopt_{ai}} \cdot \sum_{t=1}^{m} k_{UP_{ai_{m_t}}} \tag{12}$$

where:

$K_{UP_{ai_{KT}}}$ - the cost of launching the production of item a_i in the classic approach,

P_{ai} - the production program for item a_i,

$nopt_{ai}$ - the optimal item a_i lot size,

$\sum_{t=1}^{m} k_{UP_{ai_{m_t}}}$ - the total costs of changeovers necessary to produce item a_i (m is the number of technological operations).

After calculating the costs of launching the production of an item, it is possible to calculate the total costs for the whole set of items dedicated for the given production system. This is the formula for the total cost:

$$K_{UP_{KT}} = \sum_{i=1}^{a} K_{UP_{ai_{KT}}} \tag{13}$$

where:

$\sum_{i=1}^{a} K_{UP_{ai_{KT}}}$ - the total costs of launching the production of a set of product ranges (a – the number of ranges in the set) in the classic approach

Another type of cost considered here is the cost of production (understood as the cost of maintaining WIP inventory). In the classic theory, the cost of maintaining WIP inventory is equal to the value of the inventory multiplied by the cost of maintaining the inventory in the considered unit of time. Based on this, the production cost for the selected item equals the following:

$$K_{PR_{ai_{KT}}} = r_{ai} \cdot n_{opt_{ai}} \cdot c_{ai} \cdot \mu_{\tau_{ai}} \tag{14}$$

where:

r_{ai}- the number of machines processing the a_i^{th} item

c_{ai}- the unit price of item a_i (equal to the cost of materials),

$\mu_{\tau_{ai}}$- the coefficient of the cost of maintaining inventory in a unit of time corresponding to the duration of item a_i production cycle (the duration should include an allowance for enqueueing operations on each machine).

The total cost of production in the classic theory approach is calculated using the following formula:

$$K_{PR_{KT}} = \sum_{i=1}^{a} K_{PR_{ai_{KT}}} \tag{15}$$

where:
$\sum_{i=1}^{a} K_{PR_{ai_{KT}}}$- the sum of production costs for a set of product ranges (a – the number of ranges in the set) in the classic approach

Based on the assumptions discussed in subsection 3.1., the total production cost in the classic approach is calculated using the following formula:

$$K_{C_{KT}} = K_{UP_{KT}} + K_{PR_{KT}} \tag{16}$$

The total production cost of a given product range set will be used as the criterion for the selection of a better lot size determination method.

3.3. Optimisation in lean manufacturing

To determine lot size in lean manufacturing, the EPEI index is used, which on the one hand allows for minimising lot size and improve flexibility, but on the other hand increases the number of changeovers. Thanks to EPEI, we can determine the maximal number of changeovers and the time needed to produce a sequence of all product ranges. Since the example we provide is set in a production system in which a set of product ranges is produced, it is necessary to determine the EPEI of the production process. In this option, EPEI is assumed to be the greatest of the EPEI values calculated separately for each machine in the system.

Knowing production process EPEI and, consequently, the possible number of changeovers, we can calculate the total costs of launching the production of a given item:

$$K_{UP_{ai_{LM}}} = C/O_{EPEImax} \cdot \sum_{t=1}^{m} k_{UP_{ai\,m_t}} \tag{17}$$

where:
$K_{UP_{ai_{LM}}}$- the cost of launching the production of item a_i in line with the lean manufacturing philosophy,
$C/O_{EPEImax}$- the number of changeovers based on the greatest EPEI,
$\sum_{t=1}^{m} k_{UP_{ai_{m_t}}}$ - the total cost of changeovers necessary to produce item a_i (m is the number of technological operations)

The total cost of launching the production of an entire set of product ranges is calculated using the following formula:

$$K_{UP_{LM}} = \sum_{i=1}^{a} K_{UP_{ai_{LM}}} \tag{18}$$

where:
$\sum_{i=1}^{a} K_{UP_{ai_{LM}}}$- the sum of the costs of launching the production of a set of product ranges

(a is the number of ranges in the set) in line with the lean manufacturing philosophy

Production costs for the lean manufacturing solution are calculated analogically to the classic theory solution. The lot size for each machine is calculated on the basis of the quotient of the production program for each item and the possible number of changeovers determined on the basis of production process EPEI. The cost of the production of each item equals the following:

$$K_{PR_{ai_{LM}}} = r_{ai} \cdot \frac{P_{ai}}{C/O_{EPEImax}} \cdot c_{ai} \cdot \mu_{EPEImax} \tag{19}$$

where:
$K_{PRlm_{ai}}$- production costs for item a_i in line with the lean manufacturing philosophy,
r_{ai}- the number of machines processing the a_i^{th} item,
P_{ai}- item a_i production program,
$C/O_{EPEImax}$- number of changeovers determined based on the maximal EPEI,
c_{ai}- item a_i unit price (assumed to be equal to the costs of materials),
$\mu_{\tau_{ai}}$- the coefficient of the cost of inventory maintenance in a unit of time based on the EPEI of the production process of all items.

The total production cost in the lean manufacturing philosophy is calculated using the following formula:

$$K_{PR_{LM}} = \sum_{i=1}^{a} K_{PR_{ai_{LM}}} \tag{20}$$

where:
$\sum_{i=1}^{a} K_{PR_{ai_{LM}}}$- the sum of the production costs for a set of product ranges (a – the number of ranges in the set) in line with the lean manufacturing philosophy.

Taking into account the assumption discussed in 3.1, the total production cost in the lean manufacturing philosophy is calculated using the following formula:

$$K_{C_{LM}} = K_{UP_{LM}} + K_{PR_{LM}} \tag{21}$$

The comparison of the amount of the total cost calculated using the classic approach to determining lot size and the approach based on EPEI will allow a manufacturer to select a solution that is more beneficial from the point of view of running a production plant.

4. A sample analysis of the costs of launching and running production

To illustrate our analysis, we came up with an example for the calculation of production costs conceived of as the sum of the costs of launching and running it. For the purposes of the analysis, we assumed the following:

– the nominal available time for a two-shift work system – 4000 working hours a year,
– admissible load – 85%,
– the q coefficient (the relation between the preparation and completion time t_{pz}

to the unit time t_j) – 0.05 – assumed arbitrarily for the purposes of the analysis,

– inventory maintenance cost coefficient – 25% a year.

The analysed production plant manufactures three product ranges. The details of the annual production plan and the product range unit price (understood as the cost of materials) are presented in Table 1.

Tab. 1. Product range set details

Product	**Production program [items p.a.]**	**Unit price [PLN]**
a1	3,500	5,500.00
a2	5,000	1,500.00
a3	5,000	2,500.00

Source: own study

The production plant includes five machines. In line with the initial assumptions, the issue of streams was not taken into consideration, so each machine in the system is considered individually. The details of the production technology for each product are presented in Table 2. It is assumed that operations are carried out in the order of the numbering of the machines, and the provided times are expressed in working hours.

Tab. 2. Technological details of the set of product ranges

Machine /Product	**r1**		**r2**		**r3**		**r4**		**r5**	
	tpz	tj	tpz	tj	tpz	tj	tpz	tj	tpz	tj
a1	0.50	0.15	0.25	0.10	0.45	0.30	1.25	0.35	0.75	0.20
a2	0.70	0.25	0.30	0.12	0.50	0.12	1.30	0.25	0.60	0.16
a3	0.30	0.20	0.35	0.18	0.40	0.17	1.40	0.15	0.55	0.30

Source: own study

Based on the analysis presented in Section 3, we calculated the costs of production. To specify the duration of the production cycle, we adopted a series arrangement with the production extension coefficient at 150%. It is assumed that the variables will be not only the different options of lot size determination (the classic and lean manufacturing approaches), but also the costs of changeover. The sum of individual changeover costs is understood as the total cost of one occasion at which all machines in the production system are changed over for the purposes of producing one lot of each item. Therefore, it specifies how expensive the changeovers are in the analysed production system and what effect the applied technology has on the viability of joining or dividing production lots. Fig. 3 is the graph showing the cost of manufacturing a set of product ranges depending on the adopted lot size determination solution and the sum of individual changeover costs.

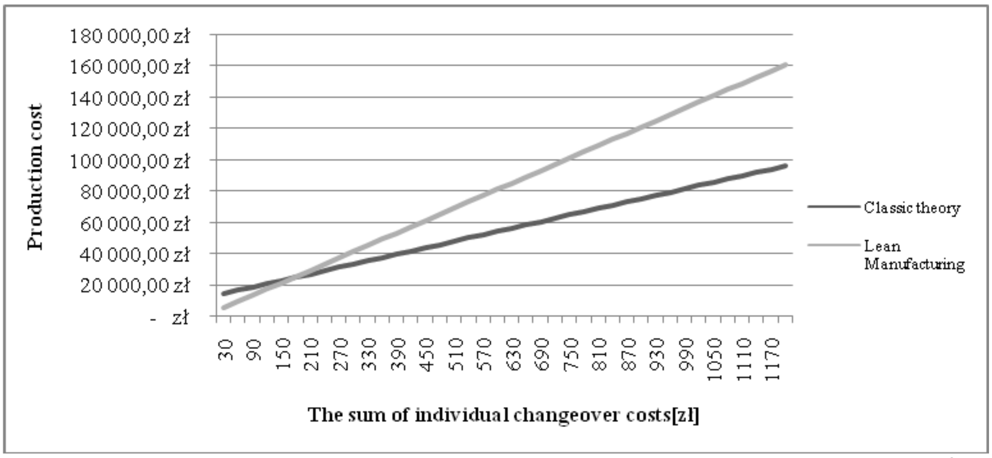

Fig. 3. Production cost depending on the lot size determination method and the sum of individual changeover costs
Source: own study

As illustrated in Fig. 3, it is justified to state that with the adopted values, there is a borderline sum of individual changeover costs for which one of the analysed solutions is more viable. This corroborates the common belief that lot size is affected by the applied production technology. As visible in Fig. 3, the EPEI (lean manufacturing) approach is more viable for low individual machine changeover costs. This is because of the maximisation of the number of changeovers and a reduction in WIP inventory. The classic approach, optimising lot size based on production technology features, seeks to increase lot size and, consequently, to reduce the number of changeovers and increase WIP inventory.

5. Conclusions

In a bit of a generalisation, we conclude that mass production is based on the paradigm of maximising lot size and minimising the number of changeovers, unlike in the case of the lean production paradigm, which promotes lot size minimisation and the maximisation of the number of changeovers (while reducing the duration of changeovers).

There is a clear and intuitively understandable relationship between lot size and lot cost. If a manufacturer decides to produce a larger lot of a given product range, the costs of this lot will be higher than in the case of a smaller lot. This is theoretically logical as long as the increase of costs caused by the increase in lot size is compensated for by the effects of this increase [9, p. 33]. At present, there is no single recommendable way of determining lot size. The literature of the subject discusses only the most popular methods [3, pp. 193-194]. However, most publications fail to provide any criteria for the selection of the method of determining lot size. The problem of the selection of the method is thus left to be solved by the practitioners and theoreticians of production management [9, p. 33].

Our aim in this work was to come up with a simplified procedure for the assessment of the viability of the two approaches to determining lot size. The two approaches are based on two distinct production management philosophies: the classic theory and lean manufacturing. It is not difficult to observe that neither of them analyse the costs of the solutions they offer.

The method of analysing lot size viability proposed here, uncomplicated to apply, may become a major instrument helping practitioners take decisions concerning lot size. At the same time, the set of data and formulas we present may be treated as guidelines for the implementation of the method in integrated IT systems supporting production management.

Cost analysis helps find the optimal solution for the adopted optimisation criterion. The simplifications in our analysis on the one hand make it easier to implement in an integrated IT system, but on the other hand leaves many unanswered questions concerning the flexibility of the company, the costs of maintaining finished product inventory, the company's liquidity or the production capacity reserves. We are going to find answers to these and other questions concerning lot size determination in our future work.

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