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Dr hab. Dariusz Milewski, prof. US
Uniwersytet Szczeciński
ORCID: 0000-0002-3483-7728
e-mail: Dariusz.Milewski@usz.edu.pl

Evaluation of the efficiency of the production changeover process using the simulation method

Ocena efektywności procesu przezbrajania produkcji przy zastosowaniu metody symulacji

Abstract

The paper presents the problem of the optimization of the length of the series and production batch, and thus the optimal frequency of production changeovers, taking into account the total cost approach and the use of the simulation method. The author has developed a model which, with the given parameters (costs and time of production changeover, costs of maintaining stocks of finished products and storage, value of manufactured products, sales variability and predictability), allows to calculate the economic effects of determining the length of a series and a production batch. In the author's opinion, the simulation method (at least in some cases) may be more appropriate in solving the problem of determining the optimal length of a series or production batch than the use of mathematical formulas. The calculations also took into account the impact of series and batch optimization on the company's profitability in order to assess the significance of this problem for financial results. The calculations were performed for two sample products and for two probability distributions — Gauss and Gamma. The results of the research show that the optimization of the production series may be important from the point of view of economic efficiency, that mathematical formulas may be less suitable for calculating the optimal production series than computer simulation, and that, in the case of significant variability of the sales level, in addition to the costs of changing production and maintaining inventories, lost sales costs should also be taken into account.

Keywords:
production management, manufacturing processes, optimal production series, optimal production batch, computer simulation, trade-off, trade up, SMED, costs of production, costs of maintaining inventories, lost sales costs

Streszczenie

W artykule przedstawiono problematykę optymalizacji długości serii i partii produkcyjnej, a więc i optymalnej częstotliwości przezbrojenia produkcji przy uwzględnieniu podejścia całkowitokosztowego i zastosowaniu metody symulacji. Autor opracował model, który przy zadanych parametrach (koszty i czas przestawienia produkcji, koszty utrzymania zapasów wyrobów gotowych i magazynowania, wartość produkowanych wyrobów, zmienność i przewidywalność sprzedaży) pozwala na obliczenie skutków ekonomicznych ustalenia długości serii i partii produkcyjnej. W opinii autora metoda symulacji (przynajmniej w niektórych przypadkach) w rozwiązywaniu problemu ustalenia optymalnej długości serii lub partii produkcyjnej może być właściwsza niż zastosowanie formuł matematycznych. W obliczeniach uwzględniono również wpływ optymalizacji serii i partii produkcyjnej na rentowność przedsiębiorstwa, aby ocenić istotność tego problemu dla wyników finansowych. Obliczenia zostały przeprowadzone dla dwóch przykładowych produktów i dla dwóch rozkładów prawdopodobieństwa — Gaussa i Gamma. Wyniki badań wskazują, że optymalizacja serii produkcyjnej może mieć istotne znaczenie z punktu widzenia efektywności ekonomicznej, że formuły matematyczne mogą być mniej odpowiednie do obliczania optymalnej serii produkcyjnej niż symulacja komputerowa oraz że w przypadku występowania znaczącej zmienności poziomu sprzedaży, oprócz kosztów przestawienia produkcji i utrzymania zapasów, powinno się uwzględniać także koszty utraconej sprzedaży.

Słowa kluczowe:
zarządzanie produkcją, procesy produkcji, optymalna seria produkcyjna, optymalna partia produkcyjna, symulacja komputerowa, trade-off, koszty produkcji, koszty utrzymania zapasów, koszty utraconej sprzedaży

JEL: L23, M11, C61

Preface

Optimizing the length of a production series or a production batch consists in determining their length at which the total costs are the lowest. This is a typical optimization problem that takes into account the trade-off effect, *i.e.* the reduction of the costs of one process and the increase in the costs of another. This problem is similar to the problem of the optimal batch of delivery, *e.g.* from external suppliers to a supply warehouse. The mathematical optimization models used to calculate them are also similar.

The model of optimal delivery size takes into account the costs of maintaining inventories, which stem from the volume of deliveries, and the cost of creating inventories, *i.e.* order fulfillment (purchase cost, placing an order, transport from the supplier to the warehouse). This model was developed in 1918 and has since been modified in various ways. In literature, it functions as the "Wilson Formula" or Economic Order Quantity Model (Davis, McKeown, 1984). It is similar to the model of the optimal production series (or batch), with the difference that instead of the cost of order fulfillment, there is the changeover cost.

The usefulness of mathematical formulas or optimization models for the purposes of making decisions and finding the optimal solution is sometimes questioned in the scientific literature. In the case of high variability of demand, simulation may a more effective method of optimization of production series and batches, compared to the use of mathematical models (see, *e.g.*: Oleśków-Szłapka, 2020).

Another problem dealt with by the author of this paper is that of optimizing logistics processes, as research is carried out using the simulation models. Also in this case, a simulation model was developed by the author and used to carry out calculations for various variants of the production changeover. The results of these simulations were compared with the results obtained by using the mathematical formula.

The purposes of this article are as follows:
- assessment of the significance of the problem of optimizing the length of the production series from the point of view of economic efficiency of an enterprise,
- assessment of the suitability of mathematical formulas of the optimal production series in the event of demand volatility.

In order to achieve these goals, the author developed a simulation model, used it to carry out calculations for various variants of the production changeover, and then compared the simulation results with the results obtained using a mathematical formula.

The problem of the production changeover. Review of the literature

The process of changeover takes place when the change of production on the same production line or machine from one assortment to another requires its stoppage and incurring costs related therewith. The literature distinguishes between the concepts of a production batch and a production series (Kulisz, Gola, 2017), however, there seem to be no clear-cut definitions of these terms and, moreover, they are often used interchangeably. One can get an impression that the term "series" is used in relation to final products, so a production series is the number final products produced without longer production breaks[1]. The term "batch", instead, tends to be used to refer to components of the product (Głowacka--Fertsch, Fertsch, 2004).

Presented below are some sample definitions of a **production batch**:
- "the number of items processed in sequence on one workstation, without interruptions for other production activities" (Burshe, 1963);
- "the total number of products of the same type (*i.e.* part of a series) made in a specific technological line without breaks, in which this line would be involved in the production of other products" (Liwowski, Kozłowski, 2011);
- "the number of details made in a strict sequence with a one-time expenditure of preparation and completion time" (Brzeziński, 2000).

The production changeover process may occur in the following situations:
- **Start of production of a new product** — which requires investment and employee training.
- **Production to a specific order** — length of production series is mainly due to customer orders.
- **Repetitive production** — the length of the production series is the result of a decision made by the manufacturer (the problem of the optimal length of the production series or batches).

The problem considered here concerns precisely the latter situation.

The process of production changeover may involve three phases:
- tidying up the workplace after previous production (*e.g.* in the food, chemical, pharmaceutical industries — cleaning up leftovers and cleaning the production line);
- preparation for the production of the next assortment (*e.g.* stopping the machines and changing the tool settings);
- start of a new series or a batch (checking compliance with the parameters assumed, production of a prototype, quality control, restarting).

One should also take into account the appearance of logistic aspects related to the changeover of production, because the efficiency of production processes may also be affected by the process in the material procurement (frequency of deliveries, the size of delivery of materials for production), as well as the distribution of products to the customer (the volume of customer orders, level of the customer service).

There are two approaches to the problem of the length of a series and the length of a batch (Milewska, Milewski, 2000):

- **passive** — optimization of their lenght to reduce total costs;
- **active** — looking for the possibility of shortening the production changeover time and reducing the costs of this changeover.

The first is of an economic nature, as it consists in looking for a solution at which the total costs associated with this process are the lowest. This problem is related to the so-called "cost conflict", referred to in the literature as trade-off. The second approach is based on streamlining the process of changeover and reducing the total costs of this process (the so-called "trade-up" effect). This is an approach characteristic for Lean Management.

The SMED method is a method that is used to improve the production changeovering process (Milewska, 2004), which is applicable to a wide variety of industries (see, for example: Silva, Sá, Santos, Silva, Ferreira, Pereira, 2020). Thanks to the streamlining of this process, the flexibility in responding to market needs is also increased, which may result in not only lower production and logistics costs, but also higher sales. However, as shown by the results of the research conducted, the effectiveness of the SMED method depends on various factors, including the nature of the company's operations (Walentynowicz, 2015, 2013).

Other factors also influence the efficiency of the production changeover process (Milewska, Milewski, 2001) — investments in automated machines, reorganization of production stations, forms of organization of production, standardization of parts or components used in the production of various products, training of employees, elimination of manual control methods, change of a changeover procedure, change of prevention strategy in relation to equipment and tools. Specific solutions are, for example — providing workstations with appropriate tools, their standardization, placing them closer to the point of wear, introducing tool hangers. However, if it is not possible to shorten the changeover time and reduce the costs associated with it, the problem of determining the optimal length of a production batch or a series should be solved.

Later in the paper, the author uses the term "a series" for the number of finished products produced at one workstation (or production line) in the case of repetitive production.

An optimal series length

Determining the optimal length of a production series requires taking into account many factors (Brzeziński, 2013). Increasing a series may result in both positive and negative effects (Brzeziński, 2000; Brzeziński (ed.), 2002).

Positive effects of increasing the length of the production series include, *e.g.*:

- reduction of unit costs of setup and production preparation,
- better use of employees' working time and increasing their efficiency (so-called learning curve),
- simplification of the organization and management of production.

On the other hand, there may be negative effects, such as:

- extension of the production cycle,
- increased inventories of work-in-progress, more space and storage rooms needed, the resulting costs of their maintenance and the capital tied up in inventories, inventory taxation, *etc.*,
- reduced flexibility and adaptability of the production process.

The costs of changeover can be divided into direct and indirect costs.

Direct costs are, for example:

- cost of production lines clean-up;
- product losses;
- documentation costs;
- cost of energy consumption when starting machines, faster wear of these machines caused by lines stopping lines and starting up, and the resulting costs of repair.

Indirect costs may result from:

- underused productive resources (downtime);
- deterioration of customer service and the resulting lost sales costs.

The costs of changeover can be particularly high in industries where the production of another product requires cleaning the production line. This mainly concerns food, clothing, chemical and pharmaceutical industries (Winatie, Perwitasari Maharani, Hangga Riksa, Hasibuan, 2019; Karim, 2015).

Examples of costs more or less related to the changeover may include:

- production of salty snacks — after the production of chips with an intense flavor and aroma (*e.g.* onion chips) the line must be thoroughly cleaned;
- production of cold cuts — one of the stages is meat grinding, as a result of which a certain portion of meat is always wasted;
- flour production — starting the mill means higher energy consumption and faster machinery wear;
- production of fertilizers — cleaning of lines before starting production.

- clothing production — cleaning and airing the rooms in the sewing room, preparing machinery for the production of the next batch of clothing, low efficiency at the beginning of the process.

To calculate the optimal length of a production series, similar models have been developed as those for calculating an optimal order quantity (Kulisz, Gola, 2017):

$$EWP = \sqrt{\frac{2 \times K_{zp} \times U}{I \times K_j}},$$

where:
K_{zp} — production start-up cost;
U — average annual demand;
I — the cost of inventories per year — maintaining inventories, warehousing;
K_j — unit manufacturing cost.

However, if we take into account the volatility of demand, safety stocks should also be created. There is an analogy to problems in the field of logistics. According to a research the author carried out for many years by, both parameters should be considered together in one model (Milewski, 2007). A similar approach should be applied to the problem of determining the optimal production series.

Moreover, in the author's opinion, the calculation of production costs and inventory costs only is too simplified. Stopping the production line for an extended period reduces the production potential, which undermines the ability to meet customer demand, so the cost of lost sales may increase.

The production scale is another important factor for the efficiency of this process. With a larger scale of production there is an economic justification for dedicating production lines to the production of a specific assortment. Then, there is a possibility that with relatively lower production costs, the costs of inventories and the cost of lost sales may also decrease ("trade-up" effect).

Total cost model of a production series

The author has developed a simulation model to assess how a change in the length of the production series affects the total costs, which are calculated according to the following formula:

$$C_t = C_{inv} + C_{ch} + C_{ls}$$

where:
C_t — yearly total costs;
C_{inv} — yearly inventory cost (inventory maintenance and storage);
C_{ch} — yearly changeover costs;
C_{ls} — yearly costs of lost sales.

The individual components are calculated as follows:

$$C_{inv} = A \times \left(I \times c_{pu} + c_{wu} \times D\right),$$

where:
A — average level of inventories;
I — inventory maintenance cost;
c_{pu} — unit cost of production;
c_{wu} — storage unit cost (*e.g.* daily storage rate of a storage unit — *e.g.* pallets);
D — number of days in the year when the product is stored;

$$C_{ch} = c_{chu} \times N_{ch},$$

where:
c_{chu} — cost of one changeover;
N_{ch} — number of changeovers during a year;

and

$$C_{ls} = P_u \times L_s,$$

where:
P_u — unit price of a product;
L_s — lost sales.

Table 1 shows the data used in the simulations. The calculations were carried out for two types of products (food and electronics), which are characterized by different parameters (cost of changeovers, cost of inventories, storage, value, production costs).

The assumptions are as follows:

- The sales volume in units is the same in both cases — 6,000 pcs per day.
- The cost of one production changeover in the case of food is higher than in the case of electronic products, as it is required to clean the production line before starting the production of the next assortment.
- Inventory costs are also higher for food, due to the greater risk of spoilage during storage.
- There is a need to create appropriate storage conditions for food, however, taking into account the parameters of the products along with the packaging, ultimately the cost of warehousing electronic products is higher than that of food products.

- The differences also concern the value of sales and production costs — electronic products are much more expensive and their production costs are higher.

Table 1

Data for calculation

Products	Food	Electronics
Changeover time [h]	0.5	0.5
Changeover cost [PLN/unit]	250	100
Changeover time [h]	0.25	0.25
Changeover cost [PLN/unit]	150	25
Capital costs of inventories	10%	8%
Warehousing cost [PLN/unit/year]	0.16	0.90
Selling price [PLN/unit]	4.00	200.00
Variable production cost [PLN/unit]	3.65	39.10
Fixed costs [PLN/year]	640,000	1,070,000,000

Source: author's own study.

The calculations were carried out for different frequencies of changovers for two variants of the production changeover time: longer (0.5 h) and shorter (0.25 h) and for two types of demand distributions: Gaussian (normal distribution) and Gamma. The model randomizes the daily demand with a given probability over one year. So it recreates (simulates) everyday production processes and, to some extent, also logistics.The model also takes into account the possibility of adjusting the production volume to changing demand. If the stock is too low on a given day, the model increases the production volume, but the degree of flexibility depends on the size of the available production potential. Production in long series increases this potential as less time is spent on changeovers.

Simulation results

The simulation results with the adopted assumptions for these two product groups and the Gaussian distribution are presented in Tables 2 and 3 as well as Figures 1 and 2.

In the case of food, with a longer production changeover time (0.5 h), and thus higher changeover costs and small sales fluctuations (standard deviation 5% of the average sales), the third variant "1 product per day" is the most advantageous (see Table 2 and Figure 1). The reduction in the time and cost of changeovers also does not affect the length of the optimal series. This, however, does not mean that sales variability and production flexibility are irrelevant. Total costs increase as sales fluctuate more; instead, they significantly decrease as the flexibility of the production process increases.

The profitability of individual variants is different in the case of electronic products (see Table 3 and Figure 2). With long production changeover times, the optimal series is the same as for food for low variability of sales, but the same as in case of food (1 product/day) when the fluctuation of sales are higher (standard deviation — 10% of average sales). That means that system ensures more variable sales by lengthening a series.

However, increasing the flexibility of production makes it most profitable to produce all products in one day, *i.e.* the shortest series. In the case of these products determining the optimal length of the production series has a much more significant impact on total costs than in case of food.

Tables 4 and 5 show the changes in individual cost items and the cost structure in more detail.

In the case of food products (Table 4), the costs of production changeovers have a very large share (even when the changeover time is shortened), which explains why production series of these products are relatively long. However, a slight change in the level of customer service causes a significant change in the cost of lost sales.

Lost sales costs account for the largest share of electronic products (Table 5). The proportion of changeover costs is the lowest in all variants, which explains why optimal production series can be shorter in case of these products.

Table 2

Calculation results — total production and logistics costs (food)

Standard deviation/average sales	5%	10%	5%	10%
Changeover time [h]	**0.5**	**0.5**	**0.25**	**0.25**
4 products/day	500,857	558,033	200,626	211,257
2 products/day	189,052	210,996	122,861	150,997
1 product/day	151,737	136,279	121,737	106,279
2 product/2 days	174,488	179,197	159,419	164,128

Source: author's own study.

Table 3

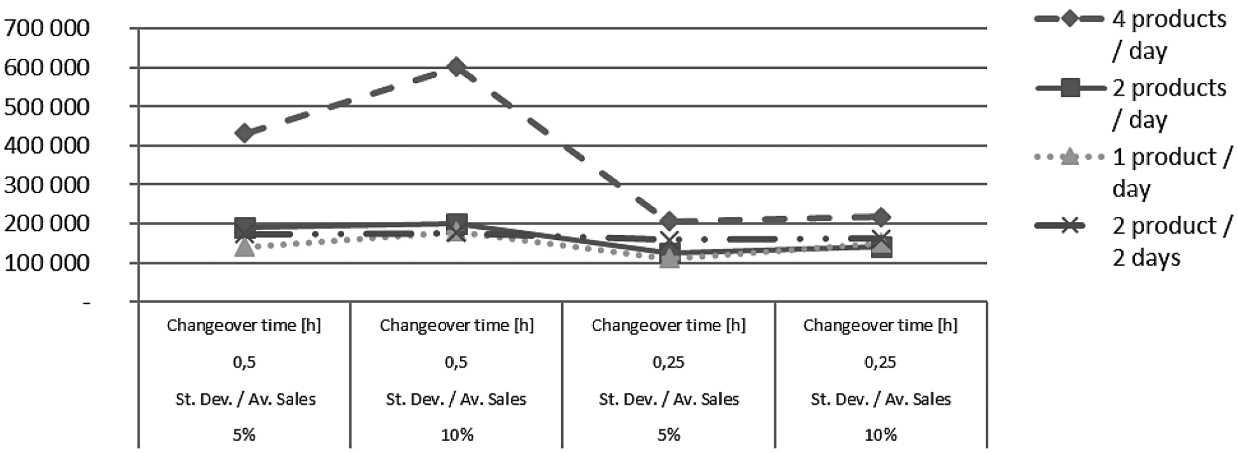
Calculation results — total production and logistics costs (electronics)

Standard deviation/average sales	5%	10%	5%	10%
Changeover time [h]	**0.5**	**0.5**	**0.25**	**0.25**
4 products/day	9,592,556	12,405,933	453,183	910,269
2 products/day	1,140,577	2,162,060	1,095,577	2,117,064
1 product/day	2,464,900	1,618,166	2,442,400	1,595,666
2 product/2 days	4,056,608	4,230,206	4,046,222	4,219,819

Source: author's own study

Figure 1

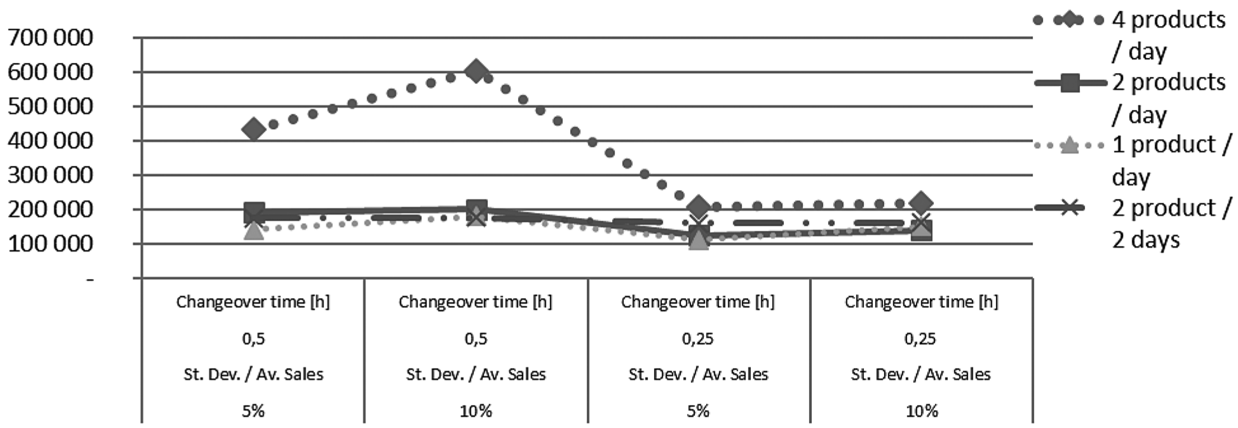
Calculation results — total production and logistics costs (food) [PLN/year]



Source: author's own study.

Figure 2

Calculation results — total production and logistics costs (electronics) [PLN/year]



Source: author's own study.

Table 4
Simulation results for food products

Variants of production	Customer Service [%]	Changeover costs [PLN/year]	Costs of inventories [PLN/year]	Costs of lost sales [PLN/year]
Changeover time [h]	**0.5**	**Standard deviation/average sales**		**5%**
4 products/day	99.35	300,000	13,490	187,366
2 products/day	99.94	150,000	20,628	18,424
1 product/day	99.85	75,000	33,162	43,575
2 product/2 days	99.75	38,000	65,826	70,662
Changeover time [h]	**0.5**	**Standard deviation/average sales**		**10%**
4 products/day	99.15	300,000	14,566	243,467
2 products/day	99.87	150,000	22,419	38,577
1 product/day	99.91	75,000	34,909	26,370
2 product/2 days	99.74	38,000	67,289	73,908
Changeover time [h]	**0.25**	**Standard deviation/average sales**		**5%**
4 products/day	99.98	180,000	14,386	6,240
2 products/day	99.94	90,000	14,437	18,424
1 product/day	99.85	45,000	33,162	43,575
2 product/2 days	99.75	22,800	65,957	70,662
Changeover time [h]	**0.25**	**Standard deviation/average sales**		**10%**
4 products/day	99.95	180,000	16,147	15,110
2 products/day	99.87	90,000	22,420	38,577
1 product/day	99.91	45,000	34,909	26,370
2 product/2 days	99.74	22,800	67,420	73,908

Source: author's own study.

Then, based on the data assumed, simulations of the impact of changing the strategy of production changeovers on the company's profitability were conducted to determine whether this problem could be significant in terms of benefits for a company.

The results are shown in Tables 6 and 7 and Figures 3 and 4. The impact is significant and, again, it is worth emphasizing that the most significant change in the size of the production batch affects the profitability not in the food industry, but in the electronics industry. Thus, the cost of lost sales seems to be an important factor here, which is another proof that (at least in some cases) it should be included in optimization models. In addition, extending the production series causes an increase in profitability in food production, while in the case of electronic products, in some variants, the same can even result in a decrease.

The model also allows for an assessment of the economic effects of shortening the production changeoverover time thanks to the use of *e.g.* the SMED method. Reducing the production changeover time by half, and of the related costs by 1/6, allows for the reduction of total costs by up to 68% in the case of food products (Table 6 and Figure 3) and up to 87% in the case of electronic products (Table 7 and Figure 4).

Assessment of the effectiveness of using optimization models

In order to assess the usefulness of mathematical formulas for finding the optimal lengths of production series, calculations were carried out, the results of which are presented in Tables 8–9. The results obtained thanks to these formulas and the simulation model developed by the author were compared. The simulations were performed for two types of probability distribution — Gauss and Gamma.

The results obtained with these two methods are very different. Moreover, the differences are not only in the different lengths of production series. The results obtained thanks to the mathematical formula in the case of Gaussian distribution clearly show the influence of the time and costs of changing production as well as of value of foods upon the

Table 5
Simulation results for electronic products

Variants of production	Customer Service [%]	Changeover costs [PLN/year]	Costs of inventories [PLN/year]	Costs of lost sales [PLN/year]
Changeover time [h]	**0.5**	**Standard deviation/average sales**		**5%**
4 products/day	99.35	120,000	104,248	9,368,307
2 products/day	99.94	60,000	159,384	921,192
1 product/day	99.85	30,000	256,166	2,178,734
2 product/2 days	99.75	15,200	508,325	3,533,083
Changeover time [h]	**0.5**	**Standard deviation/average sales**		**10%**
4 4 products/day	99.15	120,000	112,559	12,173,374
2 products/day	99.87	60,000	173,225	1,928,835
1 product/day	99.91	30,000	269,659	1,318,507
2 product/2 days	99.74	15,200	519,621	3,695,385
Changeover time [h]	**0.25**	**Standard deviation/average sales**		**5%**
4 products/day	99.98	30,000	111,171	312,012
2 products/day	99.94	15,000	159,384	921,192
1 product/day	99.85	7,500	256,166	2,178,734
2 product/2 days	99.75	3,800	509,338	3,533,083
Changeover time [h]	**0.25**	**Standard deviation/average sales**		**10%**
4 4 products/day	99.95	30,000	124,775	755,494
2 products/day	99.87	15,000	173,229	1,928,835
1 product/day	99.91	7,500	269,659	1,318,507
2 product/2 days	99.74	3,800	520,634	3,695,385

Source: author's own study.

Table 6
Calculation results — profitability (food)

Standard deviation/average sales	5%	10%	5%	10%
Changeover time [h]	**0.5**	**0.5**	**0.25**	**0.25**
4 products/day	5.42%	5.39%	5.85%	5.83%
2 products/day	5.93%	5.91%	6.14%	6.12%
1 product/day	6.14%	6.12%	6.24%	6.22%
2 product/2 days	6.14%	6.11%	6.19%	6.17%

Source: author's own study.

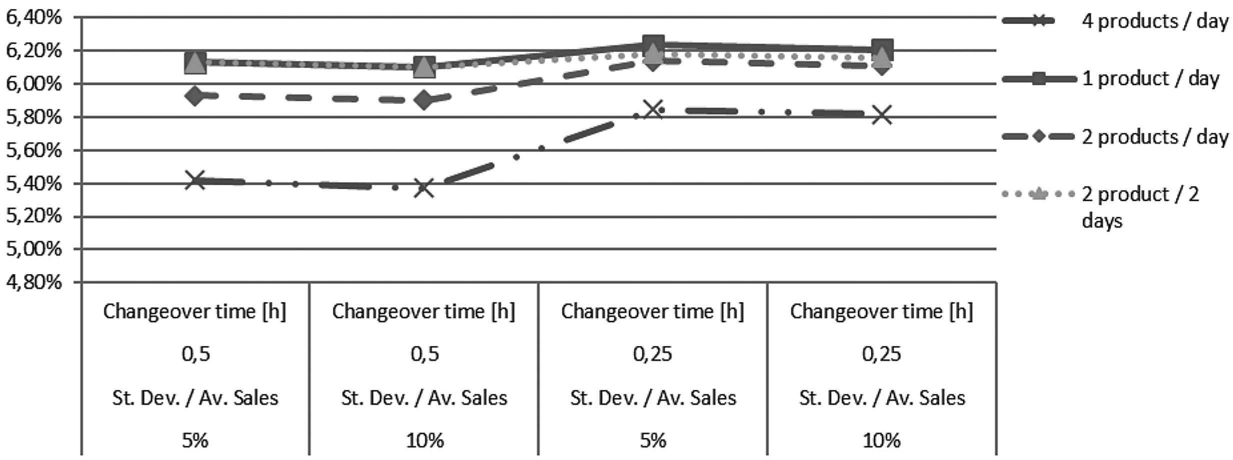
Table 7
Calculation results — profitability (electronics)

Standard deviation/average sales	5%	10%	5%	10%
Changeover time [h]	**0.5**	**0.5**	**0.25**	**0.25**
4 products/day	5.68%	5.10%	6.15%	5.71%
2 products/day	6.12%	5.64%	6.12%	5.65%
1 product/day	5.69%	5.24%	5.69%	5.25%
2 product/2 days	5.23%	4.66%	5.23%	4.66%

Source: author's own study.

Figure 3

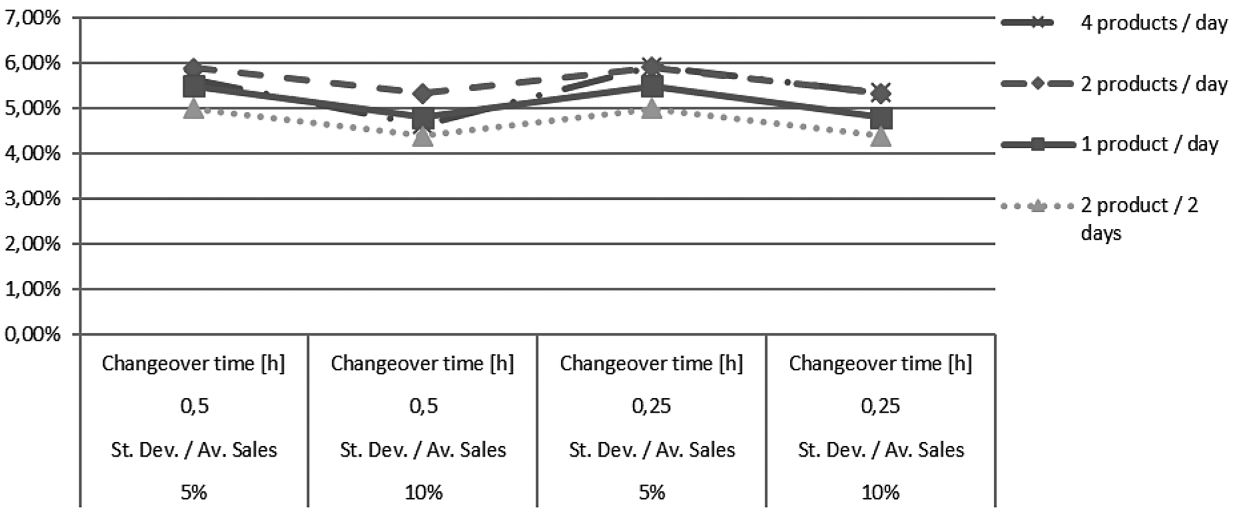
Calculation results — profitability (food)



Source: author's own study.

Figure 4

Calculation results — profitability (electronics)



Source: author's own study.

optimal length of the production series. The production series of electronic products are much shorter than those of food products. The time and costs of changing production of these type of goods have a much greater impact than in the case of food products.

The results obtained with the simulation method differ significantly from these results. It is difficult to indicate any regularity concerning the length of the series, the identification of which would allow for the modification of the mathematical formula. The optimal lengths of production series obtained by these two methods do not increase and decrease in the same directions. Moreover, in the case of the Gamma distribution, the production runs were very long in all variants.

It is therefore doubtful whether the classic formula of the optimal production series, even after its modification, could be useful in a situation of fluctuating demand. Various factors have an impact here, probably rather difficult to be captured in a mathematical formula. Perhaps it applies only in the event of constant demand, which may actually be the case in some sectors of the economy, or even companies that, for example, cooperate with regular customers.

Table 8
Optimal production series — simulation results (food)

Changeover time [h]	Standard deviation/average sales [%]	Formula results [pcs]	Simulation (Gauss) [pcs]	Simulation (Gamma) [pcs]
0.50	5.00	40,136	24,912	62,000
0.50	10.00	39,972	62,000	62,000
0.25	5.00	31,191	24,912	63,000
0.25	10.00	31,096	63,000	63,000

Source: author's own study.

Table 9
Optimal production series — simulation results (electronics)

Changeover time [h]	Standard deviation/average sales [%]	Formula results [pcs]	Simulation (Gauss) [pcs]	Simulation (Gamma) [pcs]
0.50	5.00	9,204	24,912	62,000
0.50	10.00	9,167	62,000	62,000
0.25	5.00	4,617	6,903	63,000
0.25	10.00	4,603	63,000	63,000

Source: author's own study.

The simulation results also confirm the existence of relations between economic processes identified by the author in the course of research on the effectiveness of logistics processes (see the previously cited items). Namely, increasing the size of the batch of goods delivered to the warehouse increases the level of logistic customer service, measured by the availability of the goods, because the risk of running out of stock is reduced. Apparently, a similar phenomenon is related to the optimization of the production series.

Conclusions

The results of the simulations conducted by the author presented in the article show that the problem of the optimization of a production series, like many other optimization problems, should take into account the system approach and the influence of various factors. One should consider not only the costs of changeovers and the costs of maintaining inventories, but also the costs of lost sales, because the length of the production series affects the size of the available production potential and its flexibility and, indirectly, sales.

A high degree of complexity of the influence of various factors makes it difficult to apply mathematical formulas. They would have to take into account complex relations of processes. It is difficult to say whether such a formula can be developed and if it can, how useful it would prove for decision-making purposes. However, it is worth researching this problem, because the optimization of the production batch length can have a significant impact on the profitability of a company.

The distribution of the probability of demand occurrence in the case of more expensive products is important. This distribution may be influenced not only by the demand characteristics of final recipients (consumers), but also by the length of the distribution channel and purchasing strategies of companies. A manufacturing company may sell its products to stores or to distribution companies (*e.g.* wholesalers) that may place orders in large quantities and irregularly.

In this case, the optimization process should take into account the level of inventories at several levels of the logistics chain, which means that the mathematical formula should be appropriately developed. This is another argument in favor of using the simulation method, which uses a model that reflects the complex relationships of production and logistics processes.

The most important conclusions from the simulations are as follows:

- Optimization of the production series can be important from the point of view of economic efficiency.
- Mathematical formulas may be less appropriate for calculating the optimal production series than computer simulation.
- In the case of significant volatility of the sales level, in addition to the costs of production changeovers and maintaining stocks, the costs of lost sales should also be taken into account.

In the opinion of the author, for the reasons presented above, the research on the problem of optimizing the production series should be continued.

Przypisy/Notes

[1] The following series are distinguished: construction, production and assembly.

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Dr hab. Dariusz Milewski, prof. US

Profesor Uniwersytetu Szczecińskiego, obecnie pracuje na Wydziale Ekonomii, Finansów i Zarządzania w Instytucie Zarządzania. Obszary jego pracy naukowo-badawczej obejmują zagadnienia związane z efektywnością ekonomiczną, optymalizacją i zarządzaniem logistyką, transportem i procesami produkcyjnymi.

Dr hab. Dariusz Milewski, prof. US

Professor at the University of Szczecin, currently working at the Faculty of Economics, Finance and Management at the Institute of Management. The areas of his research work include issues related to economic efficiency, optimization and management of logistics, transport and production processes.