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CHARACTERISTICS AND STUDY OF MAKE-TO-STOCK AND MAKE-TO-AVAILABILITY PRODUCTION STRATEGY USING SIMULATION MODELLING

Olga Ciechańska, Cezary Szwed
Warsaw University of Technology, Management Faculty, Poland

Corresponding author:
Cezary Szwed
Warsaw University of Technology
Management Faculty, Chair of Innovativeness and Entrepreneurship
Narbutta 85, 02-524 Warsaw, Poland
phone: +48 228499443
e-mail: Cezary.Szwed@pw.edu.pl

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Abstract
Make-To-Stock (MTS) and Make-To-Order (MTO) are the two traditional strategies in production management. In the case of the MTS there is a growing demand for a new approach, which is called Make-To-Availability (MTA) strategy. The paper characterizes and compares the MTS and MTA strategies. The comparative analysis based, among others, on computational experiments carried out in a computer program developed in Microsoft Visual Studio 2017 Environment was presented. The models have been prepared for both strategies with the same assumptions: external conditions (market demand) and internal conditions (structure of the production process). The investigation of how the strategies respond to various scenarios of demand intensity was done. The simulation models were prepared and validated for the case of the production line in one of the industrial automation company. The research shows that the use of the MTA strategy in the majority of cases gives much better results than the use of the MTS strategy due to the minimization of storage costs and the costs of non-fulfillment of the customers' demand. The directions for further research were also presented.

Keywords
Make-To-Stock strategy, Make-To-Availability strategy, simulation modelling.

Introduction

Manufacturing companies have identified the need to orientate their logistics strategies towards time, allowing them to increase supply chain efficiency while gaining a competitive advantage. The reason for these changes is, among other things, external pressure to shorten the order cycle, reduce its volatility, and deliver the order at the time and place required by the customer or the end-user of the product. This can be done by improving the ability to manage and control information in the supply chain as well as inside and outside the organization. Companies increase their sensitivity to customer needs, trying to answer them without interruption, and at the same time reduce inventories throughout the supply chain [1]. Based on [2], a key element affecting the supply chain efficiency is a good choice of the four-driven supply chain performance model that supports the overall supply chain strategy. The supply chain efficiency drivers are the following: inventories, information, equipment, and transportation.

In practice, this affects, among other things, the need of making decisions and verifying their correctness at the level of inventories held, which is directly related to decisions on schedules and volumes of production orders being launched. In most cases, these decisions are made expertly and only partially supported by external support systems or quantitative analyses performed. The support systems mainly use typical, basic stock management models, which do not always ensure sufficient financial efficiency. This state of affairs requires the search for new, more advanced solutions, both in terms of inventory management models and in terms of algorithms that can be practically implemented in decision support systems. The purpose of this study is to focus on the inventory decisions that affect the plan, the cycle, and the security of the stock, as well as its size and the schedule of operations. The new models, which allow for more efficient stock management, should in practice contribute to making the optimal decisions in terms of balancing the minimization of business costs with meeting customer demand for products. At the operational level, they should also make it possible to improve the work of the personnel responsible for making decisions in this area of business activity.

The basic production strategies for the combined production and storage system are described in [3]: order-production or make-to-order (MTO) – all incoming orders from customers go directly to production where there is no finished goods buffer; stock-production or make-to-stock (MTS) – all incoming orders go to the finished goods storage and only the internal replenishment orders are present in production. In [4], a kind of hybrid MTS-MTO system is proposed, where part of the orders is executed in production and part in the finished goods storage. In [5], inventory and production strategies are divided into two parts: MTS and MTO. Both have their variants, e.g. in MTO approach there is the assemble-to-order model (ATO), the engineer-to-order model (ETO) and the finish-to-order model (FTO), as mentioned in [6]. On the other hand, the make-to-availability approach (MTA), described by Schragenheim in Sec. 10 [7], can be derived from MTS. While the MTS and MTO models have been known for many years and they are well described, the MTA (make-to-availability) model is not formalized in terms of mathematics and has not been thoroughly tested.

In companies operating in the FMCG (fast-moving consumer goods) sector, currently, the dominant model is production to stock, but demand for MTA is growing. This is caused by the need to keep the number of finished products in the storage on such a level that the current value is dynamically minimized, at the same time the product is immediately available for the customer. Therefore, the computational experiments were focused on demonstrating differences in inventory costs and related order quantities. The results of those studies, conducted using real-world data, should allow for practical verification of the effectiveness of the proposed solutions. They should also allow for obtaining information on the impact of decisions made on the costs of meeting customers' needs. In general, the approach with the use of simulation modelling should support the analysis of various inventory management strategies in enterprises and their evaluation based on the predefined optimization criteria. The authors recognize that there are many emerging areas relating to MTS/MTA decisions such as judgmental forecasting [8] or behavioral inventory decisions [9]. However, this paper focuses on showing the initial differences between the strategies, and it is not possible to tackle or mention other threads if there are so many. It is certainly a place to continue research in the field of mentioned emerging areas.

This paper describes and analyzes inventory management strategies: Make-to-Stock strategy (especially the periodic review model) and a new approach, Make-to-Availability. The latter approach is described in the literature only at the level of concept and general guidance on how to use that concept in practice. There are no detailed proposals for decision-making models, quantitative research results nor practical conclusions. For this reason in this paper:

- the authors' mathematical models based on MTS/MTA literature descriptions are proposed,
- cost optimization criteria have been defined within the models,
- calculation algorithms were developed and implemented,
- data were prepared for calculations (based on actual data obtained in one of the companies),
- computational experiments and results calculations were performed,
- practical conclusions have been formulated that can be applied in the area of manufacturing companies' activity.

The main purpose of using simulation modelling and then performing computational experiments was to indicate the differences between systems based on basic planning standards and to show cost structure related to inventory control.

The theoretical background of MTS/MTA production models

The two basic manufacturing models in production management are make-to-stock and make-to-order [9]. The article is focused on the make-to-stock model. There are two basic types of order policies in a make-to-stock strategy based on [10]:

- Continuous review – in a continuous review system with fixed order quantity, the inventory is reviewed daily, and a fixed quantity is ordered whenever the stock drops below a certain point. This point is called the re-order point.
- Period review – the inventory is reviewed at regular intervals and every time a sufficient quantity is ordered to raise the inventory level to a certain level. This order quantity depends on the relative stock position at each moment of the review, i.e. at each review point. This model is called the min-

max policy because the stock planner tries to keep inventory between a minimum and a maximum stock level.

The Economic Order Quantity (EOQ) variations are widely used, but they do not provide ideal answers. One of the frequent complaints of managers is the varying time between orders. For one of the EOQ methods, it is assumed that the order size remains fixed and any change in demand is dealt with by changing the time between orders. This fixed quantity approach is not suitable for some organizations that prefer a fixed order or periodic review. In [12], the best time between regular orders is to be found, and then any change in demand is dealt with by placing orders of different sizes. Importantly, as the review point is approaching zero, the periodic review system will approach a corresponding continuous review system, which is described in [13].

The min-max method is recommended when the demand may be greater and there is a risk that the available stock may fall below the re-ordering point before the company places an additional order. In this case, the min-max method allows you to increase the ordered quantity by the difference between the reordering point and the available stock. As a result, this method proposed by [1] allows determining the minimum amount of stock that the company should order to reach the expected maximum quantity when the order is received. The case study under consideration (in the following sections) and the prepared mathematical model have based on the system of periodic reviews thanks to the models proposed by [12] and [14]:

- the case of increased demand,
- production planning according to this model is recommended for products from group C (according to Pareto), where the intensity of deliveries from the warehouse is relatively constant and predictable (demand forecasts are accurate),
- fluctuations in demand for products in this model are minimal – thus the production flow is assumed to be conventionally constant.

In the periodic review, it is possible to plan the stock purchases, just as on the production line: the production schedule is prepared in advance based on a forecast. The following part of the article describes the control principles of the periodic review system based on the mathematical model for the make-to-stock strategy, which was prepared in Sec. 3.

The stock control model chosen to simulate the production of the stock model (MTS) is an order cycle model, i.e. one with a fixed delivery period. In this model, orders are issued in fixed cycles, while delivery volumes are variable.

Stock values are shown in Fig. 1. The symbols shown in Fig.1 mean: $Q1$, $Q2$, $Q3$... – order quantities in each delivery; Cd – delivery cycle, ΔCd – delivery cycle delay; Td – delivery periods; $Zmin$ – minimum stock level; $Zmax$ – maximum stock level; Zsi – current stock level.

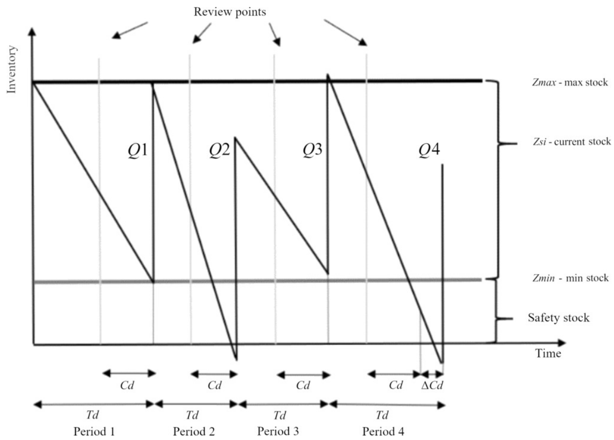

Fig. 1. Periodic review – fixed order cycle [13].

In the first period, the actual consumption of products (real demand intensity) was equal to planned consumption. The volume of stocks decreased to the minimum level at the time of the first delivery. After the delivery, the stock level increased to the maximum level.

In the second and fourth periods, the actual consumption of the details was higher than planned and as a result, the delivery took place after exceeding the minimum stock level. Moreover, in the fourth period, there was a delay in delivery. If the actual consumption in the second period or the delay in the fourth delivery was even greater, there may have been a lack of stocks.

Such a state would indicate that a planning system with a fixed delivery period is inappropriate for the production cell under analysis, due to the high variability of the outgoings intensity and the occurrence of delivery delays and/or poorly predicted outgoings intensity.

In the third period, the actual consumption of the parts is less than planned and the third delivery comes without delay. Achievement of a minimum ($Zmin$) and a maximum ($Zmax$) state is signaled for intervention purposes.

The definition of the basic standards used in the periodic review system is based on the following formulae described in Brewer, Button, Hensher [12] and Christou [13]:

$$Q = Zmax - Zs + pCd, \tag{1}$$

where Q – production order volume [pcs], $Zmax$ – maximum stock level (target level) [pcs], Zs – current stock level in the generating order point [pcs], p – average planned consumption of product per unit of time during the entire planning period (in all delivery periods) [pcs/unit of time], Cd – delivery cycle [unit of time].

When you place an order, you must give enough stock to hold on to your next order, which is the lead time plus the review period away. In other words, the target stock level must be high enough to meet the expected demand at that time. Then, if we allow for uncertainty, we will maintain the safety stock that we receive:

$$Zmax = Zmin + pTd, \tag{2}$$

where $Zmin$ – minimum stock level [pcs], p – average planned consumption of product per unit of time over the entire planning period (in all delivery periods) [pcs/unit of time], Td – delivery period [unit of time],

$$Zmin = p\Delta Cd, \tag{3}$$

where ΔCd – estimated maximum delay of the delivery cycle [time unit].

However, both models – the reordering point and the periodic review – are still calculated based on projected demand. The problem, of course, is that forecasts are never completely accurate. Security stocks allow this, while larger security stocks give more amortization. Unfortunately, the authors in [1] claim that very large safety stocks would be needed to cover any type of unforeseen circumstances. And the most important point about these strategies is overproduction – basically, too much production. This logistical issue related to the system of periodic reviews has a very important impact on production planning and strategy in production management. A production cell produces overproduction that may not be needed by the customer, thus reducing the availability of products that are not currently produced. In the example based on [15], some stocks end up in a warehouse or other storage location. The models described above exist in the practice of manufacturing companies for years. Is there any other approach that would allow timely delivery of products to the customer without overproduction while maintaining high availability of the range in the warehouse?

The MTA – new approach to the production management

The concept of "make-to-availability" was introduced by Elijahu Goldratt, who is also the creator of the Theory of Constraints (TOC). Further research was developed by Goldrath's colleague E. Schragenheim. Make to Accessibility (MTA) as defined by Cox [7] is a variant of production to stock (MTS), the basic assumption of which is to keep the level of finished products in the warehouse at a minimum value, but is characterized by the fact that the product is available to the customer at any time, i.e. it is on the warehouse shelf and is available "on-site".

The MTA concept is very poorly described in the literature. The only general information is contained in the book "Theory of Constraints – Handbook" by James Cox and John Schleier – other Goldratt colleagues. Based on Schragenheim [7] it can be concluded that the basic assumptions of MTA are:

- monitoring the market situation and ensuring that products can be purchased by each customer,
- daily determination of the quantity and scope of manufactured products, based on current monitoring of product sales – refreshing stocks more frequently than in the MTS,
- maintaining a minimum level of stock in the warehouse,
- the parameters used to prioritize production orders are buffer state and bottleneck production capacity,
- treating the delivery cycle not as a prescriptive one, but as a variable whose value depends on the current capacity of the production department, and in particular on the bottleneck.

The MTS Model is characteristic for the FMCG, food, pharmaceutical, cosmetic, household chemistry, small domestic appliances, furniture, household appliances and appliances industries. The MTA Model covers similar industries with a selection of those in which it is essential to respect the timeliness and shelf life of the products and the guarantee of product suitability. Schragenheim [7] describes MTA as follows:

- the forecast is only a statistical model and the EOQ is only a parameter – production plans should be based on on-line production plans by studding – in order to establish the traceability of the requirements, which allows the source of the requirements to be traced by logging links;
- daily production should start by producing the exact amount of what was sold yesterday, so it is important to continuously improve the internal flow;
- the target stock level should include the average demand during replenishment multiplied by the 'paranoid factor (taking into account sales peaks and lock-ins in production);
- the stock buffer helps to prioritize on the floor: when two-thirds or more of the finished goods tar-

get level is in stock, the buffer is green (stocks in preparation); when finished goods stocks contain between one-third and two-thirds of the target level, it is yellow (hand-held stocks); when hand-held stocks are less than one-third, the status is red (emergency level). Detailed management of the buffer is described below.

The parameters for MTA described above are listed in the formulae below. These formulae are transferred from the general description to the algorithm rules (Sec. 3). The determination of the basic standards used in the manufacturing process for inaccessibility is not clearly defined as in the periodic review system. It is based on a general description transferred to the following formula:

- target level = average replenishment demand · paranoia coefficient (factor),
- paranoia factor ≈1.5 (additional 50 percent for peak sales and production interruptions),
- Q > minimum batch ≈ volume of yesterday's sales.

The stock buffer is divided into three zones: status green – stock level available immediately; status yellow – stock level available "on-site"; status red – level warning of the need to start production immediately to replenish stocks.

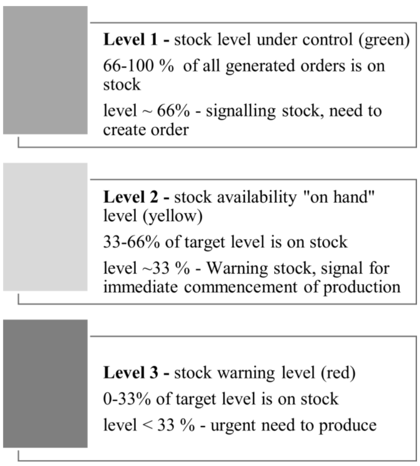

Fig. 2. Buffer status for MTA production model.

The priority of the buffer status for production start-up is clear: red orders should take precedence over all other orders and yellow over green. How to optimize stock levels in the warehouse? The answer is dynamic buffer management (DBM). Too much green – the target is too high, too much red – the target is too low. The "green check period" should not be more than twice the replenishment time. "Cooling period" for red should have one replenishment time. The decision on how much the buffer will increase or decrease is based on an assessment of the combination of supply and demand.

Based on the information contained in the literature, it can be concluded that the production intensity of the products, MTA Model should not take into account the situation in which it was impossible to deliver to the customer. When switching from the MTS Model to MTA, it can be seen that the established minimum and maximum reserve levels appear to be too high in relation to the outflow intensity and therefore it can be concluded that these standards have been lowered and so have been the average cost of the stock. In order to be able to conclude the basic standards, it is necessary to prepare mathematical models for both models and to carry out some experiments in the simulation program. No mathematical formula nor algorithm has been developed for the MTA Model based on the studies conducted so far by the authors of MTA descriptions. Such a comparison of MTS and MTA Models with algorithms is presented in the next section of this paper.

Problem definition and proposed solution

Two models and computational algorithms were prepared according to the analyzed cases – MTS and MTA. The subject of this work is assumed to be the switching of the warehouse stock management from the MTS to the MTA Model.

MTS Model

The MTS Model was developed for the case of inventory and supply control in an independent demand period review system with a fixed delivery period, typically analyzed in the literature. This inventory control system was chosen due to the possibility of treating the flow of the production stream as contractually continuous, which corresponds to the analyzed problem. In this model, orders are issued in fixed cycles, while the delivery volume is variable.

It was assumed that, at the starting point, the stock level was equal to the maximum (target) level and the production capacity enabled refilling the maximum stock level within one delivery cycle (non-active production capacity constraints). The output data for the first delivery period assumed that there was no delivery cycle delay in the previous delivery period. The entire planning horizon (e.g. a year) may be divided into delivery periods (e.g. weeks, months, quarters), each delivery period may consist of a specified number of terms – time units (e.g. hours, shifts, business days). Basic production standards were determined in accordance with the previously given descriptions as well as formulas (2)–(3). Those standards preserve their values along the entire planning period, as it is assumed for the MTS Model. Product storage costs were determined as the product of the stock level at the end of each term of the planning period and the cost of storing one item of the product during one term. The costs of lost benefits related to the failure to meet customer demand were determined as the product of the number of products undelivered to customers during each term of the planning period and the profit that was lost for one piece of undelivered product.

In the MTS Model simulation process, in each term of each of the delivery periods, the number of the products in stock at the end of that term is calculated as the sum of the following: the product quantity at the beginning of the term, the quantity of the product delivered to the stock as a result of the fulfillment of the earlier production order and the quantity of the product received from the stock by the customers in that term. If there is not enough of the product in stock to satisfy the customers' demands, then the nonfulfillment is also calculated in that term, equal to the lacking quantity of the product. For each delivery period, there are calculated: the size of the production order meant to supplement the stock (as in formula (1)) and the term of the delivery of the order to the stock (depending on the delivery cycle length and estimated delay of that cycle for a given delivery period). As assumed in the MTS Model, in each delivery period, one production order should be accomplished. If the estimated delay of the delivery cycle is positive (greater than zero), the delivery will be accomplished in the next delivery period.

The meaning of the used symbols is as follows: i – delivery period index; $i = 1..I$; I – number of delivery periods; D_i – expected consumption of the product during the delivery period i [pcs]; k – index of an individual term (time unit); T_{ki} – number of terms k in delivery period i; Cd – delivery cycle [time unit]; ΔCd – estimated maximum delivery cycle delay [time unit]; Td – delivery period [time unit]; $Zmin$ – minimum stock level [pcs]; $Zmax$ – maximum stock level [pcs]; p_i – the average planned consumption of the product per unit of time over the delivery period i [pcs/ time unit]; p– the average planned consumption of the product per unit of time over the entire planning period (in all delivery periods) [pcs/time unit]; Q_i – the size of the production order in delivery period i[pcs]; t_i – actual delivery term in delivery period i [time unit]; Zs_{ki} – stock level at the beginning of term k in a delivery period i [pcs]; Zk_{ki} – stock level at the end of term k in a delivery period i [pcs]; Uk_i – number of undelivered products at the end of term k in a delivery period i [pcs]; CoS – product storage costs [monetary unit]; $CoLB$ – lost benefits costs related to the failure to meet customer demand [monetary unit].

It was also assumed:

$$Td > Cd, \tag{4}$$

$$0 \leq \Delta Cd_i \leq (Td - Cd) \forall i = 1..I. \tag{5}$$

Here follows the proposed algorithm:

(1) read I; D_i; T_{ki}; Cd; ΔCd_i, Td;
(2) calculate p; $Zmin$; $Zmax$;
(3) for $i = 1$ **to** I {
  for $k = 1$ **to** T_{ki} **calculate** Zs_{ki}; Zk_{ki}; U_{ki};
  calculate p_i; Q_i; t_i (Cd, ΔCd); }
(4) calculate $CoS(Zk_{ki})$; $CoLB(U_{ik})$;

In the description of the computational algorithm, the pseudocode convention, appropriate for higher-level programming languages, was adopted. The computational complexity of the algorithm is polynomial.

In step (1) of the algorithm, the input data, consisting of the expected product consumption in each term of the delivery period, the length of the delivery cycle (the same in each of the delivery periods) and the estimated delays of the delivery cycle (different between distinct delivery cycles), is loaded into the computational experiments. In step (2) the production standards of the MTS Model are determined. Step (3) concerns the calculation of the stock availability at the beginning and at the end of each term of the planning period, as well as nonfulfilled customers' demand. In this step, the size of the production order needed to supplement the storage stock is calculated, due to the MTS Model assumptions. Also, the term of that order delivery to the storage facility is determined in this step. In step (4), the total cost of the product storage, as well as the total cost of the nonfulfillment of the customers' demand due to the lack of the product in stock, are calculated, as the respective sums of those costs in each term of the planning period.

MTA Model

The MTA Model was developed taking into account selected elements of the approach described in Cox, Schleier [7]. In this model, product deliveries to customers are carried out in subsequent terms of the entire planning period. As well as in MTS Model, it was assumed that, at the starting point, the stock level was equal to the maximum (target) level and the production capacity enabled refilling the maximum stock level within one delivery cycle (non-active production capacity constraints). For each term of the planning period, a temporary status of the buffer, dependent on the consumption of the product, was calculated according to the predefined ranges of stock levels – signaling, warning and urgent stock. Detailed explanations of such a situation were given in Sec. 2.

In the MTA Model simulation process, similarly to the MTS Model case, the number of the products in stock at the end of that term is calculated as the sum of the following: the product quantity at the beginning of the term, the quantity of the product delivered to the stock as a result of the fulfillment of the earlier production order and the quantity of the product received from the stock by the recipients in that term. If there is not enough of the product in the stock to satisfy the customers' demands, then the nonfulfillment is also calculated in that term, equal to the lacking quantity of the product.

Depending on the product quantity, the buffer status (G, Y, R) is calculated at the end of the delivery term. In the examined cases, the 'R' buffer status of the stock level was in the left-close, right-close interval with endpoints respectively equal to 0/3 and 1/3 of the storage capacity, the 'Y' buffer status was in the left-open, right-close interval, with endpoints respectively equal to 1/3 and 2/3 of the storage capacity, and finally, the 'G' buffer status was in the left-open, right-close interval, with endpoints respectively equal to 2/3 and 3/3 of the storage capacity. The buffer status determines the urgency level of the need to issue the production order (G – do nothing, Y – generate the order, R – immediately issue the order).

In the case when after the completion of the client's order the buffer status is G (Green), i.e. the buffer level can be considered safe (under control), there is no need to issue a production order to refill the stock.

If the buffer status is Y (Yellow), i.e. the buffer level is in the warning state, there should be generated an order to fill up the stock to the maximum level. This order should be added to the end of the list of orders waiting for execution.

If the buffer status is R (Red), i.e. the buffer level is in the critical (urgent) state, there should be generated an order to fill up the stock to the maximum level. This order should be added to the beginning of the list of orders waiting for execution. This is to restore the stock level and to change the buffer status to G or Y (depending on the storage capacity and production capacity).

In any case, when deciding whether to issue an order, the stock level expected after the execution of orders already waiting in the queue should be taken into account. If the list of orders is not empty, the first order from the list should be immediately started. The quantity of the products in the production order supplements the stock so it becomes full. The term of accomplishment of the production order depends on the following: availability of the production system (i.e. if it is not engaged by an earlier order), delivery cycle length (uniform along the whole planning period) and the estimated delay of that cycle with respect to the term from the given delivery period. As a result of such an approach, the number of the production orders varies between subsequent delivery periods – it depends on the temporary consumption of the product by the customers. The product storage costs and the costs of lost benefits were defined the same as in the case of the MTS Model.

The meaning of the additionally used symbols is as follows: k – index of individual term, $k = 1..Tk$; Tk – number of terms in the entire planning period, $Tk = I \cdot Tk_i$; d_k – expected consumption of the product during the term k [pcs]; Zs_k – stock level at the beginning of the term k [pcs]; Zk_k – stock level at the end of the term k [pcs]; U_k – number of undelivered products at the end of the term k [pcs]; ΔCd_k – estimated maximum delivery cycle delay in the term k [time unit]; Bs_k – buffer status in the term k, after delivery of the product to the customer, $Bs_k \in \{G, Y, R\}$; Zl_k – decision variable, $Zl_k \in \{0, 1\}$, $Zl_k = 1$ if the decision on issuing the production order was made in the term k, $Zl_k = 0$ otherwise; $Q(Zl)_k$ – the size of the production order issued in the term k [pcs]; L – list of production orders. The computational complexity of the algorithm is polynomial. Here follows the proposed algorithm:

(1) read $\forall k: d_k;\ T_k;\ Cd;\ \Delta Cd_k;$
(2) calculate $Zmax\ (MTS);$
(3) for $k = 1$ **to** T_k {
    calculate $Zs_k(d_k, Q(Zl)_{k-Cd-\Delta Cd});\ Zk_k(d_k, Q(Zl)_{k-Cd-\Delta Cdk}, Zs_k);\ U_k;$
    calculate $Bs_k(Zk_k,\ Zmax(MTS));$
      if $Bs_k ==$ 'G' **then**
      { $Zl_k := 0;\ Q(Zl)_k := 0;$ }
      else
      { $Zl_k := 1;\ Q(Zl)_k := Zmax(MTS) - Zk_k;$
        if $Bs_k ==$ 'Y' **then**
        { **add**$(Zl_k, Q(Zl)_k)$ **to** L[last]; }
        else // $Bs_k =$ 'R'
        { **add**$(Zl_k, Q(Zl)_k)$ **to** L[first]; }
        if $L \neq$ null **then start** L[first]; }
(4) calculate $CoS(Zk_k);\ CoLB(U_k);$

In step (1) of the algorithm, the input data, consisting of the expected product consumption in each term of the planning period, the length of the delivery cycle (equal along the whole delivery period) and the estimated delays of the delivery cycle (different for the terms belonging to distinct delivery cycles), is loaded into the computational experiments. In step (2) only one production standard parameter is calculated, identically as in the MTS Model – the maximum stock availability. This parameter is inevitable to determine the buffer status in the next step. Step (3) concerns the calculation of the stock availability at the beginning and at the end of each term of the planning period, as well as nonfulfilled customers' demand. Subsequently, the current status of the buffer is determined by the comparison of the stock availability at the end of the given term to the thresholds of the stock capacity, corresponding to different states of the buffer. Depending on the buffer status, a production order is issued (for Y or R status) and placed on the appropriate position on the list of orders waiting to be run (respectively, at the end or at the beginning of that list). If the list of orders is not empty, the first order from the list is sent to the production system. In the step (4), the total cost of the product storage, as well as the total cost of the nonfulfillment of the customers' demand due to the lack of the product in stock, are calculated, as the respective sums of those costs in each term of the planning period.

Data source for computational experiments – case study

The case study is coming from the global manufacturing enterprise of industry automation from cooling and refrigeration segment. The data used in mathematical and computational experiments were prepared based on the real production line which produces view types of products. The yearly sale is in thousands of parts.

The mathematical models and experiments were prepared with the usage of data from the U-shape production line with product specialization. The water regulating valves are assembled on this line. They are used in cooling systems. The production is medium-lot, which means that several types of valve models are produced on the line. The products flow sequentially through the stations. One model of the product was selected for the analysis, in which the production cycle is at least two working days (assuming low value of machine failure indicator and excellent availability of all production components).

Production planning takes place as a 'manual' without the use of specialized software – it is based only on the sales forecast for the period from Material Requirement Planning (MRP) system. The minimum delivery time of the product to the customer (the customer is an external central enterprise warehouse) is two days. This time is counted from the moment the order is put into the system until the finished goods are sent to the central warehouse. The product delivery time may change (increase) due to problems in the production process or logistic problems what is included in the next section. The case study meets the assumptions described in Sec. 2 of this paper:

- The continuous flow of products through the production cell,
- Deliveries to the warehouse take place periodically,
- The ordered quantities are fixed and repeatable over time – demand fluctuations are minimal,
- Manufacturing enterprise is from a make-to-stock production environment (it can be considered to change to make-to-availability model),
- Product variant number is small; one type of product is considered in the experiments.

It is an example of a periodic review system with a fixed order cycle. The analyzed case from the manufacturing enterprise will give the answer to whether the classic MTS system obtains better results for the criteria proposed in the next section.

Results of experiments

Computational experiments were carried out in the Microsoft Visual Studio 2017 environment. The algorithms were implemented in the C programming language. The time of execution of a single test was shorter than 1s. Computational experiments were conducted on the raw, as well as pre-processed, real data from the enterprise of the automation industry described in Sec. 4. The case of storage of one product was analyzed.

The planning horizon was a calendar year, divided into 12 months. Each month consisted of 20 business days. The experiments were varied by the values of parameters Cd and ΔCd. The delivery cycle defined as the difference between the production order moment and the moment of delivery of the product to the warehouse varied between 2 to 5 days for individual test cases. The estimated maximum delivery cycle delay ranged from 0 to 9 business days, depending on the delivery month.

The annual product demand was over 900 thousand pieces. The production capacity enabled a maximum refill of the warehouse as part of a single order. Four curves of demand for the product were tested:

a) Curve with a constant (average) level of demand (on average 75 thousand pieces per month),

b) Curve with an increasing trend of demand (from about 60 thousand pieces to about 90 thousand pieces per month),

c) Curve with a decreasing trend of demand (from about 90 thousand pieces to about 60 thousand pieces per month),

d) Curve with a seasonal fluctuation around the increasing trend of demand (from about 60 thousand pieces to about 90 thousand pieces per month with fluctuations of about plus or minus 5 thousand pieces month by month, in relation to the base value).

The total demand of the product had the same value for each studied demand curve. It was assumed that the unit cost of lost benefits for one piece of the undelivered product was equal to the unit cost of the storage of this piece of the product throughout the planning period (one year).

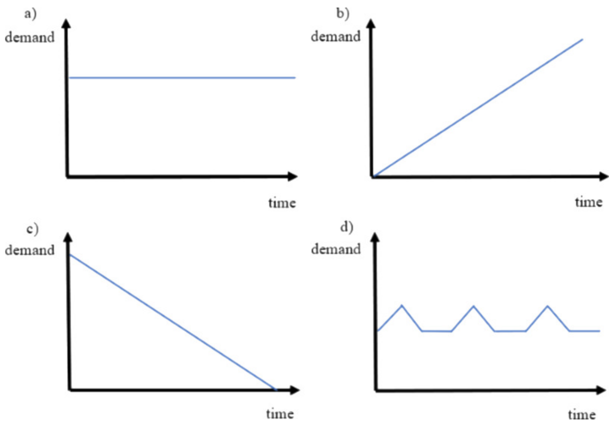

Fig. 3. Variants of customer demand used for experiments.

In the studies on the MTS Model, it was assumed that deliveries to the warehouse were carried out once a month, at the end of the month. The quantity of the order, the minimum and maximum stock levels were determined in accordance with the previously given formulas (1)–(3).

For the final comparison of the results of both algorithms, the numbers of undelivered products for each day and the stock values in the warehouse at the beginning and at the end of each day of the planning horizon were determined.

The results of the experiments are presented in Tables 1–4. Symbols used in the tables are as follows: Co – total costs, expressed in monetary units [mu]; CoS – product storage costs [mu]; $CoLB$ – lost benefits costs related to the failure to meet customer demand [mu]; N – number of orders during entire planning horizon; Q – average order quantity [pcs]; η – relative costs changing after applying the MTA Model in comparison to applying the MTS Model [%], where:

$$Co = CoS + CoLB, \tag{6}$$

$$\eta = (Co\text{MTS} - Co\text{MTA})/Co\text{MTS}. \tag{7}$$

For the curve with constant level of demand average relative cost improvement after applying the MTA Model was equal 21,89%. In this group of experiments, applying the MTA Model gave distinctly better results in 5 out of 8 cases. In one case (No. 6) the results were comparable and in two cases (No. 2, No. 4) applying the MTS Model gave better results. MTS Model can be treated as an acceptable one only for the storage costs of constant demand curve (Fig. 4).

Table 1
Results of the experiments – Curve with a constant (average) level of demand (real data).

No.	1	2	3	4	5	6	7	8
Cd [days]	2	2	3	3	4	4	5	5
ΔCd [days]	0	0–9	0	0–9	0	0–9	0	0–9
Co MTS [thous. mu]	102935	72091	98533	71418	93936	70745	94174	70072
CoS MTS [thous. mu]	41985	61850	42700	61635	43018	61420	43724	61206
$CoLB$ MTS [thous. mu]	60950	10241	55833	9783	50918	9325	50450	8866
N MTS	12	11	12	11	12	11	12	11
$\underline{Q}$ MTS [pcs]	71313	78442	71894	78444	72458	78445	72652	78446
Co MTA [thous. mu]	60758	77490	57033	73616	53257	69921	49165	62867
CoS MTA [thous. mu]	60758	77490	57033	73616	53257	69921	49165	62867
$CoLB$ MTA [thous. mu]	0	0	0	0	0	0	0	0
N MTA	32	23	32	23	32	22	31	21
$\underline{Q}$ MTA [pcs]	27944	39609	27944	39609	27944	39964	28845	42581
η [%]	40.97	−7.49	42.12	−3.08	43.31	1.17	47.79	10.33

Table 2
Results of the experiments – Curve with an increasing trend of demand (pre-processed real data).

No.	1	2	3	4	5	6	7	8
Cd [days]	2	2	3	3	4	4	5	5
ΔCd [days]	0	0–9	0	0–9	0	0–9	0	0–9
Co MTS [thous. mu]	225115	162969	215446	168084	205797	173207	197758	178334
CoS MTS [thous. mu]	45382	66878	46829	67500	48297	68132	49720	68767
CoLB MTS [thous. mu]	179733	96091	168617	100583	157500	105075	148037	109567
N MTS	12	11	12	11	12	11	12	11
Q MTS [pcs]	61098	64235	62341	63827	63585	63419	64690	63010
Co MTA [thous. mu]	60713	77324	56978	73048	53244	68589	49081	63443
CoS MTA [thous. mu]	60713	77324	56978	73048	53244	68589	49081	63443
CoLB MTA [thous. mu]	0	0	0	0	0	0	0	0
N MTA	32	22	32	22	32	21	30	19
Q MTA [pcs]	28006	40355	28006	40736	28006	42676	29873	45806
η [%]	73.03	53.01	73.55	56.54	74.13	60.52	75.18	54.62

Table 3
Results of the experiments – Curve with a decreasing trend of demand (pre-processed real data).

No.	1	2	3	4	5	6	7	8
Cd [days]	2	2	3	3	4	4	5	5
ΔCd [days]	0	0–9	0	0–9	0	0–9	0	0–9
Co MTS [thous. mu]	228845	163944	219095	167799	208989	171697	199976	175613
CoS MTS [thous. mu]	45054	67794	46716	68403	48022	69055	49121	69726
CoLB MTS [thous. mu]	183792	96150	172379	99396	160967	102642	150854	105888
N MTS	12	11	12	11	12	11	12	11
Q MTS [pcs]	61185	72296	62344	72202	63504	72107	64556	72012
Co MTA [thous. mu]	60537	77019	56814	72483	53092	69278	48759	65245
CoS MTA [thous. mu]	60537	77019	56814	72483	53092	69278	48759	65245
CoLB MTA [thous. mu]	0	0	0	0	0	0	0	0
*N*MTA	32	23	32	22	32	22	30	20
Q MTA [pcs]	27919	39565	27919	41055	27919	41364	29780	43726
η [%]	73.55	53.02	74.07	56.80	74.60	59.65	75.62	56.64

Table 4
Results of the experiments – Curve with seasonal fluctuations around the increasing trend of demand (pre-processed real data).

No.	1	2	3	4	5	6	7	8
Cd [days]	2	2	3	3	4	4	5	5
ΔCd [days]	0	0–9	0	0–9	0	0–9	0	0–9
Co MTS [thous. mu]	224738	179138	213181	183355	202220	187580	196973	191559
CoS MTS [thous. mu]	45213	66513	46594	67455	48020	68405	49236	69109
CoLB MTS [thous. mu]	179525	112625	166587	115900	154200	119175	147737	122450
N MTS	12	11	12	11	12	11	12	11
Q MTS [pcs]	60779	62413	62173	62115	63521	61817	64375	61519
Co MTA [thous. mu]	60253	75275	56535	74855	52818	79577	48673	82104
CoS MTA [thous. mu]	60253	75275	56535	71892	52818	67414	48673	62742
CoLB MTA [thous. mu]	0	0	0	2963	0	12163	0	19362
N MTA	32	22	32	21	32	21	30	19
Q MTA [pcs]	27881	41318	27881	41945	27881	42707	29740	45497
η [%]	73.19	58.08	73.48	59.17	73.88	57.58	75.29	57.14

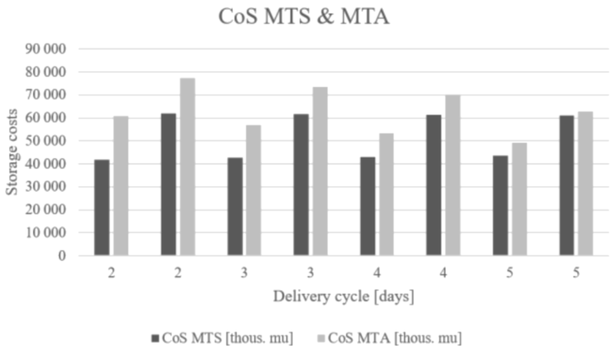

Fig. 4. Storage costs of MTS and MTA models for constant level of demand.

The MTS Model turned out to be definitely worse for the cases where there was no delay in the delivery cycle (No. 1, No. 3, No. 5, No. 7). It was a result of the production order size being insufficient in those cases, as it was in direct proportion to the value of the standard parameter $Zmin$ ($Zmin = 0$, when $\Delta Cd = 0$). When the delivery cycle delay was positive, the results of applying the MTA Model kept getting better along with the delivery cycle elongation, for it was possible to dynamically generate production orders, responsively to the shrinking storage stock.

For the curve with increasing trend of demand average relative cost improvement after applying the MTA Model was equal 65.07%. In this group of experiments, applying the MTA Model gave distinctly better results in all of the cases. In each case, applying the MTA Model allowed to fully satisfy the customers' demands which is visible at lost benefits costs. There were no costs of lost benefits for the MTA Model, except the variant of seasonal fluctuation in demand where these costs were slightly higher (Fig. 5).

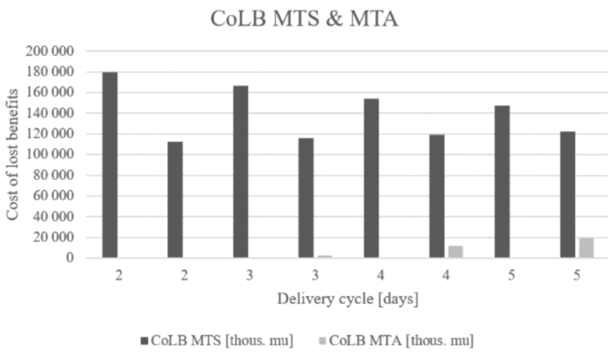

Fig. 5. Costs of lost benefits for MTS and MTA models for seasonal fluctuations of demand.

In the case of the MTS Model, the main problem was nonfulfillment of the customers' demands following the too small size of the production order when $\Delta Cd = 0$, or, in other cases, following too rapid (constantly growing) consumption of the products from the storage facility, in relation to the ability to supplement the stock (periodically supplemented by some value dependent on the production standards calculated for the mean values along the whole planning period). The stock was supplemented once in a delivery period. $Zmin$, $Zmax$, p parameters were calculated once in a planning period, which resulted in the size of the order being unadjusted to the temporary needs. This regularity applied particularly to the second part of the planning period (second half of the year), when the demand values exceeded the yearly average values (at the assumed constant yearly demand of approx. 900 thousand pieces of the product). Similarly to the previous case, the advantage of the MTA Model was a result of the possibility to dynamically calculate the moment of the execution of production order supplementing the stock to its full capacity.

For the curve with decreasing trend of demand average relative cost improvement after applying the MTA Model was equal 65.49%. In this group of experiments, applying the MTA Model gave distinctly better results in all of the cases. In each case, applying the MTA Model allowed to fully satisfy the customers' demands. Similarly to the results presented in Table 2, the main reason that applying the MTS Model gave worse results was the way of calculating the production standards and followingly the order size, as well as the limited number of issued production orders. This can be found in the results of total costs for seasonal fluctuations of demand (Fig. 6) where the highest average value for the MTS Model and the lowest average value for the MTA Model occurred.

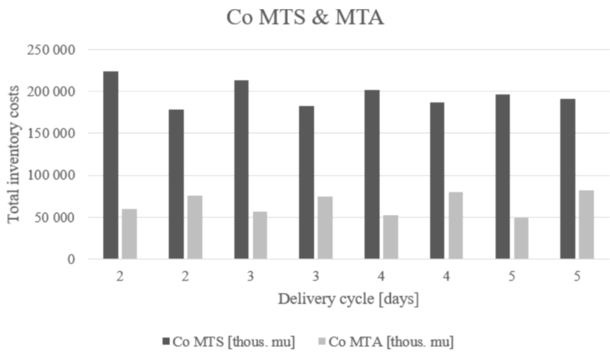

Fig. 6. Total costs (storage and lost benefits costs) for MTS and MTA models for seasonal fluctuations of demand.

In the case of the MTA Model, those quantities were calculated dynamically. In this very case that applied to the first half of the year, when the demand values exceeded the yearly average values (at the assumed constant yearly demand of approx. 900 thousand pieces of the product).

For the curve with a seasonal fluctuation around the increasing trend of demand average relative cost improvement after applying the MTA Model was equal 65.98%. In this group of experiments, applying the MTA Model also gave better results in all the cases. The reasons of the MTS Model's relatively worse results were analogical to those explained for the previous experiments. In this very group of experiments the nonfulfillment of the customers' demand was also observed in three cases for which the MTA Model was applied (No. 4, No. 6, No. 8). It was a result of the presence of demand seasonal fluctuations (momentary growths and declines of the demand, independent on the long-term trend). In this situation also the MTA Model parameters (thresholds differentiating buffer states), prearranged statically and proportionally for the whole planning period (0/3, 1/3, 2/3, 3/3), turned out to be inadequate to the rapid changes of the demand vector, particularly to the seasonal demand growths enhancing the upward trend. Lowering the buffers states' thresholds (especially for G and Y buffers) seems to be a probable solution of that problem.

Conclusions

The results of the conducted experiments lead to the finding that the MTS Model can be treated as an acceptable one only for the constant demand curve in the situations, when there are significant delivery cycle delays present in the production system (in two such cases the MTS Model gave even better results than the MTA Model).

The MTS Model does not enable total fulfilment of the customers' demand in any of the examined cases, no matter the demand curve. However, it enables to keep the stock on the lowest level possible. By design, this model does not require frequent issuing of production orders for the stock supplementation. Inside the examined class of cases, the MTS Model should not be applied for the demand changing in a long-term manner (trend, trend and seasonal fluctuations).

The MTA Model gave acceptable results virtually in every case. This model enabled the fulfilment of the customers' demands in the vast majority of cases (29 of 32). The cost of this was, however, the need to keep the stock relatively high (even 30% higher than in case of the MTS Model) and to frequently issue production orders (even 2–3 times more frequently than in case of the MTS Model) of lower individual size (20–40% lower than in case of the MTS Model). The MTA Model can be applied in case of constant, as well as varying demand, but the nonfulfillment of the customers' demand increases along with the growth of the test cases difficulty (trend and seasonal fluctuations). The MTA Model is scalable by design, so its parameters can be adjusted to a range of practical requirements. The efficiency of such actions, however, has to be proved experimentally.

In the examined case, applying the MTA Model gave distinctly better results than applying the MTS Model, in terms of the total storage cost and the cost of the customers' demands nonfulfillment (22–68% in average, depending on the demand curves and even 75% in some individual cases). It applied, however, to the mutual relation of those costs, considered in this elaboration. It also indicates the need of detailing and extension of the values of individual parameters differentiating individual computational experiments.

As previously indicated, the unit cost of lost benefits for one piece of the undelivered product was equal to the unit cost of the storage of this piece of the product throughout the planning period (one year). In a general case, the decision on choosing one of the models should depend, on one hand, on the relation between the storage cost and the cost of issuing the production orders, and on the other hand, on the cost of the nonfulfillment of the customers' demand.

Taking into account the described results, despite their initial status, it can be summarized that the MTA strategy could be directly applied in manufacturing companies. This mainly concerns improving the ability to manage and control information in the supply chain, as well as improving decision-making and verifying its correctness at the level of inventory held. Extention of the MTA Model with further practical aspects and quantitative numerical experiments should give the possibility to assess the impact of the model execution on the schedules and volumes of production orders launched. As a result, it should be possible to increase the financial efficiency of the entire process and streamline the work of planners who make key decisions in this process.

In accordance with the objectives set out in the introduction, the scope of research and the results presented in this paper are centered on issues of practical importance. They can be treated as the first step towards verifying the possibility of implementing the MTA strategy in manufacturing companies. However, this requires further detailed research of individual elements composing proposed approach. In the first place, the further research should be focused on the improvement of the MTA Model, the increase of the number of products in the production system, and the use of MTA Model to optimize the results of the whole problem, also considering the production order costs.

Further work in this area should also concern the definition and calculation of various cost criteria influencing the financial efficiency of the process, including the costs of execution of individual production orders. The cost of production orders should depend on their frequency, ordered batch size and actual availability of production resources. In this regard, the potential research area may also include the formulation of the problem or the main part of the problem as a mathematical optimization model. Solving such a model should give an assessment of the possibility of further improvement of the results.

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