Production Systems

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Introduction

Any system can be regarded as some sort of "black box" or "machine" that turns a certain number of inputs into one or multiple output. Production systems do not escape that definition and can be viewed as a system transforming raw materials into final products. Actually, the inputs are more general and complex than just raw materials, for example, one can consider energy, workforce, decisions and many others as inputs of our system. As well, the outputs are generally not only a final product but also scraps or waste. Scrap corresponds to the portion of raw material that we loose with respect to the technology we utilize for transforming the raw materials into final products. Wastes, on the other hand, are immaterial. The figure (1) sums up what have been said.
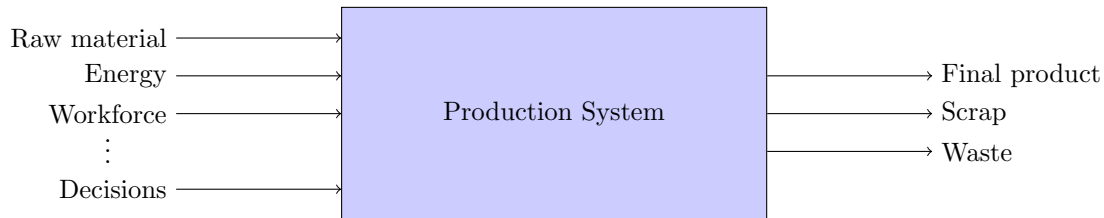

Figure 1: General production system

The objective of this course is to analyse how we can make our production system more efficient with respect to some criteria (time, money, ...). Of course, our production depends on the methods and on the technolgies we use to manufacture our goods, but these are rather concerns for mechnanical engineers or more specific fields (chemistry, process engineering, ...). Actually, this course focuses on the only input we can, at our level, act uppon, which is : decisions.

To understand how decisions can improve (or worsen) our productivity, let's take a very simple example. Consider the following task : "Drilling four holes in a piece of wood". And let X be the rate of production. Consider as well that the "drilling" operation needs some set-up time in order to prepare the right borer and to turn on the machine. Let's denote by T_S this set-up time and by T_H the operation time which is necessary to actually drill the wooden piece. There are plenty of ways to perform such task, one idea is to drill one hole at a time, stopping the machine after each drill. But this wouldn't be a very clever way since we would have to wait for the set-up time for each hole we want to make. Another idea is to perform a batch of holes in a row so that we only account for the set-up time once for all the batch. The two situations are presented in the GANT diagram in figure (2).
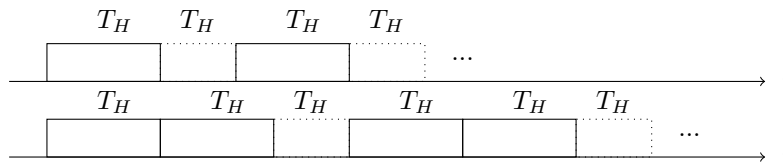

Figure 2: Two GANT diagrams showing how decisions can influence productivity

In the first situation, the rate of production can be expressed as

$$X_1 = \frac{1}{T_H + T_S}$$

meaning that we produce one item every $T_H + T_S$ unit of times. For the second situation however, the rate can be computed as

$$X_2 = \frac{2}{2T_H + T_S} = \frac{1}{T_H + \frac{T_S}{2}}$$

which means that we produce one item every $T_H + \frac{T_S}{2}$ unit of time, which is smaller. In fact, as long as the batch size increases, the set-up time becomes less and less influent on the production rate since

$$X_k = \frac{k}{kT_H + T_S} \xrightarrow{k \to \infty} \frac{1}{T_H}$$

which clearly demonstrates that we can influence our production by making some decisions rather than others.

The first part of this course will deal with the inventory management in which we'll try to answer to questions like "How and when should we order goods for our production system ?". In fact, we will deal with the different stakeholders to establish good strategies to make our orders. These stakeholders are represented in figure (3). Firstly, the suppliers provides us with some raw materials which can then be stored in a warehouse. When needed, the production system will take some of these materials to transform them into final products. Once done, he will then leave them in another warehouse which will be used to fulfill the demand of such final goods.
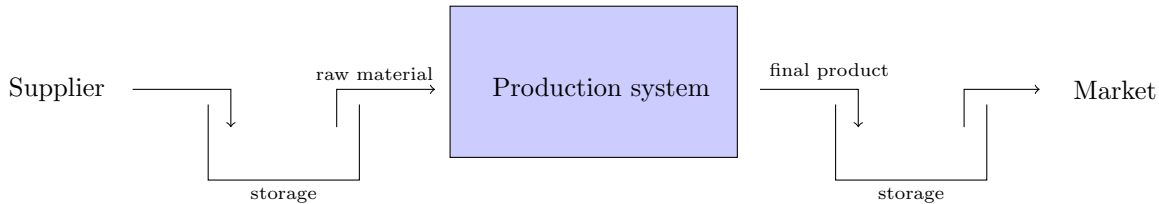

Figure 3: Production system agents

That being said, it is clear now that any production system aims to fulfill a certain demand taking into account the supply constraints it may encounter. This will be largely discussed futher on.

The figure (4) depicts the different production system types we can encounter :

- Job shops : very specialized entities where, often, solely one product can be produced at the same time. Car repairers are a good example of such production systems. This kind of system is not easily formallized because they are too specific. We will not discuss them in this course.

- Mass production : produces an average number of varieties of goods at average to high rate.

- Continuous flow process : produces continuously a given product at very high rate but with very small variety of products.

We will focus on both mass production and Continuous flow processes.

The second part of this course will take interest in the bill of materials (which will be further defined) in which we'll look at how to optimize production with respect to the production rate taking into account bottleneck machines in a production site.
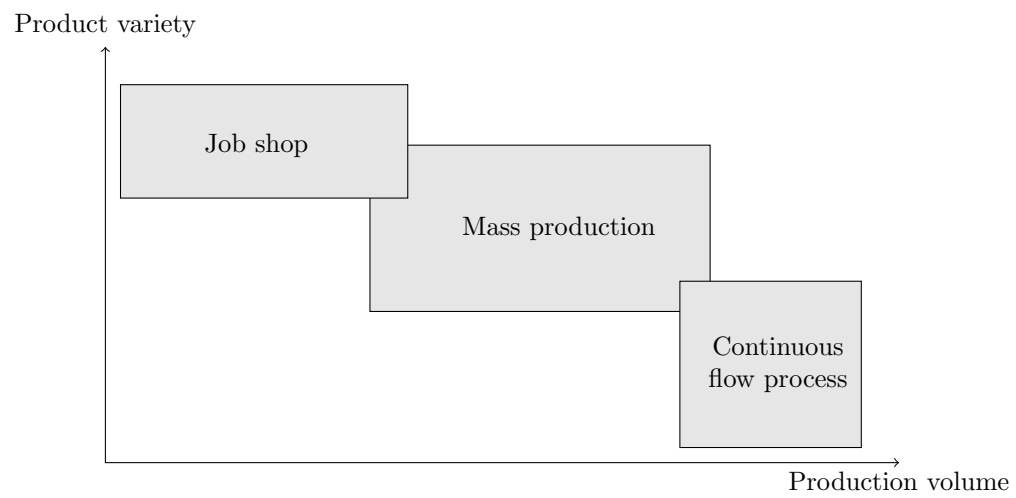
Figure 4: Production system types

Part I

Inventory management

Chapter 1

Continuous review

Inventory management, or storage management, can be qualified as the art of storing and ordering goods in a clever way with respect to some criteria (most often the cost). It can be applied at both the beginning and the end of the production system (even in between actually). At the beginning of this chain, raw materials are delivered by the suppliers and are stored in a warehouse. The storage is emptied when the production site requires some raw materials to be used for production. On the other side of the chain, at the end, the storage is filled with final products and is emptied by the market demand. Though the two situation may appear different in some kind, we can jointly study them considering some sort of "abstract demand" (either production demand or market demand) and some sort of "abstract supplier" (either a real supplier which provides raw material or the production site itself). See figure (1.1) for graphical representation.
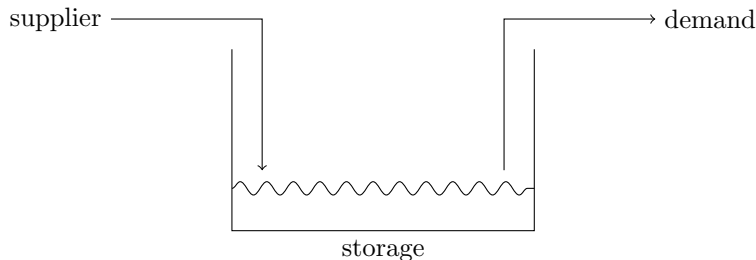

Figure 1.1: Storage management parameters

To study the inventory management, we introduce models that tend to represent real life cases. Making different assumptions on the demand and supplier, we end with different models. The simplest model is the so called "deterministic model" where all the input data for our problem are supposed to be perfectly known in advance (both the supply and the demand). We will start by studying this model before focusing on a "stochastic model" where the supplier and the demand are modeled by random variables.

In this chapter, we will study what is called "continuous inventory management". What we mean by this is that the time is modeled by a continuous variable ($t \in \mathbb{R}$). In the next chapter, we'll deep into "periodic inventory management" where the time is modeled by a discrete variable ($t \in \mathbb{N}$).

1.1   Deterministic model

The deterministic model supposes that we exactly know both the demand and the characteristics of our supplier. We denote by λ the rate at which the storage is emptied. In the case where our warehouse is at the end of our chain,

just after the production site, λ represents how many items (final products) we sell by unit of time. If considered at the beginning of the chain, it corresponds to how many items (raw materials) are needed by our production site. This coefficient can be computed as

$$\lambda = \frac{\text{nb of items leaving the warehouse}}{\text{observed time}}$$

To fullfill that demand, we need to order a certain quantity of good, which will cost us some amount of money. In fact, the costs are of three kinds :

- A **fixed cost** which we have to pay for each order we make to our supplier. Let K denote this cost, expressed as *euros/order*

- An **inventory cost** which we pay for storing goods in our warehouse, expressed as *euros/(time × item)*. Let h be the inventory cost.

- A **unitary cost** which corresponds to the price of each item per se. We will refer to this cost as c, expressed as *euros/item*

For sure, it is easy to see that choosing the right time and quantity to order goods is a matter of balancing between the fixed cost we pay for ordering an independent amount of product and the inventory cost which we pay for storing the goods. If storing products in our warehouse is very expensive for us, we might prefer to order often and pay the fixed cost multiple times rather than paying it just once and be left with a lot of goods we pay a fortune for storing. If, however, the inventory cost is very low (which means that we can store many items for a small amount of money), we'd rather order a lot of products and store them for a long time if needed. So, how do we compute the total cost ?

Let T be the period of time between the moment we order some goods and the moment our storage goes empty. Note that since the demand is deterministic and known in advance there is no risk of "unpredicted" events which could lead us to be unable to fullill the demand nor to order too many items in such a way that some would remain after some time. Finally, let Q be the number of items we will buy at the beginning of that period. The figure (1.2) sums up some of the introduced variables.
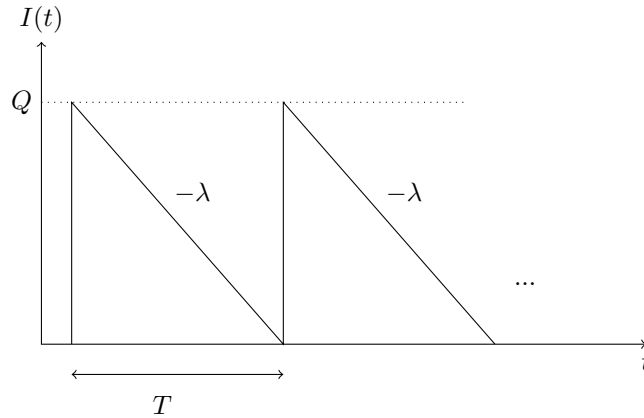

Figure 1.2: Inventory level in the deterministic model

For a given period of time T, we can then compute the total cost as

$$J_T = \underbrace{K}_{\text{fixed cost}} + \underbrace{cQ}_{\text{price for } Q \text{ items}} + \underbrace{\int_0^T hI(t)dt}_{\text{storage cost}}$$

where the integrated part is simply given by $\frac{QT}{2}$ (are of a triangle[1]).

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[1] $\int_0^T hIt(t)dt = \int_0^T h \times Q - \lambda t dt = h[Qt - \lambda \frac{t^2}{2}]_0^T = h\frac{2QT - \lambda T^2}{2}$ and since $Q = \lambda T$ we get $\frac{QT}{2}$ by substituting λ

For sure, we want to minimize the cost for a given period of time. That cost is given by

$$J = \frac{1}{T}\left(K + cQ + \frac{hQT}{2}\right) = \frac{K\lambda}{Q} + c\lambda + \frac{hQ}{2}$$

Note that we used the fact that $Q = \lambda T$ holds. Regarded as a function of Q, we can analyse its variations by derivation (since $Q = 0$ does not make any sense for our purpose, it is for sure differentiable) :

$$\begin{cases} \frac{dJ}{dQ} &= -\frac{K\lambda}{Q^2} + \frac{h}{2} \\ \frac{d^2J}{dQ^2} &= \frac{K\lambda}{Q^3} \end{cases}$$

Solving the optimality condition $\frac{dJ}{dQ} = 0$ we get that

$$Q^* = \sqrt{\frac{2K\lambda}{h}}$$

can be regarded as a critical point of J. And, since the second derivative of J is positive, the value Q^* corresponds to a minimum of our cost function. This quantity is known as the **Economic Order Quantity** (EOQ) and corresponds to the number of items we should order every Q/λ unit of time in order to minimize the total cost.

We may discuss the obtained formula noting that : (1) if the fixed price for order is very large with respect to the inventory cost, we will by a large amount in once and store it for a long period of time ; (2) if the demand is high, we buy more ; (3) if the inventory cost is large with respect to the fixed cost per order, we will prefer making multiple orders in order to store as less as possible.

The moment at which we should order that quantity Q^* of goods is given by the characteristics of our supplier. Let τ be the lead-time of our supplier (difference between the moment we make an order and the moment we actually recieve the products). We define the so called **reorder point** as $R = \lambda\tau$ which corresponds to the inventory level at which we should call the supplier to make an order[2].

1.2   Stochastic model

In the previous model, we supposed that we could both know perfectly the demand and the lead-time of our supplier. In real life however, such quantities are often subject to variations and are found by estimation. That being said, we can not afford to trust a deterministic formula since we know that life is full of unpredicted and unpredicatable events. Let x be a random variable such that $x \sim \mathcal{N}(0,1)$. We now model the demand (denoted d by convention in the stochastic model) by a random variable given by $d = \bar{d} + \sigma_d x$ and the lead-time by $\tau = \bar{\tau} + \sigma_\tau x$.

Actually, the stochastic model is a generalisation of the deterministic model and a lot of common aspects will remain true in this model (in the sense that we can derive the deterministic case from the stochastic case). But, since the demand now variates with time, we can no longer rely on an exact formula giving us *exactely* how many goods we have to order in order to have a 0-inventory-level when we re-order some other goods. Instead, we'd rather save some goods to prevent the fact of being short on stock. That amount of goods is called the **safety stock** and will be denoted by the variable $s.stock$. Given these informations, what is reasonnable to expect ?

The expected value of the demand (resp. the leadtime) is $\bar{d}$ (resp. $\bar{\tau}$). The reorder point is thus expected to be given by $\bar{d}\bar{\tau}$ which, in average, would bring the inventory level to 0 before re-ordering. To this quantity, we add the safety stock to prevent us from delays of our supplier.

$$R = \bar{d}\bar{\tau} + s.stock$$

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[2]Note that in the deterministic case, directely using the lead-time is strictly equivalent to using the reorder point, however, three arguments to use the re-order point rather than the lead-time : (1) the reorder point is linked to a quantity that the warehouse can directly control, (2) the deterministic case is a model, which can or can not reflect the reality, using the reorder point assures us that if, for unexpected reasons, we get to the reorder point sooner than planned, we can still make an order at the right time for the new period of time, (3) we will keep using that quantity in the stochastic case.

In average, the stochastic model should be exactly the deterministic model shifted up by precisely *s.stock* goods in the inventory. The figure (1.3) represents two realisations of the demand while figure (1.4) represents the expected value of our inventory level.
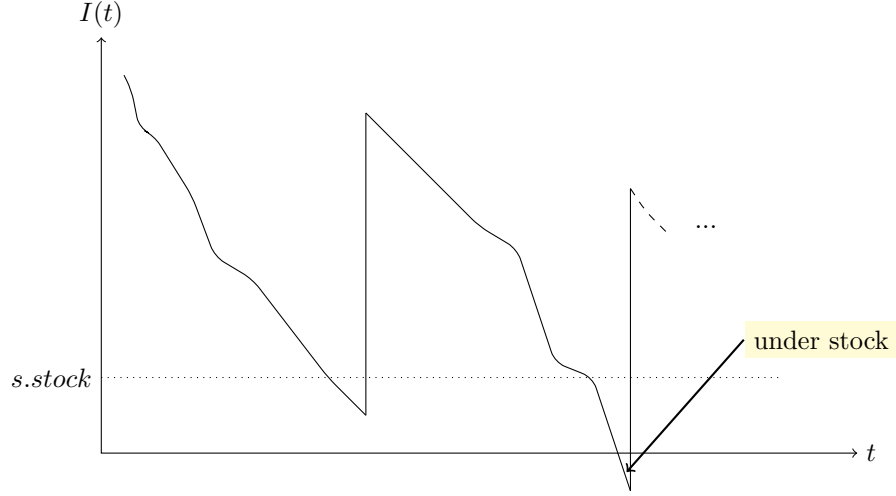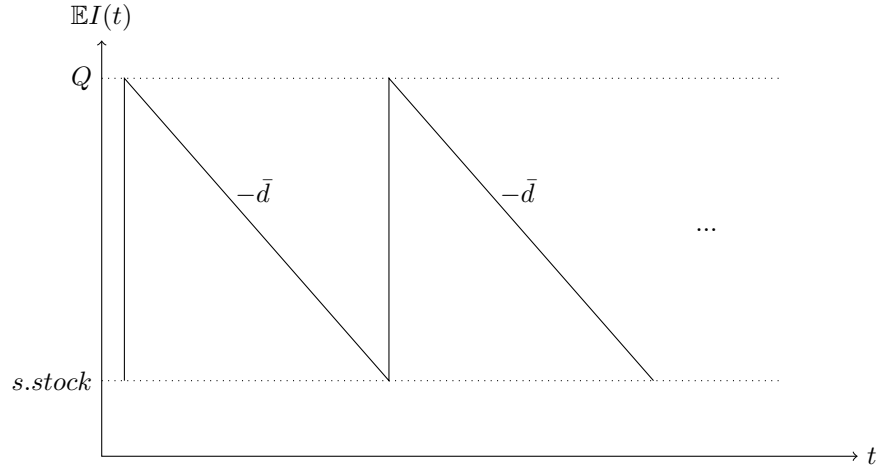

Figure 1.3: Two realisations of the demand

Figure 1.4: Expected inventory level

The expression of the cost must now be updated since we no longer only pay for ordering and storing the goods which are used to fulfill the demand but also for storing some goods as a safety-stock. The total cost is now given by :

$$J = \frac{K\bar{d}}{Q} + c\bar{d} + \frac{hQ}{2} + h \times s.stock$$

This function of two variables (Q and *s.stock*) is actually well splittable into two functions of one variable denoted by $f(Q)$ and $Q(s.stock)$. It is clear that minimizing the total cost can now be done by minimizing both functions seperately. Regarding the first function f, the computations remains the same as in the previous section (deterministic model) and we still have $Q^* = \sqrt{2K\bar{d}h}$. Minimizing g how ever, requires some more analysis. Of course, g is linear with respect to *s.stock* so the global minimum is 0 since it cannot be negative. But setting it to 0 would mean risking to be short on stock at some point. We, somehow, want to control the risks we take and two strategies can be opted for :

1. Let d_τ be the demand over the lead-time τ. It is clear that d_τ is *linked* to both d and τ but it is a rather strong assemption to say that these two random variables are *dependent*. Indeed, the realisation of the leadtime of a supplier is not dependent on the global demand[3]. d_τ is thus given by $d_\tau = \bar{d}_\tau + \sigma_{d_\tau} x$ where $\bar{d}_\tau = \bar{d}\bar{\tau}$ and $\sigma_{d_\tau} = \sqrt{\sigma_d^2 \bar{\tau} + \sigma_\tau^2 \bar{d}^2}$. One idea to select effectively the safety stock is to make sure that the probability of being short on stock is lesser than a certain number which we control. Being short on stock is realised when the demand over the lead-time is greater than the reorder point we have choosen. This strategy implies choosing $s.stock$ so that

$$\mathbb{P}(d_\tau \le R) \ge \alpha = \mathbb{P}\left(x \le \frac{R - \bar{d}_\tau}{\sigma_{d_\tau}} \right) \ge \alpha$$

where α is called the "fill rate". Using this strategy can be done as follow :

   (a) Choose an acceptable probability α

   (b) Solve the eqution for X and let $\bar{X}$ be the solution

   (c) Subsitute X by $\bar{X}$ in $s.stock = \bar{d}_\tau + \sigma_{d_\tau} X$

2. As it has been previously said, it holds that we are short on stock when $d_\tau > R$ (more demand during the lead-time than the reorder point). Let $n(R)$ be the average number of unused items (items remaining in the warehouse when we re-order again). We can compute this quantity with the following formula[4] :

$$n(R) = \int_R^\infty (d_\tau - R) f(d_\tau) d(d_\tau)$$

However, it is analytically hard to compute. To deal with that problem, we introduce the function L which is called the loss function expressed as

$$L(X) = \int_X^\infty (t - X) f(t) dt \text{ where } f \text{ is the density of the normal law } \mathcal{N}(0,1)$$

so that

$$n(R) = \sigma_{d_\tau} L(X)$$

Finally, by defining the average percentage of unused items with respect to the total number of goods we buy, denoting it by $\beta = \frac{n(R)}{Q^*}$ we can find $s.stock$ so that

$$L(X) = \frac{\beta Q^*}{\sigma_{d_\tau}}$$

where β should of course be defined *a priori* depending of the market requirements, of course, the lowest β is, the greatest is the service.

Using this second strategy can be done like so :

   (a) Compute σ_{d_τ}

   (b) Compute $\frac{\beta Q^*}{\sigma_{d_\tau}}$ and use the table to find the corresponding X denoted $\bar{X}$

   (c) Subsitute X by $\bar{X}$ in $s.stock = \bar{d}_\tau + \sigma_{d_\tau} X$

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[3]it is surely linked, for example, during peak demands of a given good, one supplier may have difficulties to satisfy all of his clients, but we cannot consider that a truck getting lost, or breaking down depends on the demand

[4]For any random variable X with density function f, the average value of X is given by $\int_0^\infty x f(x) dx$

Chapter 2

Periodic review

In the previous section, time was supposed to be continuous. In this new chapter however, we will regard time as a discrete variable meaning that we consider fixed size time intervals for our inventory management study. To each of these periods corresponds a certain demand, denoted d_i for period i, and a decision (called "action") that we take in order to satisfy the demand, denoted a_i. We represent this situation with plots similar to figure (2.1) where each box stands for a period of time. The question we have to answer in this chapter is : "What actions do I have to take in order to fulfill the demand minimizing the total cost ?", or similarly : "How many items a_i should I buy in period i to minimize the cost ?"
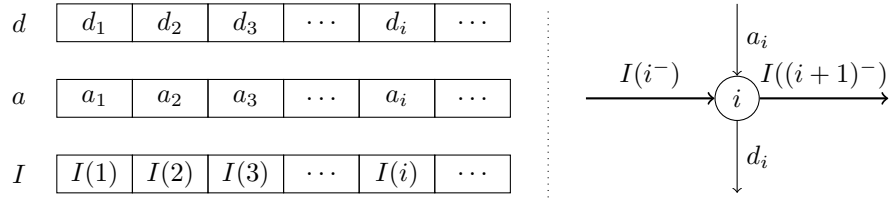

Figure 2.1: A representation of the periodic review model

With this representation, it becomes clear that, at the end of the i-th period, the inventory level, denoted by $I((i+1)^-)$, corresponds to the inventory level we had at the beginning of that period, $I(i^-)$, to which we should add the number of items we have ordered, a_i, minus the demand, d_i, which corresponds to goods which have been sold out. Hence,

$$I((i+1)^-) = I(i^-) + a_i - d_i$$

Thus, by denoting by h the inventory cost and by K the fixed cost per order as we have been doing so far, the total cost can be computed as :

$$J = \sum_{i=1}^{N} \left(K\delta(i) + hI((i+1)^-) \right) \text{ where } \delta(i) = \begin{cases} 1 & \text{if } a_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

Our goal is to minimize this function by choosing relevant a_is. For example, we need to discuss whether it is more profitable to order goods for two periods in a row instead or ordering period per period with respect to the demand. This can be solved by mixed integer linear programming models in an exact way. However, the cost of these methods are not worth it since efficient Heuristics have been developed which are very simple to implement. In this chapter, we will focus on the "Silver-Mill Heuristic".

Even though it appears clear, note that, if the inventory level in period 0 is 0 and if we suppose knowing in

advance the exact demand for each period, then it holds that

$$\sum_{i=0}^{N} a_i \geq \sum_{i=0}^{N} d_i$$

This can easily be demonstrated by recursivity. Let's suppose that $I_0 = 0$. Then, and because $I_i \geq 0, \forall i$ in the deterministic model, $I_1 = a_1 - d_1 \geq 0$ which means that $a_1 \geq d_1$. So the property is true for the first rank. Let's now suppose, that, for a given rank k, we have $\sum^k a_i \geq \sum^k d_i$. Considering I_{k+1}, it holds that $I_{k+1} = I_k + a_{k+1} - d_{k+1}$ with $I_k = \sum^k a_i - \sum^k d_i$ so that in definitive $\sum^{k+1} a_i \geq \sum^{k+1} d_i$.

2.1 The Wagner-Within Theorem

The Wagner-Within Theorem tells us about the shape of the solution to our problem. It stipulates that the optimal solution is either that (1) we buy exactely the demand of multiple time periods or (2) we buy exactely the current period demand, but in no case we would buy a fraction of the demand for one time period and buy the rest in another period. The optimal solution cannot be splitted into periods of time. For instance, the optimal solution cannot be to buy 70% of the forecasted demand of November in September and 30% of that same demand in October, but rather buy all the corresponding demand for November in September or all the corresponding demand for Novemeber in October. We do not split the orders for one time period. So that, considering a_1 for example, we now know that

$$a_1 \in \{d_1, d_1 + d_2, d_1 + d_2 + d_3, \ldots\}$$

In this section we will demonstrate this theorem for the case of two time periods **WLOG**.

Let's consider a time horizon of two periods and, since the demand is supposed to be known in a deterministic way, we can impose that the inventory level at the end of the horizon is zero, $I_2 = 0$. As well, we'll assume that I_0 is zero (no initial inventory level). The inventory level at the end of this time horizon is given by $I_2 = a_1 + a_2 - d_1 - d_2 = 0$ which leads to the equality

$$a_1 + a_2 = d_1 + d_2 \tag{2.1}$$

In the first time period, we at least have to order enough goods to fulfill the demand of the first period, so that $a_1 \geq d_1$ which we'll rather right as $a_1 = d_1 + \epsilon$ where ϵ is a positive number (which in any case should be less than d_2 because it would violate our will to end with an inventory level of zero). From equation (2.1), it holds that $a_2 = d_2 - \epsilon$, and so, at the end of each period we end with :

Inventory level at the end of each periods :

ϵ	0

This allows to compute the total cost like so :

$$J = K + h\epsilon + \begin{cases} K & \text{if } \epsilon = 0 \\ 0 & \text{if } \epsilon = d_2 \\ K & \text{if } \epsilon < d_2 \end{cases} = \begin{cases} 2K + h\epsilon & \text{if } \epsilon < d_2 \\ K + hd_2 & \text{if } \epsilon = d_2 \end{cases}$$

Indeed, we always pay at least one order (which corresponds to the first order in period one) and the inventory cost for the remaining items after the first periods (which is ϵ). In the case where $\epsilon = d_2$, we already have ordered enought products to fulfill both the demand of the first period and the demand of the second period, so we don't have to make another order and we don't pay for ordering nothing. Otherwise, we have to order again, so a new K cost has to be paid. We then have two cases :

- if $\epsilon < d_2$, then clearly, the minimum is reached by choosing $\epsilon = 0$

- if $\epsilon = d_2$, then minimum is $K + hd_2$

What this discussion means, is that, in order to choose a value for ϵ in order to minimize our cost, the only "good" decisions we can make are those of buying once for two periods or buying once at each period but in no case should we buy more in period one and buy again a smaller amount of goods in period two. That's the meaning of the Wagner-Within theorem.

2.2   The Silver & Mill Heuristic

The Silver-Meal heuristic is a very simple algorithm which relies on the Wagner-Within theorem. It often drives the solution near the real solution which in most cases is acceptable. In fact, the algorithm finds a local minimum of the cost function (instead of a global minimum). Simply sumed up, this heuristic considers incrementing periods of time and looks at whether or not it would be a good idea to buy more than what is needed for that specific period of time. We know from the Wagner-Within theorem that if we buy more than needed, then whe should buy exactly the amount of good sufficient to satisfy the demand of the next period (otherwise it's not worth it). The algorithm computes a series of costs making this kind of assumptions until a local minimum is reached. Here is how it works : let $c(i)$ be the cost we would pay if, starting from the first period, we were to buy as many products as needed to statisfy up to the i-th period's demand. Clearly, the cost $c(1)$ is simply K since we only make one order and don't pay for inventory since all our order is consumed by the demand in the first period ($a_1 = d_1$). For the second period, the cost $c(2)$ is now the fixed price K, since we order once for two periods, to which we have to add the inventory cost we pay for the remaining inventory level after period one which corresponds exactly to hd_2. In order to compare $c(1)$ and $c(2)$, we'll focus on the *average* cost that we pay per period of time instead of the absolute value. It holds then that $c(2) = \frac{K+hd_2}{2}$. Similarly, we can compute $c(3)$ as $c(3) = \frac{K+h(d_2+d_3)+hd_3}{3} = \frac{K+hd_2+2hd_3}{3}$ since we order once for the three subsequent periods of time and that we have to pay for inventory in period one (whose inventory level is then $d_2 + d_3$) and in period two (whose inventory level is then d_3). Continuing like so, and searching for a local minimum, we get the Silver-Mill heuristic for choosing our actions.

The general formula (which can be recursively demonstrated) for computing the coefficients $c(i)$s is given by

$$c(i) = \frac{K + hd_2 + 2hd_3 + \ldots + (i-1)d_i}{i}$$

Indeed, we assume paying once in period one, so we pay the order price K just once, then we have to deal with inventory costs. The quantity d_k will remain in the inventory untill period k is reached. So the associated inventory cost is given by $(k-1)hd_k$ since we pay for having it in store in every preceding periods of time.

The figure (2.2) shows how the heuristic works. The algorithm continues to compute total costs (incrementing the number of periods considered) until a local minimum is found. In this example, our action will be to order in the first period for three periods of time since $c(3)$ is a local minimum of our function J. Note that, if we had continued to search for lower values we may have eventually found that (in this case), $c(5)$ was more advantageous from an economical point of view and we would have better done to buy all the products for 5 periods instead of four. But in general, this approach gives a really good approximation of the optimal value for the problem and, with respect to the simplicity of the algorithm, it often doesn't worth it to use more advanced and complex models.

2.3   Analysis of the method

In this last section of this chapter, we would like to discuss on the accuracy, or rather plausibility, of this method. In particular, we will have a look at what happens the demand for each period of time is homogeneous. Let d be
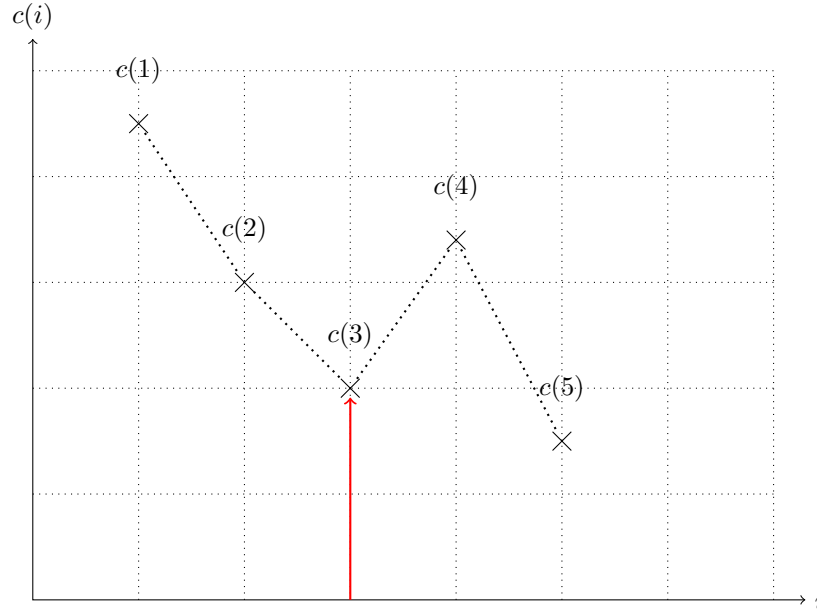
Figure 2.2: Silver-Mill heuristic example

that demand. Using the previously established formula, it holds that :

$$
\begin{aligned}
c(n) &= \frac{K + hd + 2hd + \ldots + (n-1)hd}{n} \\
&= \frac{K + \sum_{i=1}^{n-1} ihd}{n} \\
&= \frac{K + \frac{n(n-1)}{2}}{n} \\
&= \frac{K}{n} + \frac{nhd}{2} - \frac{hd}{2}
\end{aligned}
$$

and let us relax our problem considering the function $c(x)$ where x is no longer discrete but continuous. Derivating this function, we get

$$
\begin{cases}
\frac{dc}{dx} &= -\frac{K}{n^2} + \frac{hd}{2} \\
\frac{d^2c}{dx^2} &= \frac{K}{n^3} > 0, \forall x \in \mathbb{R}
\end{cases}
$$

The second derivative being greater than zero for any x means that the function c is convex. Knowing that, it is legit to compute the minimum of this function by truncating the solution of $\nabla c = 0$ to find the actual minimum of the non-relaxed problem (where $x \in \mathbb{N}$). Solving this equation we get :

$$
\frac{dc}{dx} = 0 \Leftrightarrow x^* = \sqrt{\frac{2K}{hd}}
$$

And since $Q = dn^*$, it holds that

$$
Q = dx^* = \sqrt{\frac{2kd}{h}}
$$

which is the exact same formula which we found in the first part of this course in the deterministic model.

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Part II

Bill of materials

Chapter 3

Model without set-up times for production

Chapter 4

Model with set-up time considerations

List of Figures