Production Scheduling of a Multi-site Manufacturing Facility

06−665 Process Systems Modeling, Spring 2018

Team 04

Kedar Dabhadkar (kdabhadk), Geethanzali Kamalanathan (gkamalan), Apurva Pradhan (aapradha), Dong Qin (dqin)

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Abstract

Manufacturing any product or service involves connectivity and cooperation between many independent sites. Usually, the total outcome of the network is merely the sum of the outcomes from these individual sites, and any disturbance in production propagates both downstream and upstream. Usually, all of these sites operate under a single organization but are fiscally and operationally independent. Therefore, comparing results obtained by scheduling using global optimization strategy and site-by-site local optimization would give us valuable insights regarding the disturbance propagation.

In this paper, we propose a model that can be used to optimize an organization's manufacturing processes through a lot sizing and scheduling problem (LSSP) in a multi-site manufacturing system. The proposed model is applied to a case study involving a multi-site manufacturing system of braking equipment for the automotive industry. A schedule for this process, assuming an integrated approach (global strategy) as well as one assuming a site-by-site approach, is created. This optimization problem includes multi-product demand and cost constraints (fixed and inventory costs). The LSSP is then formulated into a mixed integer problem and the optimization problem is solved in GAMS using a CPLEX (MILP) solver. Through this model, we demonstrate that optimizing a schedule considering a global optimization encompassing all sites in a manufacturing process results in a lower total cost than optimizing each site individually on a local level.

1) Introduction

Modern industrial organizations, such as the automotive industry, recommend synchronization of information flowing into the supply chain. They introduce structural changes to obtain an optimum between customer satisfaction and production cost (Haag and Vroom, 1996; Proff, 2000). A common method employed by the automotive industry is outsourcing production to other parties or sites. In outsourcing, the main contractors are the suppliers involved during the production and engineering phases. A study of the supply chain of a European car manufacturer (Svensson, 2000) shows that the disturbances appearing at the subcontractor level propagate downstream and upstream in the supply chain causing increases in production costs. To overcome the vulnerabilities occurring in the supply chain, a thorough integration and cooperation among car manufacturers and subcontractors are necessary (Frolich and Westbrook, 2001).

This study focuses on demonstrating the effect of demand variability on production costs by considering both a local site-by-site optimization and a global optimization strategy. An industrial case study of a multi-site manufacturing system producing braking equipment components for the automotive industry is used to demonstrate this effect. The network is in the form of a linear tree with three sites as shown in Figure 1.

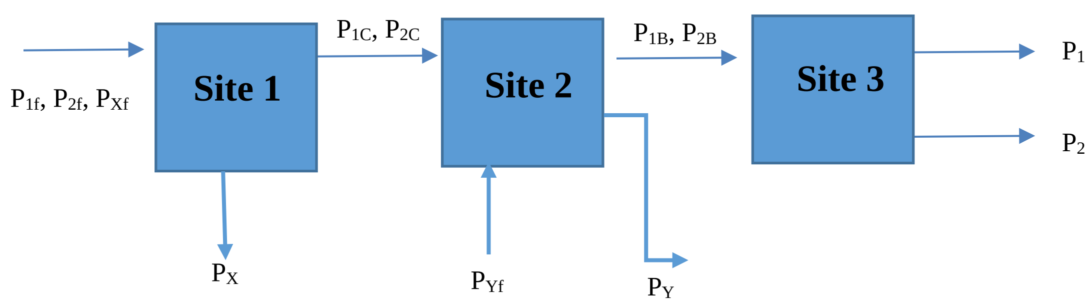


Figure 1: Linear tree network with three sites

P_1, P_2, and P_3 are the final products which are sold to customers. P_{1B} and P_{2B} are the products from site 2 which are processed further in site 3. P_Y is the byproduct of site 2 which is sold to a different set of customers. Similarly, products P_{1C}, P_{2C}, and P_X are products from site 1 as shown. Additionally, P_{Yf} is used as an additional raw material to site 2. Site 1 processes raw materials P_{1f}, P_{2f} and P_{Xf} obtained from an outside supplier. The objective is to minimize the total cost of the production process by creating a optimal production schedule. The constraints in this process arise out of the bottlenecks created in each of these sites. Gopalakrishnan *et al*. (1995) discuss the solution strategy that is needed to tackle such a problem. All required data are obtained from Gnoni *et al*. (2003).

The scheduling problem is solved as an MIP using the formulation and solution strategy given by Aucamp (1987), Gopalakrishnan *et al*. (1995) and Gopalakrishnan (2000). The objective function to be minimized is written as the sum of fixed and inventory costs for each product at each site. We assume that only a single production process can take place at any site at a given time. GAMS (GAMS Development Corporation, 2013) is the software used for this MIP optimization.

2) Literature Survey

Gopalakrishnan, Miller and Schmidt (1995) addressed single-level capacitated lot sizing problem (CLSP) with setup carryover. Multiple products are produced in a given time period on a given facility. This includes a changeover-based setup time and a setup cost. The paper considers the instances where developing a feasible schedule becomes possible only if setups are carried over from one period to another. The model is then extended to include multiple machines and tool requirements. The proposed model is tested on a case study of a paper products manufacturing company. This work provided insights on formulating the constraints for the concerned case study on a multiple site manufacturing system involving multiple products by considering both planning and lot sizing decisions.

Gopalakrishnan (2000) further extended his previous work and proposed a modified framework to model set-up carryovers in the capacitated lot sizing problem. The former work focused on modelling set-up carryovers for the constant set-up time scenario. This work further helped in understanding the incorporation of product dependent set-up times and costs. However, in relation with the peculiarity of the case study investigated, both the work and the case study in question neglect the sequence dependency of the setup times of products, period by period.

This is accounted in Smith Daniels and Ritzman (1988) study that presented a mixed integer linear programming model for scheduling production in process industries. It embodies capacitated lot sizing, flowshop scheduling, and sequencing with sequence-dependent setup times. The model is then used to schedule production in the food processing industry.

The works listed above formulate the objective function, defined as the sum of setup, inventory, and fixed costs for various case studies, and discuss methods to minimize the objective function. This provides a framework to help understand the constraints to be utilized for the problem at hand and also to understand the results obtained. Using details from previous literature, this project goes further by considering different scenarios of the LSSP by pursuing a local optimization strategy (LOS) and a global optimization strategy (GOS), and comparing the results.

3) Mathematical Models and Methods

The objective of this project is to optimize the schedule for a break manufacturing facility that consists of three different stations or sites. At site 1, P_{1f}, P_{2f}, or P_{xf} can be converted into P_{1c}, P_{2c}, or P_x respectively. However, only one process can take place at one time and each process takes $\tau(P_{1c})$, $\tau(P_{2c})$, and $\tau(P_x)$ days per unit respectively. Similarly, at site 2, P_{1c}, P_{2c}, or P_{yf} can be converted into P_{1b}, P_{2b}, or P_y respectively and each process takes $\tau(P_{1b})$, $\tau(P_{2b})$, and $\tau(P_y)$ days per unit respectively. Finally, at site 3, P_{1b} can be converted to P_1, and P_{2b} can be converted into either P_2 or P_3. Each process takes $\tau(P_1)$, $\tau(P_2)$, and $\tau(P_3)$ days per unit.

In order to simplify the equations associated with this scheduling optimization problem, two sets were created. One set, *i*, was used to represent each intermediate and final product in the process. Another set, *t*, was used to represent each discrete day in our process over the course of a year.

$$i = [P_{1f}, P_{1c}, P_{1b}, P_1, P_{2f}, P_{2c}, P_{2b}, P_2, P_3, P_{xf}, P_x, P_{yf}, P_y] \tag{1}$$

$$\mathrm{t} = [1, 2, 3, \ldots, 365, 366] \tag{2}$$

For the purpose of this project, we have assumed that only one process can take place per site per day. Furthermore, we assumed that each site is only actively manufacturing products for 8 hours per day. The remaining time is left for switchover and maintenance. Using the sets defined above, it is possible to define residence time (τ) in days per unit, fixed cost (C_{fix}) in € per day, inventory cost (C_{inv}) in € per unit per day, and monthly demand (F_{dem}) in units per day. The fixed cost is based on the combination of cost needed to operate the machinery in a particular time and the set-up cost to start up the machinery. The residence times and monthly demand are based on the times and demands listed by Gnoni *et al* (2003). We assume that the products that are demanded are collected at the end of each month.

$$\tau(i) = [0, 0.0021875, 0.0025, 0.00417, 0, 0.0021875, 0.0025, 0.0046, 0.005, 0, 0.002263, 0, 0.0025] \quad (3)$$

$$C_{fix}(i) = [0, 462, 569, 599, 0, 462, 569, 599, 599, 0, 462, 0, 569] \quad (4)$$

$$C_{inv}(i) = [0, 0.10625, 0.03875, 0.01158, 0, 0.1265, 0.03825, 0.0115, 0.02792, 0, 0.1076, 0, 0.0419] \quad (5)$$

$$F_{dem}(i, 32) = [0, 0, 0, 20, 0, 0, 0, 0, 326, 0, 183, 0, 0] \quad (6)$$

$$F_{dem}(i, 60) = [0, 0, 0, 921, 0, 0, 0, 20, 40, 0, 1100, 0, 1520] \quad (7)$$

$$F_{dem}(i, 91) = [0, 0, 0, 986, 0, 0, 0, 60, 140, 0, 1205, 0, 1500] \quad (8)$$

$$F_{dem}(i, 121) = [0, 0, 0, 840, 0, 0, 0, 20, 104, 0, 1321, 0, 896] \quad (9)$$

$$F_{dem}(i, 152) = [0, 0, 0, 956, 0, 0, 0, 60, 146, 0, 636, 0, 714] \quad (10)$$

$$F_{dem}(i, 182) = [0, 0, 0, 244, 0, 0, 0, 0, 62, 0, 1025, 0, 975] \quad (11)$$

$$F_{dem}(i, 213) = [0, 0, 0, 500, 0, 0, 0, 80, 284, 0, 1102, 0, 1020] \quad (12)$$

$$F_{dem}(i, 244) = [0, 0, 0, 150, 0, 0, 0, 60, 116, 0, 0, 0, 0] \quad (13)$$

$$F_{dem}(i, 274) = [0, 0, 0, 720, 0, 0, 0, 102, 84, 0, 1278, 0, 1405] \quad (14)$$

$$F_{dem}(i, 305) = [0, 0, 0, 620, 0, 0, 0, 84, 120, 0, 1374, 0, 500] \quad (15)$$

$$F_{dem}(i, 335) = [0, 0, 0, 256, 0, 0, 0, 0, 0, 0, 0, 0, 0] \quad (16)$$

$$F_{dem}(i, 366) = [0, 0, 0, 120, 0, 0, 0, 0, 56, 0, 0, 0, 536] \quad (17)$$

$$F_{dem}(i, t) = 0 \quad \forall \ t \notin [32, 60, 91, 121, 152, 182, 213, 244, 274, 305, 335, 366] \quad (18)$$

Next, we need to define our binary variables in order to account for the fact that only one manufacturing process can take place at each site on any given day. Each site will have three binary variables that correspond to each of the three processes that can take place at each site. The sum of the three binary variables at each site must be less than or equal to one on any given day. This hard constraint can only be relaxed if we use continuous instead of discretized time.

$$Y(P_{1c},t) + Y(P_{2c},t) + Y(P_x,t) \leq 1 \tag{19}$$

$$Y(P_{1b},t) + Y(P_{2b},t) + Y\left(P_y,t\right) \leq 1 \tag{20}$$

$$Y(P_1,t) + Y(P_2,t) + Y(P_3,t) \leq 1 \tag{21}$$

Next, we need to create a system of equations that accounts for the amount of each intermediate and final product that is being produced on any particular day. We have defined a variable *F(i,t)* that accounts for the number of units of *i* being consumed on any particular day *t*. In the following equations, Δt is equal to the proportion of each day during which the production line is active. We have set Δt equal to 0.333 as the production lines are assumed to be active for only 8 hours per day. We need to have a separate expression specifically for intermediate P_{2b} as it can be converted to either P_2 or P_3.

$$F(i,t) = Y(i+1,t) * \left[\frac{\Delta t}{\tau(i+1)}\right] \quad \forall \quad i \notin \left[P_1, P_{2b}, P_2, P_3, P_x, P_y\right] \tag{22}$$

$$F(P_{2b},t) = Y(P_2,t) * \left[\frac{\Delta t}{\tau(P_2)}\right] + \; Y(P_3,t) * \left[\frac{\Delta t}{\tau(P_3)}\right] \tag{23}$$

$$F(i,t) = 0 \quad \forall \quad i \in \left[P_1, P_2, P_3, P_x, P_y\right] \tag{24}$$

Finally, it is now possible to determine how much of each intermediate and final product is being accumulated in inventory. For each product, the accumulation is equal to the amount of the product being generated minus the amount of the product being consumed minus the amount of the product being sold at time *t*.

$$I(i,t) = I(i,t-1) + F(i-1,t) - F(i,t) - F_{dem}(i,t) \quad \forall \quad i \notin \left[P_{1\mathrm{f}}, P_{2f}, P_{3\mathrm{f}}, P_{xf}, P_{yf}\right], t \in t > 1 \tag{25}$$

$$I(i,t) = \; \infty \quad \forall \quad i \notin \left[P_{1\mathrm{f}}, P_{2f}, P_{3\mathrm{f}}, P_{xf}, P_{yf}\right] \tag{26}$$

We also need to provide initial conditions for the amount of each intermediate and final product accumulations at time *t=0*.

$$I(i,0) = 0 \qquad \forall \quad i \notin \left[P_{1\mathrm{f}}, P_{2f}, P_{3\mathrm{f}}, P_{xf}, P_{yf}\right] \tag{27}$$

Lastly, we need to have a continuity equation that accounts for the fact that the amount of a specific product being consumed by the next step on any particular day is not greater than the amount of that product in inventory by the end of the previous day. This is a hard constraint that is based on the assumption that an intermediate product cannot be used by the next site on the same day it is produced. If we relax this assumption, then the inequality could be relaxed as well.

$$I(i,t-1) \geq F(i,t) + F_{dem}(i,t) \tag{28}$$

Now that we know how much of each product is being stored in inventory on any given day, it is possible to determine the inventory and fixed cost incurred on any given day. The total variable cost is based on the product of the inventory cost and the amount of inventory for a given product. The total fixed cost is the product of the fixed cost of a product and the binary variable that corresponds to whether that product was being produced on a given day.

$$cost(t) = \sum_{i=1}^{11} C_{inv}(i) * I(i,t) + C_{fix}(i) * Y(i,t) \tag{29}$$

For designing the ideal schedule, we must minimize the total cost incurred throughout the year. Using the relations defining each of the variables given above, the optimization problem would look like the following. In total, we would have 15,007 variables and 12,077 equations, resulting in 2,930 degrees of freedom for this optimization problem.

$$\boldsymbol{Minimize} \qquad Tcost = \sum_{t=1}^{366} \sum_{i=1}^{11} C_{inv}(i) * I(i,t) + C_{fix}(i) * Y(i,t) \tag{30}$$

$$\boldsymbol{s.t} \qquad I(i,t-1) \geq F(i,t) + F_{dem}(i,t) \tag{31}$$

$$Y(P_{1c},t) + Y(P_{2c},t) + Y(P_x,t) \leq 1 \tag{32}$$

$$Y(P_{1b}, t) + Y(P_{2b}, t) + Y\left(P_y, t\right) \le 1 \tag{33}$$

$$Y(P_1, t) + Y(P_2, t) + Y(P_3, t) \le 1 \tag{34}$$

Two additional scenarios were also tested for the purpose of this project. First, the system was optimized under the assumption that instead of a monthly delivery schedule, there was a yearly delivery schedule with the same amount of demand for each product. Second, a local optimization was completed at each individual site to see how total cost compares between global optimization and local optimization.

For the first case in which the total demand of each product was assumed to have a yearly instead of monthly demand, the only change in our system was based on the value of $F_{dem}(i,t)$. The rest of the equations remained unchanged.

$$F_{dem}(i, 366) = [0, 0, 0, 6333, 0, 0, 0, 486, 1478, 0, 9224, 0, 9161] \tag{35}$$

$$F_{dem}(i, t) = 0 \quad \forall \ t \notin [366] \tag{36}$$

For the second case in which a local optimization was done, the problem was split up into three discrete optimization problems. Starting at site 3, the production of P_1, P_2, and P_3 was optimized based on monthly demand assuming an unrestricted supply of P_{1b} and P_{1c}. Based on the results of the optimization, the demand of P_{1b} and P_{2b}, and the corresponding deadlines were determined. Next, site 2 was optimized based on these new demands and deadlines for the products P_{1b} and P_{2b} along with the monthly demand of P_y assuming an unrestricted supply of P_{1c}, P_{2c},and P_{yf}. Optimizing the schedule at site 2 will reveal the demands and deadlines for P_{1c} and P_{2c}. Using these demands and deadlines along with the monthly demand of P_x, the schedule for site 1 can be independently optimized. In this localized optimization, the continuity equations will no longer be relevant and the cost will primarily be based on the varying inventory costs for each intermediate product.

3.1) Gams Solver Information

CPLEX was used to solve this mixed integer linear optimization problem in GAMS (GAMS Development Corporation, 2013). CPLEX specializes in solving large problems efficiently. As mixed integer problems often require more computational power than similarly sized linear problems, the ability to solve larger problems efficiently is vital. CPLEX solves mixed integer problems by converting them into a series of linear sub problems and then using a branch and cut algorithm to solve them. Alternative MIP solvers such as BARON, CBC, and LINDO were tested, but could not optimize the solution to the same degree as CPLEX or did not find a feasible solution. For this reason, CPLEX is believed to be the best solver for this optimization problem. Table 1 shows the computation time and the optimized production cost generated by the different solvers that were tested.

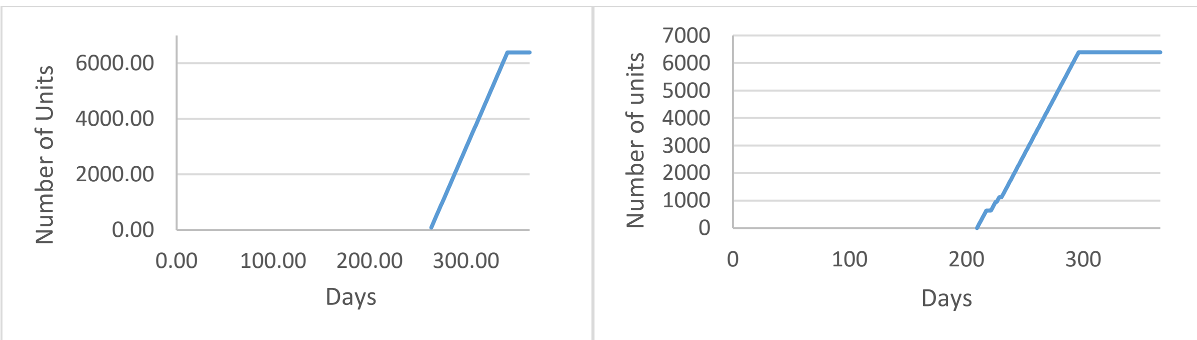
Table 1: GAMS Solver Statistics

Solvers	Objective Function Value [€]	Execution time [seconds]
CPLEX	221726.2	0.03
BARON	222749	16.44
CBC	235836.5	1001
LINDO	Not Converged	-

4) Results and Discussion

Five scheduling simulations were carried out in this study. They include a monthly global optimization strategy (MGOS), a yearly global optimization strategy (YGOS), and one local optimization strategy (LOS) for each of the three sites. The information obtained from each of these simulations is threefold, one, the binary variables (*Y*) which indicate if a given process happened on a given day, two, the amount of products (*P*) produced from raw materials on that day, and three, the status of inventory (*I*) of the products or raw materials at a site on that day. It can be seen that the amount of information given by *I* is more than *P* which is more than *Y*. The status of the inventory of a given product at a site can be used to determine the amount of products produced on any preceding day (*P*) which tells if a process was run on that day (*Y*). For this reason, all the scheduling results have been presented in terms of the inventory.

In GOS, as every site coordinates with every other site, the required raw materials are purchased only when required. This avoids unnecessary inventory cost. As a result, the entire manufacturing system produces products just in time for delivery. Thus, the peaks in inventory for all products lie towards the end of the delivery period. As seen in figure 2, the inventory cost drives production towards the delivery deadline. However, since only one product can be produced on any given day, not all peaks are at the end of time periods. In other words, a site first produces the product with the least inventory cost before producing any other product.



(a) (b)

Figure 2: Comparison of inventory of P_3 at site 3 obtained by (a) LOS strategy and (b) yearly GOS strategy

Approach	Total manufacture cost
1. LOS	€ 311,834/-
2. Yearly GOS	€ 277,160/-
3. Monthly GOS	€ 221,730/-

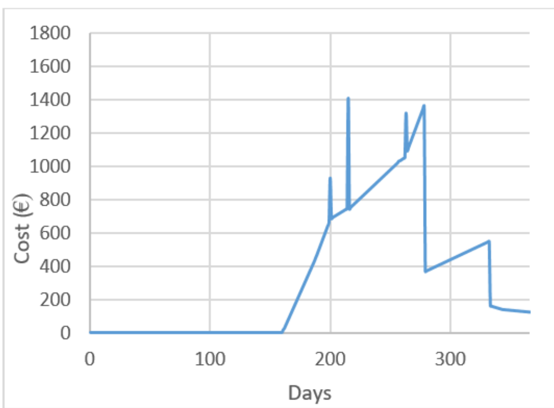
Table 2: The monthly GOS approach shows nearly 29% decrease in the manufacture cost over LOS

As opposed to this, the LOS assumes that there is no coordination amongst sites. Such a system operates on upstream flow of information. Site 3 optimizes its own operations and passes back its demands to site 2. Site 2 optimizes its operations depending on the deadline and requirements given by

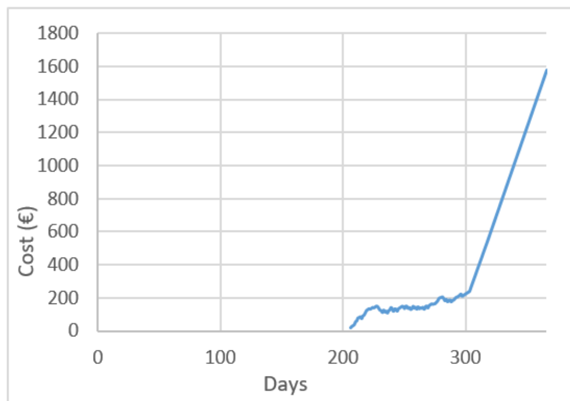
Figure 3: Gantt charts for the schedules of (a) site 1, (b) site 2, and (3) site 3

site 3 and passes back its demands to site 1. It is also important to note that the inventory cost for storing feed materials is almost three times of that for storing the final products at every site. If given a finite amount of feed material on any day, a site would prefer to store it only after processing it into products. To account for this, the inventory cost due to the added feed material inventory is not included in the objective function for the site at which it is being processed. The Gantt chart using the LOS strategy for all three sites (Figure 3) shows how all scheduling strategies minimize cost by reducing inventory and pushing production as close to the delivery deadline as possible.

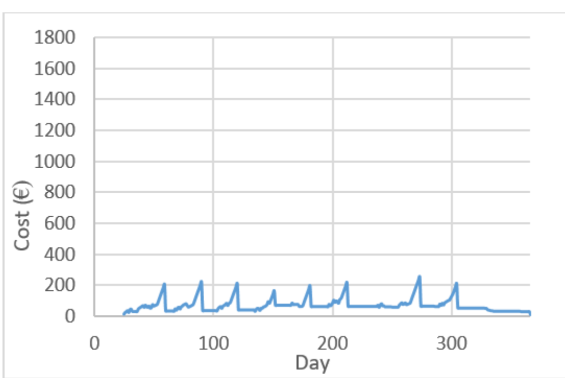
The total manufacturing cost of the LOS was obtained by summing costs incurred by the three individual sites. This was compared to the total manufacturing cost obtained by yearly GOS. An additional simulation that considered demand and delivery on a monthly basis (monthly GOS) was also run. In this simulation, the deliveries are made on a monthly basis, rather than yearly. The most important benefit of implementing this approach is that it saves inventory cost of produced materials. Figure 4 shows the daily inventory costs for the three approaches. The monthly GOS has lower inventory costs due to distributed demand. It was found that the monthly GOS approach is the cheapest of all approaches, followed by yearly GOS, followed by LOS. The results showing the total cost in each of these cases are shown in Table 2. Additionally, Figure 5 shows that the component governing this decrease in total cost is the inventory cost. According to the simulations, shifting production strategy to monthly GOS from LOS leads to a 28.89% savings in the manufacturing cost.



(a)



(b)



(c)

Figure 4: Daily inventory cost for (a) LOS, (b) Yearly GOS, and, (c) Monthly GOS

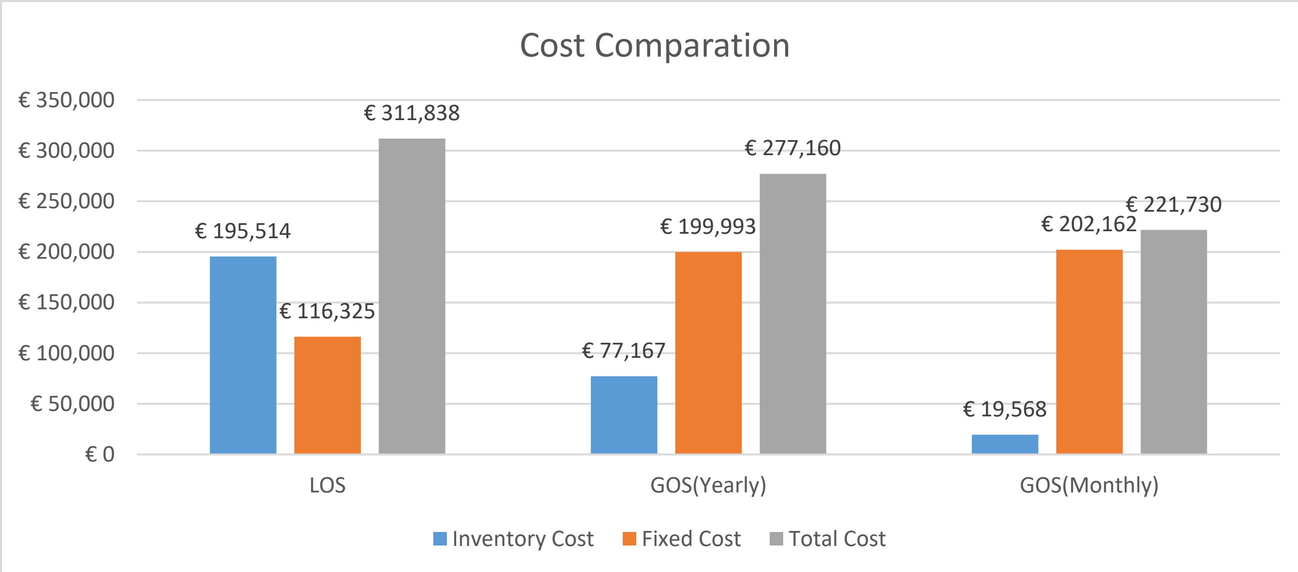


Figure 5: Comparison of inventory and fixed costs in LOS, yearly GOS, and monthly GOS

4.1) Limitations

This study discretizes time to the scale of one day. This level of discretization results in more intermediate and final products produced than necessary and also results in excess inventory cost. The demand is considered for one year in the yearly global optimization strategy. On the other hand, the monthly optimization strategy discretizes demand to one month. A significant improvement in the total manufacturing cost is seen after discretization. From this observation, further discretization to smaller time scales and eventually considering time to be continuous might result in even lower manufacture costs. Paying penalties for delayed deliveries, which is not considered, might also help achieve lower manufacturing costs by delaying production and reducing inventory cost. This model also does not take into account the costs incurred when switching operations from one process to another.

5) Conclusion and Future Work

5.1) Conclusion

In this project, we optimized a lot sizing and scheduling problem based on a case study. The model includes three different sites and each site can produce three different products. We ran the model on a daily basis considering yearly and monthly demands, and we subsequently determined an optimal schedule for each case of monthly and yearly demands. Furthermore, we also considered cases of a global optimization strategy and a local optimization strategy. We found that a global optimization strategy reduced total manufacturing costs by over 28%, and having a monthly demand instead of a yearly demand further reduced costs due to reduced costs for inventory and storage.

5.2) Future Work

In order to make our model more accurate, we hope to make it more continuous in time instead of discretized by day. This can be done by allowing the product being manufactured at any site to be changed at any time instead of just at the end of the day. This will prevent the production of more product than needed and allow for a better overall optimization.

Completing a continuous model will also allow us to account for changeover times between production processes. Currently, we are assuming that the setup and changeover in the product being produced at any site takes place overnight. We are given information on the specific time it takes to change from manufacturing one product to any other product at a given site. Incorporating these specific change-over times will make our model more accurate and potentially lead to a better cost minimization.

Our current model focuses on only three sites, but does not consider the cost or manufacturing processes of our feed (P_{1f}, P_{2f}, P_{3f}, P_{yf}, and P_{xf}). Furthermore, we do not have any information on how much revenue our products are making. By considering these outside costs and revenues, it would be possible to maximize profit instead of minimizing costs as we are doing now. This would be a better variable to optimize and will allow the company in our case study to increase their bottom line instead of just reducing costs.

Finally, this model can easily be generalized to be used in any multi-site manufacturing process. Simply by changing the number of sites, the supply, and the demand, it is possible to use the same expressions generated in this project to processes ranging from pizza production to petrochemical refining.

Nomenclature

Sets

$i = [P_{1f}, P_{1c}, P_{1b}, P_1, P_{2f}, P_{2c}, P_{2b}, P_2, P_3, P_{xf}, P_x, P_{yf}, P_y]$ Each intermediate and final product produced

$t = [1, 2, 3, \ldots, 365, 366]$ Each day of the year

Parameters

$\tau(i)$ Time it takes to produce each unit days/unit

$C_{fix}(i)$ Fixed cost for producing units of *i* €/day

$C_{inv}(i)$ Inventory cost to store units of *i* €/(unit*day)

$F_{dem}(i,t)$ The demand of product *i* on day *t* units/day

Δt The fraction of the day during which production is active

Binary Variables

$Y(i,t)$ 1 if product *i* is being produced on day *t*, 0 otherwise

Continuous Variables

$F(i,t)$ The number of units of *i* being consumed on day *t* units/day

$I(i,t)$ The units of *i* that have been accumulated by the end of day *t* units

$cost(t)$ The total fixed and inventory cost on day *t* €/day

Integer Variables

Tcost The total cost of production throughout the year €

References

Aucamp, D. C. "A lot-sizing policy for production planning with applications in MRP." International journal of production research 25.8 (1987): 1099-1108.

GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 24.2.1. Washington, DC, USA, 2013.

Gopalakrishnan, Mohan. "A modified framework for modelling set-up carryover in the capacitated lotsizing problem." *International Journal of Production Research* 38.14 (2000): 3421-3424.

Gopalakrishnan, M., D. M. Miller, and C. P. Schmidt. "A framework for modelling setup carryover in the capacitated lot sizing problem." *International Journal of Production Research* 33.7 (1995):1973-1988.

Gnoni, M. G., R.G.Mossaa,G.MummoloaA and D. Levab. "Production planning of a multi-site manufacturing system by hybrid modelling: A case study from the automotive industry." *International Journal of production economics* 85.2(2003):251-262.

Svensson, G. "A conceptual framework for the analysis of vulnerability in supply chains." International Journal of Physical Distribution & Logistics Management 30.9 (2000), 731–749.