

Chapter 5

Operations scheduling and sequencing

In this chapter¹ the previously under-researched problem of scheduling a single stage, capacitated, hybrid make-to-order (MTO) and make-to-stock (MTS) production system with stochastic demand is examined. In the pure MTS situation, cyclical production planning and Economic Lot Scheduling Problem (ELSP) procedures are widely used. For the hybrid MTO/MTS production situation, however, no mature theory exists. We build on the ELSP literature and make some modifications to incorporate MTO products. At the tactical level, *target cycles* (kept long enough to trade-off changeover and inventory costs) are calculated while at the operational level, the general idea is to try and follow these *target cycles*, and make adjustments to them in order to a) avoid stock-outs for MTS products and, b) have short lead-time for MTO products while keeping the overall costs as low as possible. Through an extensive simulation study, we evaluate various *run-out time scheduling and sequencing heuristics* and provide a more complete understanding and managerial insights in the case of hybrid MTO/MTS environment with stochastic demand. It is clear that the methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO/MTS situation.

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5.1 Introduction

The problem of scheduling the production of several products with stochastic demand on a single facility with the objective of reducing the sum of holding costs and setup costs in the long run has been studied in the literature under the name of SELSP– Stochastic Economic Lot Scheduling Problem. The solution to this problem is known to be quite difficult. It is well known that even in the absence of stochastic demand and setup costs this problem is NP hard (Hsu 1983). This is the reason for the use of heuristic procedures. Recently, some research papers are published on SELSP. Sox et al. (1999) present a detailed review of the SELSP approaches.

In many industries, especially in the food processing industries, the product variety is very large and contains a mix of make-to-order (MTO) and make-to-stock (MTS) products (see Soman et al. 2004a). This adds another dimension to SELSP because the production planning focus for the MTO products is different than the one for the MTS products. For MTS products anticipating the demand (forecasting), planning to meet the demand, and achieving high fill rates takes the center stage whereas for MTO products it is the order execution. The performance measures are also order focussed, e.g. average lead-time and average order lateness/tardiness and the competitive priority is shorter delivery lead-time. Although such a MTO-MTS combination with stochastic demand is very common in practice, limited research has been done and reported so far.

One of the first studies on combined MTO-MTS production system is credited to Williams (1984). He provides the way of estimating the waiting time for the availability of the capacity for the individual products using approximation to M/G/m queue, which aids in choosing the batch sizes for MTS and to determine the probability with which the orders for MTO products satisfy the quoted lead-time. Rajagopalan (2002) addresses a similar problem. He provides a heuristic procedure to solve a non-linear, integer programming formulation of the problem that determines the MTO/MTS partition and the batch sizes for the MTS items. He, unlike Williams (1984), allows low demand items to follow the MTS strategy.

Federgruen and Katalan (1994, 1999) address a variety of strategic questions– the number and types of products that should be manufactured to stock or to order, the effects of adding low volume specialized items to a given product line on the stock system. They present a class of cyclic base stock policies for which a variety of cost and performance measures can be evaluated by the analytical

methods suggested for the polling model. They develop cost curves for different priority rules under different circumstances, which can be used to calculate a marginal break-even price at additional utilization due to addition of MTO items.

Williams makes the assumption that lower demand items are MTO and higher demand items are MTS. The primary focus of Rajagopalan is to choose the MTO or MTS strategy for each of the items whereas Federgruen & Katalan focus on choosing the proper “interruption” discipline within the cyclic pattern. For an elaborate literature review of combined MTO-MTS situations, see chapter 2 or [Soman et al. \(2004a\)](#). The above mentioned papers provide us with insights on deciding the batch sizes for MTS items but there are certain operational issues that firms need to answer on a regular basis. The firms need to define the scheduling and sequencing rules for a variety of situations that may arise in answering the basic questions– which product to produce next, when to produce, and how much to produce?

In this chapter, we address these operational issues in MTO/MTS production situations in order to fill the gap that exists in the literature. We examine the problem of scheduling and sequencing in hybrid MTO/MTS food processing environment and report on the development of a production and inventory control policy. The main question is whether the proven dynamic scheduling methods for pure MTS situation are also suitable for the combined MTO/MTS situation? Since MTO products do not have any finished goods inventory (by definition), we explore a simple policy of giving priority to them when their demand occurs to achieve a good lead-time performance. Simulation analysis is employed to test this idea and its impact on regular MTS production and the choice of the heuristic under different environmental conditions. A production system is considered as single equipment, which is characterized by limited capacity, and stochastic stationary demand.

We build on the ELSP literature and the various dynamic sequencing methods for the pure MTS situation. The ELSP solution procedures of [Doll and Whybark \(1973\)](#) and [Haessler \(1979\)](#) are used to set *target cycle* and *target lot sizes* whereas at the operational level the dynamic sequencing methods viz. Economic Manufacturing Quantity (EMQ), [Fransoo \(1993\)](#), [Vergin and Lee \(1978\)](#), and Gascon ([Leachman and Gascon 1988](#)) vary both the production sequence and lot sizes to accommodate the demand variation. [Gascon et al. \(1994\)](#) compare these methods (elaborated in section 5.3) for a particular production data set under

different demand environments and report that Vergin and Lee, and Gascon heuristics perform better in all the situations they test. Soman et al. (2004c) compare these heuristics again for a variety of problem data sets. In addition to the conventional cost based performance measure they also include line item fill rate, cycle time stability, inventory levels, number of setups incurred, to gain more insight into the working of these methods. The effect of inventory costs, setup costs, utilization is analyzed through a simulation study. They conclude that the cost based performance measures are deceptive. Based on operational performance criteria, they provide managerial insights and guidelines on which method to use and when. In this chapter, we move further and investigate the working of these methods in the presence of both MTS and MTO products.

The organization of the chapter is as follows. In the next section, we state a general model and the assumptions of the hybrid MTO/MTS production scheduling problem in a food production system. Section 5.3, presents various scheduling approaches, which can be used in hybrid MTO/MTS production situations. Sections 5.4 and 5.5 present a simulation study and its results to compare various approaches to the lot-scheduling problem in the context of hybrid MTO/MTS production under different utilization levels. Finally, conclusions and suggestions for future research are provided in section 5.6.

5.2 Problem description

We consider a problem of scheduling a single facility with limited capacity and with multiple MTO and MTS products, each with random demand. The objective is to a) avoid stock-outs for MTS products and, b) have short lead-time for MTO products while keeping the overall costs as low as possible. We make the following assumptions in this chapter–

- Production rate for item i is deterministic and constant and is given by p_i
- Only one product can be produced at a time
- Production setup times c_i and setup costs U_i are independent of the production sequence
- Inventory carrying costs are proportional to the inventory levels
- MTS demand, when out of stock, is lost and the lost sales costs are proportional to the number of units lost and cost per unit item
- Product demands are stochastic (with normal distribution), but stationary (mean d_i)

- Total amount of demand for MTO items is stationary over a period of time but individual MTO demands (normal distribution) and timings (negative exponential interarrival) are not known
- MTO orders have priority over MTS production
- Preemption is not allowed
- Production capacity is sufficient to meet the demands

We define MTO products simply as the products for which no inventory is held in the stocks. The typical examples are products with highly irregular demand, client-specific products, tendered products, trial products, or products with very short shelf life.

5.3 Scheduling rules for the combined MTO-MTS production situation

Run-out methods of scheduling and sequencing are widely used in industry as they are easy to understand and implement. In this section, we present a brief summary of various run-out based scheduling rules that will be compared through the simulation model. At the production decision moment, the run-out time, RO_i , for each item is calculated. RO_i is the time for which current inventory levels, I_i , will last and is given as²–

$$RO_i = I_i/d_i$$

The items are re-indexed such that $RO_1 < RO_2 < RO_3 < \dots$. The first product is then chosen as the product to be produced next. In the case of MTO products RO_i takes the value of the due date, DD_i , of products minus the time at the decision moment.

We would like to stress the fact that the cycle times for products, T_i^* , in EMQ are based on EOQ calculations whereas in other heuristics, they are derived from the basic period approach of Doll and Whybark (1973) and Haessler (1979)³. Thus, we follow a two step approach– at the tactical level, we calculate a *target cycle* and *target batch sizes* for the products and at the operational level we use

²A better estimate of run-out time, $RO_i = (I_i - s_i)/d_i - c_i$, where s_i is the safety stock (defined later) can also be used instead.

³For the EMQ method, $T_i^* = (2U_i/[h_i d_i(1 - d_i/p_i)])^{1/2}$. For the other methods, $T_i^* = k_i T^*$, where T^* is the basic period calculated using the procedures described in the appendix to section 4.4.

the various methods, described in this section, to sequence and schedule them.

In the implementation of all the methods that are described below, we also included a minimum run length constraint to prevent cycle lengths from becoming too short. This constraint acts as a production quantity modifier i.e. the production quantities will be raised if the production run lengths are too small.

5.3.1 EMQ

This rule is fundamentally a multi-item (s, S) policy. It is based on the cycles of independent manufacturing quantities calculated using the EOQ formula. The reorder of an item takes precedence over completion of the replenishment of another item i.e. the production of the current item continues until inventory of that product builds to S or the inventory of some other product falls below its safety stock level s . The production quantity for the product selected for production can, thus, be given as–

$$production_qty = \min \left\{ s_1 + T_1^* d_1 \left(1 - \frac{d_1}{p_1} \right) - I_1, \left(\frac{I_2 - s_2 - c_2 d_2}{d_2} - c_1 \right) p_1 \right\}$$

The first term in the above expression is simply the difference between the S value of item 1 and its current inventory level I_1 . The second term consists of the production rate of item 1, p_1 , multiplied by the time available for item 1 till inventory of item 2, I_2 , drops to s_2 . The correction for the incurred setup time is also applied.

5.3.2 Vergin and Lee

The [Vergin and Lee \(1978\)](#) method refines the approach of [Magee and Boodman \(1967\)](#), which suggests that it is more economical to set a total inventory sufficient to provide for cyclic fluctuation in total demand for all products than to monitor the actual production operation to keep the inventory balanced among several products. They derive a ratio, a_i , for each product based on the *target run length* of each product compared with other products. [Vergin and Lee](#) use these ratios to monitor cycling of products. Production of an item continues till i) inventory of some product runs out, or ii) inventory of product i builds up to proportion a_i of the total inventory on hand. At this point production is shifted to the product with zero inventory or the one with the lowest RO_i or DD_i (in case of MTO products). The ratio a_i for each product is the ratio of maximum inventory of item i and the average total inventory in the system (i.e. all products).

It is given by the following expression–

$$a_i = \frac{(1 - d_i/p_i)k_i d_i}{1/2 \sum_i (1 - d_i/p_i)k_i d_i}$$

It may be noted that the above expression is slightly different than the one in [Vergin and Lee \(1978\)](#). Their expression assumes a common cycle (i.e. each product is produced only once in the cycle) whereas we use the basic period approach i.e. allow products to be produced more than once in the cycle. The factor k_i indicates that product i is produced once in every k basic periods.

Since this method can lead to more production than required to meet the demand [Vergin and Lee](#) advocate the prevention of excess production. This means establishing a maximum inventory level for each product. During the product build up, when inventory reaches this level production shifts to another item. We chose to use S_i , like in the EMQ rule, as this level. Thus, the production quantity of a selected product is–

$$production_qty = \min \left\{ S_1 - I_1, \left(\frac{I_2 - s_2 - c_2 d_2}{d_2} - c_1 \right) p_1, a_1 \sum_i I_i - I_1, \right\}$$

5.3.3 Fransoo

[Fransoo \(1993\)](#) suggests a simple policy aimed at achieving stable cycle times. The idea is to stick to target cycle times as much as possible. Unlike the previous two methods, the production quantity of the product chosen for the production is not affected by the event of some other product running out. In high utilization case, this may save the number of setups and hence the productive capacity but at the same time some orders may be lost. Based on the run-out times, a product i with $\min(RO_i, DD_i)$ is indexed as 1 and is selected for the production and the production quantity is given as–

$$production_qty = s_1 + d_1 T_1^* - I_1$$

5.3.4 Dynamic cycle length heuristic

This heuristic ([Leachman and Gascon 1988](#)), termed as Gascon throughout the chapter, integrates the feedback control based on the monitoring of inventory levels with the maintenance of economic production cycles. The policy is applied time period by time period to make decisions concerning which items to produce in what quantities during the next time period. These quantities reflect production cycles revised each time period in response to differences between

projected and actual inventory levels and in response to changes in demand rates. The method employs the concept of positive and negative slack- if it is estimated that there will be enough time to replenish each item after that item's inventory falls to its reorder point and before the next item's inventory falls to its reorder point, then there is a positive slack. In contrast, if there is insufficient time to replenish one item before another item runs out of stock, then there is a negative slack between those items.

In case of the negative total slack, the cycle lengths of all items are proportionately reduced from the *target lengths* just enough to eliminate negative total slack. Such adjustments restore the balance in the production system. The heuristic involves arranging the products based on the run-out lengths, RO_i , and the following steps-

1. Calculate TS_j , the total slack available for the replenishment of item j , $j = 2, 3, \dots, n$. It is obtained by subtracting the setup and production times of items to be produced before the item j from its runout time, RO_j . Mathematically it can be expressed as-

$$TS_j = RO_j - \sum_{i=1}^{j-1} c_i - T^* \sum_{i=1}^{j-1} \frac{k_i d_i}{p_i} \quad j = 2, 3, \dots, n$$

2. If for some j the slack is negative, then the target cycles $T_i^* = k_i T^*$ cannot be maintained. To resolve the infeasibility, the fundamental cycle time T^* is reduced to a value T such that $TS_j \geq 0$, $j = 2, 3, \dots, n$. This revised fundamental cycle time, T , is called the operational cycle time and is calculated using the following formula-

$$T = \left\{ \min T^*, \min_{j=2, \dots, n} \frac{RO_j - \sum_{i=1}^{j-1} c_i}{\sum_{i=1}^{j-1} \frac{k_i d_i}{p_i}} \right\}$$

3. Take a downperiod, if the total slack $TS_j > 1$. Otherwise, produce item 1, in the quantity $s_1 + d_1 T k_1 - I_1$

Here, we would like to mention that our implementation of the Gascon method does not include the availability of a forecast over a planning horizon. Hence the average demand is used for calculation of cycle times. This is a one-time calculation as against cycle time calculation at every decision moment in Gascon's original method. The current implementation can, thus, result only in lowering of cycle times (than target cycle times obtained through Haessler/Doll-Whybark procedures) when a stock out situation is foreseen. In the case of high utilization,

this will result in a high number of setups, through which productive capacity is lost and also resulting in lost sales. However, with this implementation, we use the same demand information for all methods, making it a fair comparison.

5.4 Simulation model

A simulation model is developed (using Simple++) to evaluate the performance of a hybrid MTO/MTS food processing system under different scheduling heuristics. The model has two main modules– an order generator module that generates the orders based on the demand distribution, and a shop floor control module that contains the shop configuration under investigation and the various scheduling rules to operate the shop. There are various data sub-modules to measure the performance of the shop. For MTS products, we are interested in line average fill rate and average inventory levels. For MTO products, we are interested in average flow times i.e. achievable due dates. We also gather the cycle times for the MTS products and analyze the cycle time stability. Cost measures– inventory costs, setup costs, lost sales cost– are also in place. Each of these modules is developed with a lot of flexibility and can be customized to mimic real life situations to the greatest extent possible.

5.4.1 Model dynamics

The “target cycle” times are pre-calculated either using a) EMQ, or b) [Doll and Whybark](#) and [Haessler](#) procedure. Safety stock s and order up-to levels S for MTS products are pre-calculated⁴ based on the mean and standard deviation of the demand during replenishment lead time and desired service level. These target cycle times, safety stocks, and order up-to levels are used as inputs at the operational decision level.

The timing sequence in the simulation model is as follows–

1. At the beginning of the period, the demand for each item is generated. The MTS demand is fulfilled from the stock. The inventory balance is updated. If demand cannot be met, it is lost. The MTO orders are due immediately and join the production order pool.
2. At the end of each production run, the run-out times are calculated for all the products and the one with the smallest run-out time is selected for the next production run.

⁴These calculations are provided in the Appendix B.1 of this chapter.

Table 5.1: Bomberger problem with MTO products (88% MTS utilisation)

Product	Cost per item*	Setup cost	Production rate Items/day	Demand rate** Items/Day	Setup time Hours
1	0.0065	15	30000	400	1
2	0.1775	20	8000	400	1
3	0.1275	30	9500	800	2
4	0.1000	10	7500	1600	1
5	2.7850	110	2000	80	4
6	0.2675	50	6000	80	2
7	1.5000	310	2400	24	8
8	5.9000	130	1300	340	4
9	0.9000	200	2000	340	6
10	0.4000	5	15000	400	1

* Annual inventory cost = 10% of item cost and one year = 240-8 hour days

** Normal distribution, Coefficient of variance- 0, 0.1,0.3

Lost sales cost = 10% of item cost

MTO demand Negative exponential interarrival mean 21 days

Mean order demand 280units/day, Normal distribution CoV 0.3

Setup cost 300, Setup time 4 hrs

Processing rate 4000 units/day, Orders due immediately

3. The production start times and the production quantities are calculated based on the scheduling heuristic rule chosen.

For each scheduling heuristic, a simulation run lasts for 3000 periods initially (when performance measures are re-initialized) and for another 3000 periods. At the end of this, simulation statistics are gathered and reset. There are 5 simulation runs by using five common random number seeds⁵. At the end of the simulation, there is a summarization of the output of the simulation experiments.

5.4.2 Experimental factors, levels

To evaluate and compare the scheduling rules, discussed in the earlier section, we use the Bomberger dataset, which is most commonly used in ELSP literature (e.g. Haessler 1979), as shown in table 5.1. The demand rate shown in this table is for the case where utilisation is 88% (excluding setup time and MTO production, is at almost full capacity including these factors). The demand rates for other utilisation cases are obtained by proportionately changing those shown here. For example, at 44% utilisation the demand rates for all the products will be half of the demand rates shown in the table 5.1.

We conducted a simulation study at 5 different utilization levels (22, 44, 66, 77, and 88%) and by changing various parameters such as demand coefficient of variance (0, 0.1, 0.3) over a period (a day), carrying costs, setup costs, lost sales

⁵Such common random number technique is used to reduce the variance among experiments. The same warming up period, the same run length and the same number of runs are used in all experiments to enable the use of these common random numbers. For an elaboration of this technique see Law and Kelton (1991).

costs, MTO-MTS mix, demand pattern amongst products (pareto shape). In the remaining of this chapter we will, however, stick to the discussion related to impact of MTO addition and hence won't present the impact of costs and product mix as it can be assumed to be given for a specific case. It is well known that even for the specific case, lost sales costs are probably the most difficult to determine (Silver et al. 1998, pg. 241-243). We still decided to include the lost sales cost as it gives an indication of service levels for fulfilled demand. We chose a modest value of 10% of item cost.

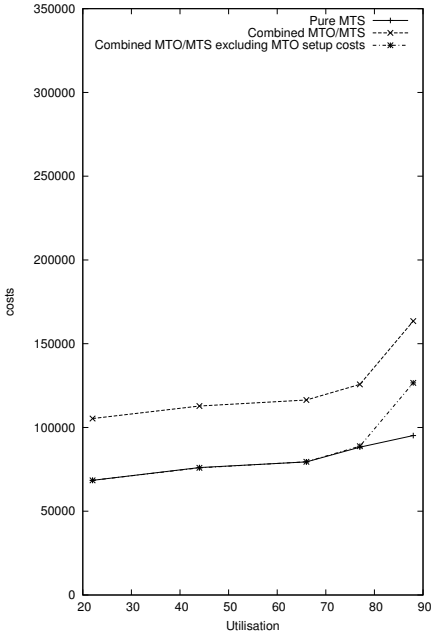
5.5 Simulation results and analysis

Figure 5.1, shows the cost performance of the different scheduling methods at different utilization levels. Vergin and Lee method clearly outperforms other methods in both pure MTS and combined MTO/MTS situation. The sum of setup, inventory and lost sales costs over the simulated period in the case of Vergin and Lee method is much less than in the case of the other three methods. EMQ and Fransoo methods have a similar cost performance. In the high utilization case, the performance of Gascon method deteriorates drastically.

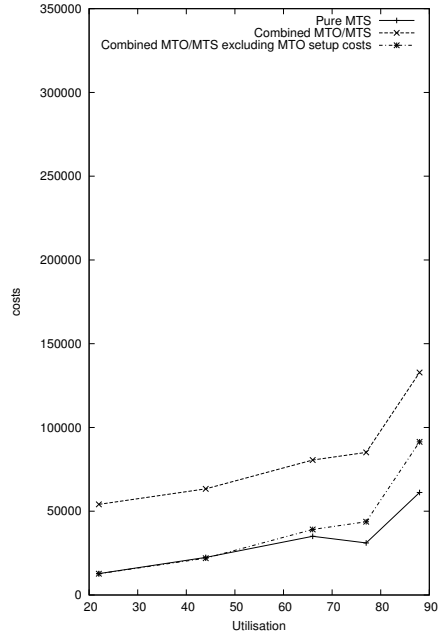
There are three curves in each of these figures⁶. The difference in "Pure MTS" and "Combined MTO/MTS" curves in each of the figures 5.1(a-d) represents the extra cost incurred because of the addition of the MTO products. We have also included a cost curve for combined MTO/MTS situation with setup costs for MTO products excluded. This curve tells us if there is any change in the cost incurring from MTS products. It is clear that at lower utilization level, there is not much impact of addition of MTO products on MTS costs but at 88% utilization, there is a significant increase in the costs. The widening differences in the curves at higher utilization indicate the need to exercise caution while accepting the, seemingly lucrative, special MTO orders.

Figure 5.2, shows the average MTO flow time for the different scheduling methods at different utilization levels. MTO flow time is the difference between the order arrival and the order completion time. In other words, it is the time spent by MTO orders in the system. The MTO flow times achieved in the experiments increase, in general, with utilization level for all the methods. For Vergin and Lee method, it increases quite rapidly as compared to other methods. It is interesting to note the lower flow times for Gascon method at 88% utilization. This is discussed later in this section.

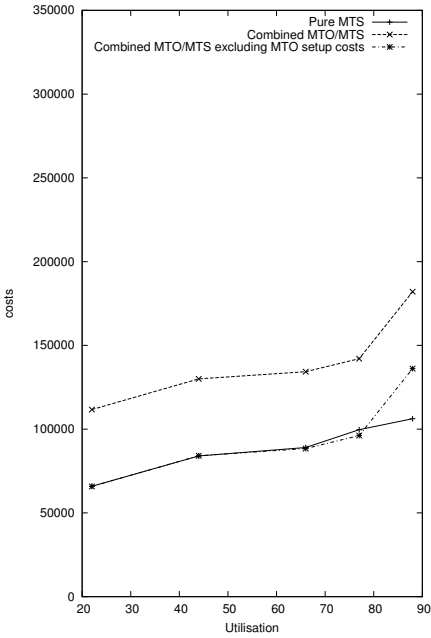
⁶The cost buildup is shown in Appendix B.2 of this chapter.



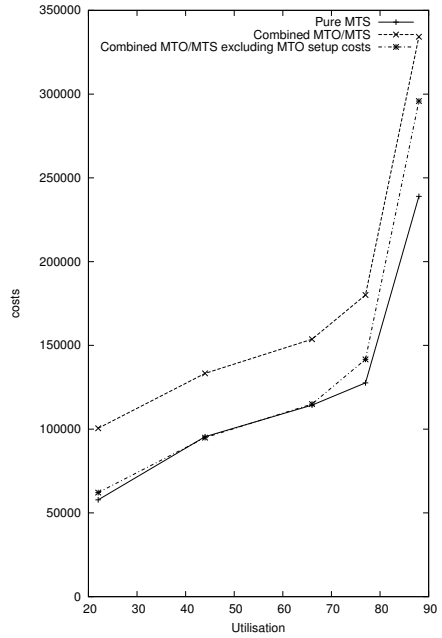
(a) EMQ



(b) Vergin and Lee



(c) Fransoo



(d) Gascon

Figure 5.1: Impact of MTO addition

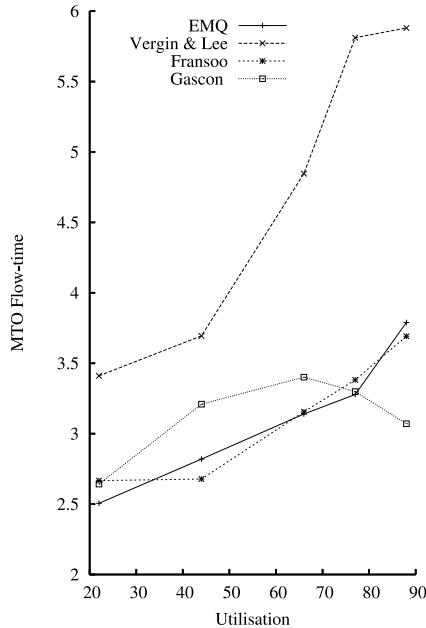


Figure 5.2: MTO flow time

The curves in figures 5.1 and 5.2 can be used as an input to the sales department in order acceptance, due date quotation and price negotiations.

Figure 5.3, shows the line item fill rates (LIFR) for MTS items of the different scheduling methods at different utilization levels. All the methods achieve more than 93% fill rate. EMQ and Fransoo methods perform better in both pure MTS and combined MTO/MTS situations. The performance deteriorated for all the methods at higher utilization levels.

The observations from figures 5.1–5.3 and from the experiments with 0.1 and 0.3 demand coefficient of variance are similar and hence the later are not shown in the form of plots.

While figures 5.1–5.3 provide us the overall performance of the methods, tables 5.2–5.5, help us in detailed understanding of the methods. These tables show the data for 88% utilization case. Table 5.2, shows the average inventory that was held in the stock during the simulated period. Vergin and Lee method carries more inventory for each of the products while Gascon has the least. This is also related to the number of production runs and hence the number of setups done.

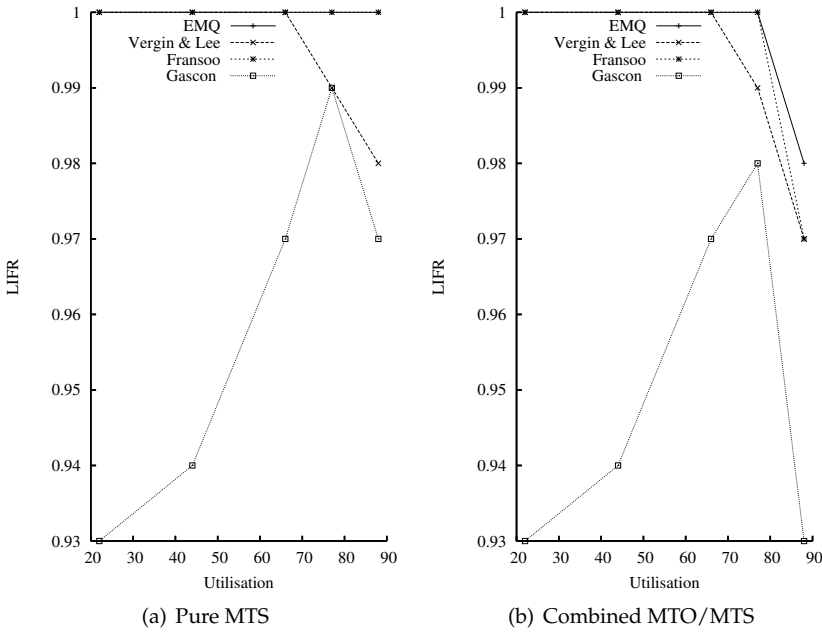


Figure 5.3: Line item fill rate for different methods

This is shown in table 5.3. The expected number of setups based on the Haessler (1979) procedure is also shown for the comparison. It is interesting to note that Vergin and Lee method has least number of setups while Gascon method has more setups in general. In case of products 4,8, and 9 the difference in number of setups is very high. It is intriguing to know that these are the products with high machine usage (d_i/p_i).

Table 5.4 shows, for each of the methods, the percentage of lost sales for each product. Gascon method has more lost sales than other methods and the differences are wider for products 4,8 and 9 which have high (d_i/p_i) ratio i.e. machine usage. Table 5.5 shows the performance of each method in terms of cycle time stability. The target cycle times from EMQ and Haessler (1979) procedure are also shown. The cycle time stability is represented by coefficient of variance (CoV) of cycle times achieved. Again, products 4,8 and 9, the products with high (d_i/p_i) ratio, are problematic. They have a high coefficient of variance for cycle times. Fransoo method, which claims to lead to better cycle time stability does not seem to do so for all products.

As seen from tables 5.3 and 5.5, it is clear that the products 4,8, and 9 i.e. the

Table 5.2: Average inventory levels for products

Product	EMQ	V & L	Fransoo	Gascon
1	32933	35479	29794	29555
2	9443	17859	10160	7679
3	15402	35803	18579	8580
4	16040	28023	17384	6907
5	2136	3918	2054	1912
6	5690	7550	5668	5935
7	2314	4180	2246	2373
8	3130	6001	3366	1277
9	7969	13341	6554	2194
10	16095	18257	15902	14745

Table 5.3: Number of setups for products

Product	EMQ		V & L		Fransoo	Gascon
	Expected	Actual	Expected	Actual	Actual	
1	18	19	32	19	21	20
2	65	73	63	39	72	81
3	76	99	63	38	81	132
4	163	262	127	107	216	348
5	60	73	63	36	72	63
6	28	23	32	17	22	20
7	15	17	16	10	16	15
8	146	321	127	104	256	487
9	49	75	63	41	92	273
10	76	41	63	36	40	40

Table 5.4: Percentage of lost sales for products (x100)

Product	EMQ	V & L	Fransoo	Gascon
1	0.00	0.00	0.01	0.01
2	0.02	0.02	0.03	0.03
3	0.03	0.02	0.02	0.11
4	0.07	0.07	0.07	0.20
5	0.01	0.02	0.02	0.02
6	0.00	0.01	0.01	0.01
7	0.00	0.00	0.00	0.00
8	0.07	0.08	0.09	0.21
9	0.01	0.04	0.04	0.11
10	0.01	0.01	0.03	0.02

Table 5.5: Cycle time stability for products

Product	EMQ		Target cycle	V & L		Target cycle	Fransoo		Gascon	
	Target cycle	Actual Cycle time		CoV*	CoV*		Actual Cycle time	CoV*	Actual Cycle time	CoV*
1	167.53	156.44	94.52	157.60	0.15	94.52	142.98	0.05	148.95	0.01
2	46.37	40.97	47.26	78.12	0.20	47.26	41.49	0.14	37.13	0.07
3	39.26	30.34	47.26	79.25	0.14	47.26	37.13	0.14	22.85	0.22
4	18.45	11.45	23.63	28.28	0.33	23.63	13.88	0.39	8.64	0.40
5	49.68	41.13	47.26	84.62	0.28	47.26	42.06	0.16	47.40	0.05
6	106.61	132.42	94.52	171.61	0.17	94.52	132.43	0.05	147.05	0.01
7	204.33	178.38	189.04	301.87	0.41	189.04	182.23	0.03	196.52	0.01
8	20.52	9.36	23.63	28.76	0.35	23.63	11.75	0.43	6.16	0.46
9	61.48	40.06	47.26	73.49	0.29	47.26	32.66	0.16	10.95	0.31
10	39.26	72.13	47.26	82.71	0.14	47.26	73.50	0.13	73.58	0.03

* Coefficient of variance of cycle times achieved

products with high d_i/p_i ratio behave specially. All the scheduling methods seem to be biased toward these products. These products are pulling their production runs forward at the expense of products with low d_i/p_i . This results in more setups and shorter cycle times. For Vergin and Lee method, which incurs lesser number of setups than expected in contrast to other methods, if we look at the cycle times achieved for each product then we can see that the number of setups for products 4,8 and 9 are relatively higher and the cycle times are relatively shorter. These products are produced more frequently and hence have relatively lesser inventory holdings. Since the runout time, defined as I_i/d_i , is used in all the methods as the priority rule it looks natural that these products with less I_i and high d_i are picked frequently for the production. It is beyond the scope of this text to investigate in detail why this phenomenon occurs.

Now, we discuss the working of each method.

5.5.1 EMQ and Fransoo methods

One interesting observation is that although EMQ method and Fransoo method are not identical, the results were often very close. One possible reason for this is the fact that although the cycle times are calculated independently for each product, the multi-item (s, S) policy take into account the capacity considerations by checking running out of other products.

These methods perform reasonably well both in pure MTS and combined MTO-MTS situation. Since these methods do not respond to every fluctuation in very short term, they achieve better cycle time stability. Line item fill rates are also very high. It seems that 'Law of averages' works here— demand is low in some period and is high in some period. It is surprising that the performance of these methods in terms of line item fill rate degrades only slightly (plots not shown) when demand variance is increased. The higher safety stocks are able to handle this.

It was expected that the EMQ procedure would result in higher costs⁷, since it does not take into account feasible schedule generation but it has resulted in cost effective solutions. There are at least two reasons that can be attributed to

⁷The similar performance of EMQ and Fransoo method is intriguing. This seems rather counter intuitive as it suggests that it does not make sense to use ELSP, but rather just use independent lot sizes. Is this a reason why EMQ methods and not ELSP methods are used in practice? A deeper look into these methods reveals that these are not too different from each other. In the EMQ method, the capacity constraints are ignored initially but are brought in later: the production quantity of the product to be produced next is modified because of some other product running out. In Fransoo method, the capacity constraints are partly taken into account via the use of ELSP method in the first step itself.

this. The production runs are longer and hence number of setups required is less. Also, the EMQ method has higher safety stocks.

5.5.2 Vergin and Lee method

This method performs extremely well in terms of costs for both Pure MTS and combined MTO/MTS situation. Addition of MTO products lowers the performance of the method drastically. MTO flow time performance is, however, the worst for this method. The method is very good at avoiding small production runs and thus can be very useful in situation where setup times are significantly high. The good feature is that it looks at inventory levels of all products. But as we have found from the set of experiments conducted, the better performance is achieved through high inventory levels. The method relies on building up the stockpiles to achieve high line item fill rate. The situations where inventory costs are higher as compared to setup costs, this method may prove costly. In the presence of MTO products, the performance deteriorates since the MTO products have to wait too long for their production turn because of long production runs of MTS products.

In food processing industries, one may think that this method will perform better since it avoids costly and time consuming setups but if there are products with short shelf life, the method may lead to product obsolescence ([Soman et al. 2004b](#)). Special cold storage requirements for products can also put a limit on holding the inventories.

5.5.3 The Gascon method

Gascon method tries to avoid stock-outs at any cost (as the problem is tackled as a stock-out avoidance problem), without due considerations to setup time and cost. This leads to higher costs and also lost sales in high utilization case since there is loss of productive capacity in the form of frequent setups. The method is too dynamic and brings nervousness to the system. It results in too small cycles, which may not be desirable economically. Though the method performs poorly in terms of costs, it is performing well in terms of MTO flow time because of smaller MTS production runs.

5.6 Conclusions and future research

The hybrid MTO/MTS production situation while very common in practice is addressed scarcely in the literature. The void is even more when it comes to the

operational scheduling in such situations. In this chapter we try to fill this gap. We use four different, proven run-out time based dynamic scheduling methods from the pure MTS literature in the case of combined MTO/MTS situation. We compare their performance by several criteria to check if they are also suitable for hybrid production mode.

When it comes to the choice of a suitable scheduling method, the simulation study presented in this chapter remains inconclusive in some respects. It is clear that the methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO/MTS situation. However, none of the scheduling methods, over a long simulated period, exhibited a clear dominance over other methods in terms of all performance measures. This in itself is a significant result. It suggests that the choice of scheduling rules to control a hybrid MTO/MTS production system, such as the ones described in this study, should not be restricted to a tool that will ensure optimal cost performance for the system. Other performance measures, and considerations such as simplicity in the applicability of the rule may well prove to be a dominant factor in deciding scheduling rules. For example, in the simulation study presented in this chapter EMQ and Fransoo methods which are simpler and unsophisticated as compared to Vergin and Lee and Gascon methods perform reasonably good for all performance measures.

It is also clear from the study that, irrespective of the method used, the companies should be very careful in accepting special business in the form of MTO products in the cases of high system utilization. In such cases (near 100% utilization), it may be wiser to phase out some MTS products in order to include special business opportunities from special orders/ MTO products, which typically have more contribution margin.

It was also observed that the products with high machine usage i.e. high d_i/p_i ratio are special in the sense that all the methods seem to be biased for these products and react too quickly in selecting them and hence have a high number of setups and also poor cycle time stability which is not desired by manufacturers. Further investigation is required on why these products are behaving in a special way?

We do not suggest that the methods compared here are the best that one can come up with and implement. These can be improved upon, for example by having the possibility of backordering in the Gascon method– When run-out

times are low i.e. working inventories are low, the scheduler may wish to avoid short production runs and may want to incur backorder penalties so as to increase the length of production runs and reduce setup costs per unit of time. The extended Gascon method will result in better performance measures since the scheduling heuristic will give consideration to the backorder/setup cost relationships as well. It will also have nice features of Gascon's original method-accommodating seasonal demand changes through the use of tactical planning level. In short, Gascon method has disadvantages in terms of cycle time stability because of overreaction and hence the extended version should have the idea of not reacting short-sightedly.

It also seems unrealistic that production decision is taken only at the end of a production run of some product or at the start of the day (as done in this chapter). This decision is also only for the next product to produce. This is definitely not going to help the raw material procurement department. The methods discussed are too dynamic and are not easily implementable. Use of a review period method looks more practical. Increased safety stocks because of use of review period, could also be a choice to avoid the stock-outs.

In this chapter, we did not include the MTO demand information in terms of additional capacity requirements while deriving the *target cycle* for the production. When MTO demand proportions are higher, than those considered in this chapter, it may be wise to either explicitly reserve the capacity for them or to include idle time in MTS schedules or MTS products might be manufactured to fill capacity in periods of low demand for MTO items in order to have stored capacity in the form of inventories. [Van Donk et al. \(2003\)](#) suggest some conceptual ways of how to incorporate MTO in ELSP. Those could be build upon to develop implementable heuristics. Although the fixed sequence strategy provides low opportunities to react to short term demand, it is appealing for situations with sequence dependent setup times (and costs) and also for two-stage (or multistage) system, where dynamic sequencing can cause unforeseen problems in the raw material (or packaging) material procurement. Comparison with [Federgruen and Katalan's \(1999\)](#) cyclic base stock policy (polling model) would also be an interesting topic for the further development in the area of hybrid MTO/MTS production.

Appendix B.1: Safety stock calculation

If product i is scheduled to be produced every T_i^* time units, the production time is $T_i^* d_i/p_i$. The remainder of the cycle, $T_i^* - T_i^* d_i/p_i$, until the product i is produced again, is used by the other products. Thus, safety stock must cover the demand uncertainties during the protection interval:

$$L_i = T_i^*(1 - d_i/p_i)$$

For stationary demand, safety stock is defined to be the expected inventory level at the time of beginning of the next production cycle. We deploy, the most commonly followed approach of providing a required service level, α_i , is through the use of safety stock, s_i , given by:

$$s_i(L_i) = f_i \sigma_i(L_i),$$

where $\sigma_i(L_i)$ is the standard deviation of the demand during the protection time L_i . The safety factor f_i which is based on the service level α_i can be specified by using the normal distribution (see pg. 266-267, 724-734 of [Silver et al. 1998](#)). The service factor is denoted as k therein. We use $f_i = 1.65$ corresponding to the service level of 95%.

The standard deviation of demand during the protection time L_i can be approximated well by:

$$\sigma_i(L_i) = \tilde{\sigma}_i L_i^c$$

where $\tilde{\sigma}_i$ is the standard deviation of one-period ahead demand forecast and c is a constant that must be estimated empirically (see pg. 114-116 [Silver et al. 1998](#)). Values for c generally ranging from 0 to 1. We use a value of 0.5 in this study.

Once the safety stock is calculated, the order up-to levels S_i are calculated as follows:

$$S_i = s_i + T_i^* d_i(1 - d_i/p_i)$$

Appendix B.2: Total cost buildup

The following table shows the cost elements used to build up figure 5.1.

Inventory cost									
Utilization	Pure MTS				Combined MTO + MTS				
	EMQ	V & L	Fransoo	Gascon	EMQ	V & L	Fransoo	Gascon	
22	359.88	645.97	345.22	150.28	358.22	658.60	343.32	153.31	
44	604.10	1021.12	650.60	320.93	596.44	1001.01	648.80	314.64	
66	794.55	1045.14	856.31	474.41	783.03	974.38	842.22	488.66	
77	791.48	1225.26	859.77	554.50	770.72	1322.32	822.02	554.74	
88	902.64	1262.78	995.20	737.06	804.47	912.56	794.82	736.99	

Setup cost									
Utilization	Pure MTS				Combined MTO + MTS				
	<i>MTS Setup costs</i>				<i>MTS Setup costs</i>				
	EMQ	V & L	Fransoo	Gascon	EMQ	V & L	Fransoo	Gascon	
22	68070	12085	65555	24495	68070	12055	65445	24235	
44	75460	21425	83380	37470	75320	20895	83440	37450	
66	78670	31215	88195	55575	78710	33460	87535	58970	
77	87430	20295	98795	88100	84710	21615	93155	92620	
88	94280	26200	105265	159465	78720	33085	72205	140050	
22					<i>MTO Setup costs</i>				
					36900	41400	45900	38400	
44					36900	41400	45900	38400	
66					36900	41400	45900	38700	
77					36900	41400	45900	38400	
88					36900	41400	45900	38400	

Lost sales cost									
Utilization	Pure MTS				Combined MTO + MTS				
	EMQ	V & L	Fransoo	Gascon	EMQ	V & L	Fransoo	Gascon	
22	0.00	0.00	0.00	33178.35	0.00	0.00	0.00	37745.19	
44	0.00	0.00	0.00	57681.28	0.00	45.90	0.00	57144.33	
66	0.00	2797.59	0.00	58268.93	0.00	4706.95	0.00	55495.87	
77	0.00	9575.82	0.00	38946.56	3340.25	20785.03	2190.13	48494.46	
88	0.00	33707.54	0.00	78760.18	47101.88	57439.30	63157.38	155038.48	