Integrated Operations Planning for a Multicomponent Machine Subjected to Stochastic Environment

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Abstract: Operations management decisions related to production, maintenance, inventory and supplier selection has attracted researchers since long. Traditionally each of these areas was planned and optimized individually. Soon interdependencies between these elements of value chain were realized, which prompted researchers towards integrated planning of these functions. Superiority of integrated approach over conventional operations management approaches has already been demonstrated in past. Therefore, models integrating shop floor functions like production planning, maintenance planning and inventory planning are abundant in recent literature. However, there exist functions which significantly contribute towards operations planning, but have still not been considered for integration. One such important area is procurement planning (supplier order allocation).Current work aims to integrate procurement decisions with maintenance and production plan so as to minimize Total Cost of Operations (TCO). It considers a stochastic environment where production and maintenance processes are imperfect and where there is significant dubiety related to demand and supply of material. Further, present model considers uncertainties in parameters like supplier quality, machine yield etc., by using appropriate probability distributions for these parameters. Therefore a simulation based Genetic Algorithm (GA) approach is used to solve this optimization problem. The final results are illustrated in the form of an integrated operations plan. It explicitly communicates (i) Order quantity for individual suppliers (ii) Job production sequence (iii) Production lot size (iv) Preventive maintenance schedule for individual machine components. Current work aims to contribute towards development of a paradigm where multiple disjoint functions are integrated at planning level itself.

1 INTRODUCTION

Fulfilling customer's requirement is of prime importance to all the organizations. These requirements are fulfilled when all the functions of the organization are aligned and perform efficiently. Production, maintenance, quality and supply management are few of such critical functions. Supply management facilitates the availability of raw material for production. Production is then carried out through well maintained machines which contribute towards good quality of products, which are finally delivered to customers. In between, inventory acts as cushion to accommodate uncertainties and ensures availability of material. Thus each of these functions together forms a strong channel through which customer demand is realized.

Emphasizing on individual function, from a diverse supplier base, supply management function identifies suppliers which best fulfils the criteria like capacity, capability and cost. Optimization of supply management is linked with decisions like order allocation, order quantities etc. On the production planning front, job scheduling, manufacturing lot size, allocation of job to different machine etc. are amongst the key decisions to be optimized. Similarly, which component / components to select for preventive maintenance and when to perform preventive maintenance are the decisions which affect effectiveness of maintenance function. Similar to such decisions is the decision related to inventory management of raw materials and finished goods. Extra inventory is considered to be waste as it calls for capital expenditure which could otherwise be used elsewhere. On the other hand fewer inventories may lead to risk of material unavailability and may result into non fulfilment of customer demand on time.

Conventionally, planning of above mentioned functions is performed individually. After individual

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function's plans are finalized, they are communicated to other functions. However, during execution of these plans, priorities of individual functions do clash. Supply management may plan all the material at once to reduce the ordering cost, impacting the raw material inventory carrying cost. Similarly, production may plan to manufacture the maximum quantity so as to reduce cost related to changeover, set-up etc. This increases the finished good carrying cost. Also, it may deprive machine for getting timely preventive maintenance leading to catastrophic machine failure. Such failures calls for prolonged corrective maintenance actions and also affects quality of produced goods.

It is thus evident that performance of one function severely affects performance of the others. It therefore becomes imperative that the planning of these functions must be carried out using an integrated approach. Present paper aims to integrate decisions related to supply management with that of production, maintenance and inventory. In particular, it aim to integrates supplier selection and order quantity with shopfloor decisions like job production sequence, manufacturing lot size and preventive maintenance schedule.

2 LITERATURE REVIEW AND PAPER CONTRIBUTION

Operations' planning has gradually evolved from optimization of individual parameters in a simplistic environment to multi criteria optimization under much complex environment. On scheduling, (Jones et al., 1999) and (Chan et al., 2013), has exhaustively reviewed the models developed for job shop scheduling. Literature can also be found on development of scheduling models for specific objectives like minimizing job tardiness (Adamu and Adewumi, 2014), or sequencing under uncertain environment (Mula et al., 2006).

On the maintenance front the research expands from maintenance optimization (Sharma et al., 2011) to maintenance performance (Kumar et al., 2013). Brief consolidation of the development in the field of maintenance is mentioned in review by (Garg and Deshmukh, 2006) for identifying the on-going trend and future directions.

Concurrently, research has also progressed in the field for supply management. Numerous decision making approaches were proposed for optimizing the decisions related to supplier selection as mentioned in (Wilson, 1994). Review by (Aissaoui et al., 2007) concentrates on mainly such models. It proposes different classifications of the multiple models which were published over the time.

Recent literature reflects that current focus of researchers is towards the development of "integrated" approaches (Hadidi et al., 2012).

There exist models which successfully integrate:

- Production and Maintenance (Zhao et al., 2014)
- Maintenance and Quality (Alfares et al., 2005)
- Quality and Inventory (Peters et al., 1988)

Literature mentioned above demonstrates superiority of integrated models compared to conventional models. However, it can be noticed that all the efforts for integration were confined mainly to production, maintenance, inventory and quality. But, there exists other equally critical functions beyond those mentioned above, which also contributes significantly towards the overall performance of organization, but have been overlooked for integration. Current work is an attempt to extend the existing integrated models by incorporating one such function namely Procurement Planning / Supply Planning.

3 INDUSTRIAL PROBLEM DISCRIPTION

The problem considers a multi component machine as the central element of a small value chain with customers at its one end and raw material suppliers at the other end. Each customer can demand variety of products in random quantity, to be delivered by specific date. This demand needs to be processed on a machine in a sequence which optimizes the total cost of operations. To ensure the availability and quality of output of machine, maintenance becomes essential. Timely preventive maintenance is performed in addition to corrective maintenance, which is performed at the time of random machine failure. Aligned with demand from each customer and accounting for uncertainties, raw materials are ordered from the set of previously screened suppliers.

To elaborate further, consider a multi component machine. Let the component be labelled as C_i $(0 < i \leq n,\ n \in N)$. The components are reliability wise mutually independent and are in series. Time to failure for each of these components follows two parameter Weibull distributions, having shape parameter and scale parameter as β_k and η_k respectively. These distribution parameters, along with other factors, affect the stochastic failure of components. Such failure can be reduced if timely preventive maintenance (PM) action is performed as each well planned PM activity positively influences the life and performance of the machine. Effectiveness of PM is measured as the factor by which the life of the component can be restored and is denoted by restoration factor (R). Though PM is beneficial, it incurs time and resources which could otherwise be used elsewhere. However in the absence of PM, machine deteriorates speedily and leads to frequent random failures. Such random failures are addressed by corrective maintenance (CM). Since causes of abrupt breakdowns are unsure and CM activities are unplanned, they tend to consume more time as compared to PM activities. It is therefore necessary to carefully plan overall maintenance schedule.

The manufacturing process carried out on the machine is also imperfect in nature. An imperfect process implies that the output will not always be perfect and certain normal rejections are bound to occur which affects the yield of the machine. The machine is used to process the demand of multiple products in different quantities from various customers. This demand can be forecasted using past records for each product and each customer. The forecasted demand of individual product is consolidated and further augmented by considering the variability in the machine yield.

This augmented demand for products it translated in to raw material requirements which is to be fulfilled by group of previously identified suppliers. The distribution of raw material order quantity amongst the supplier is based on their performance indicator like quality rating, cost, discounts and capacity. Normal rejections are expected from raw material supplied by supplier and therefore quality rating refers to percentage of "OK" parts received by suppliers. This rating is influenced by operations at supplier's end which are again stochastic in nature and therefore considered as normally distributed.

Machine is assumed to work for 16 hours per day for 25 days in a month. In case the customer order cannot be completed before due date, there is a delayed delivery cost which is imposed by customer. There is also a backorder cost which is imposed if the delivered quantity is less than the ordered quantity from supplier. Such backorders are lost forever and are not added to requirement for next month.

For a multi component machine, the problem lies in preparing an optimized operations plan which precisely quantifies conflicting decisions related to production, maintenance and procurement while accommodating uncertainties.

4 MATHEMATICAL MODAL

As stated above, using an integrated approach, current work aims at minimizing the total cost of operation. Total cost of operation (TCO) is calculated as:

TCO = TMC+TCOPM+TCOCM+TBOC+ TDDC+TICC +TPC

Where,

TMC =Total Machining Cost

TCOPM = Total Cost of PM

TCOCM= Total Cost of CM

TBOC = Total Backorder Cost

TDDC = Total Delayed Delivery Cost

TICC =Total Inventory Carrying Cost

TPC = Total Procurement Cost

Individual models for above mentioned cost components are mentioned here under.

If "s" be the number of suppliers, "m" be the number of months in planning horizon, "p" be number of products and "k" be the number of components in the machine, then:

4.1 Machining Cost

If q_{ij} is the manufactured quantity of product p_i in j^{th} month and MT_i is machining time for i^{th} product, then Total manufacturing cost (TMC) is calculated as:

$$TMC = \sum_{j=1}^{j=m} \sum_{i=1}^{i=p} (q_{ij} \times MT_i) \quad (1)$$

4.2 Maintenance Cost

Total cost of preventive maintenance (TCOPM) is calculated as:

$$TCOPM = \sum_{j=1}^{j=m} \sum_{p=1}^{p=p} \sum_{k=1}^{k=k} [PMF_{kpj} \times (TTRPM_k \times MLC)] \quad (2)$$

where PMF_{kpj} is preventive maintenance factor for k^{th} component before p^{th} production run in j^{th} month such that,

$$PMF_{kpj} = \begin{cases} 1 & if\ component\ goes\ for\ PM \\ 0 & if\ component\ doesnot\ go\ for\ PM \end{cases} \quad (3)$$

$TTRPM_k$ is the time to perform preventive maintenance on k[th] component. MLC is the maintenance labour cost per hour. Similarly, Total Cost for Corrective Maintenance (TCOCM), is calculated as:

$$\text{TCOCM} = \sum_{j=1}^{j=m}\sum_{p=1}^{p=p}\sum_{k=1}^{k=k}\left(NF_{kpj} \times TTRCM_k \times MLC\right) \quad (4)$$

where $TTRCM_k$ is time to perform corrective maintenance of k[th] component. NF_{kpj} is number of failures of k[th] component during p[th] production run in j[th] month.

NF_{kpj} is calculated using formula published by (Lad and Kulkarni, 2012)

$$NF_{kpj} = \left[\frac{\left((MT_{pj}) + Ia_{kpj}\right)^{\beta_j}}{\eta_j}\right] - \left[\frac{(Ia_{kpj})}{\eta_j}\right]^{\beta_j} \quad (5)$$

where MT_{pj} is machining time for p[th] production run in j[th] month. η_k, and β_k are scale and shape parameter of k[th] component respectively. Ia_{kpj} is the initial age of k[th] component before p[th] production run in j[th] month.

4.3 Backorder Cost

Total cost of backorder, (TBOC) is calculated as:

$$TBOC = \sum_{i=1}^{i=p} BOC_i \quad (6)$$

where, BOC_i is the backorder cost for i[th] product.

4.4 Delayed Delivery Cost

This is a penalty cost which is imposed by customer in case the delivery of products is made after the committed due date. It is calculated as:

$$TDDC = \sum_{j=1}^{j=m}\sum_{i=1}^{i=p} DDC_{ij} \quad (7)$$

Where,

$$DDC_{ij} = \begin{cases} 0 \\ for\ all\ AD_{ij} \le DD_{ijc} \\ , \\ \sum_{c=1}^{c=c}\left(ADD_{ijc} - CDD_{ijc}\right) \times PC_{ic}, \\ for\ all\ AD_{ij} \ge DD_{ijc} \end{cases} \quad (8)$$

where ADD_{ijc} and CDD_{ijc} are the actual delivery date and committed delivery date respectively for the i[th] product in j[th] month from c[th] customer. PC_{ic} is the penalty cost per hour for the i[th] job and c[th] customer.

4.5 Inventory Carrying Cost

The goods which are left over after fulfilling the monthly demand of customers are stored till next delivery and thus cost extra for their storage. Inventory carrying cost is the cost of stocking these extra units.

$$TICC = \sum_{j=1}^{j=m}\sum_{i=1}^{i=p}\left(ICC_i \times qe_{ij}\right) \quad (9)$$

where ICC_i is the inventory carrying cost for i[th] product and qe_{ij} is the extra units produced, if any.

4.6 Procurement Cost

It is the sum of ordering cost and material cost i.e. Procurement Cost (PC) = Ordering Cost (OC) + Material Cost (MC).

Each supplier has a different procedure for processing the order and thus has different ordering cost. Therefore total ordering cost is the sum of ordering cost for each product from respective supplier / suppliers. Total Ordering cost (TOC) is calculated as:

$$TOC = \sum_{j=1}^{j=m}\sum_{s=1}^{s=s}\sum_{p=1}^{p=p}\left(OC_{ps} \times SSF_{psj}\right) \quad (10)$$

where SSF_{psj} supplier selection factor for p[th] product for s[th] supplier in j[th] month, such that SSF is 1 if supplier is selected for delivering p[th] product and “0” otherwise

Total Material Cost is the product of unit price of product, discount factor, quantity ordered and supplier selection factor. It can be mathematically written as:

$$TM = \sum_{j=1}^{j=m}\sum_{s=1}^{s=s}\sum_{i=1}^{1=p} Q_{isj} \times UP_{is} \times DF_{is} \times SSF_{isj} \quad (11)$$

Where Q_{isj} is the quantity ordered of i[th] product by s[th] supplier in j[th] month and UP_{is} and DF_{is} is the unit price and discount factor for of i[th] product by s[th] supplier.

Table 1: Machine Component Characteristics.

k^{th} Component	Initial Age (hours) Ia_k	Scale factor η_k	Shape factor β_k	Restoration factor for PM R_k	PM Fixed Time	CM Fixed Time	CM Variable Time (hours)	
							Mean μ_k	Standard Deviation σ_k
1st Component	3000	1200	2	0.5	3	1	8	2
2nd Component	3000	900	2.5	0.5	3	1	8	2
3rd Component	3000	1100	3	0.5	3	1	8	2
4th Component	3000	600	1.5	0.5	3	1	8	2
5th Component	3000	1500	1.8	0.5	3	1	8	2

5 NUMERICAL EXAMPLE AND RESULTS

To illustrate the above mentioned model, consider a multi component machine with five components with characteristics as mentioned in table 1.This machine manufactures four different products namely P1, P2, P3 and P4 .Characteristics of these products are as shown in table 2 and 3.

Table 2: Product Characteristics.

	Product			
	P1	P2	P3	P4
Manufacturing time (Hours)	0.2	0.25	0.22	0.25
Labor Cost per hour	60	60	60	60
Inventory carrying cost Per Unit	0.25	0.25	0.25	0.25

Table 3: Due Dates and Penalty Costs.

		P1	P2	P3	P4
Due date (Days)	Customer 1	15	15		
	Customer 2			18	18
	Customer 3	17	17	17	
	Customer 4		16	16	16
Penalty cost /per hours delay	Customer 1	7	7		
	Customer 2			8	8
	Customer 3	5	5	5	
	Customer 4		9	6	6
Back Order Cost Per Unit	Customer 1	68	68		
	Customer 2			70	70
	Customer 3	72	72	72	
	Customer 4		69	69	69

These products can be demanded from multiple customers. The monthly demand of each product for the products is forecasted. However, actual demand is uniformly distributed and uncertain. The demand pattern for a month is as mentioned in table 4.

Material planner orders raw material by considering forecasted demand, average supplier quality rating and average percentage rejections at machine. The raw material order quantity is thus calculated as:

$$TOC = OQ_{ij} = \left[FD_{ij} \,/\, (SQR_i \times MQR_i) \right] \quad (12)$$

where, OQ_{ij}= Order quantity for raw material of i^{th} product in j^{th} month, FD_{ij} is forecasted demand of i^{th} product in j^{th} month, SQR_i is average supplier quality rating for i^{th} product and MQR_i is machine quality rating for i^{th} product.

Table 4: Monthly Demand.

C= Customer		Product			
		P1	P2	P3	P4
Demand Forecast (units)	C1	90	90		
	C2			85	95
	C3	85	95	85	
	C4		95	95	100
Aggregate of Demand Forecast		175	280	265	195
Uniformly Distributed Actual Demand (units)	C1	81-99	81-99		
	C2			76-94	85-105
	C3	76-94	85-105	76-94	
	C4		85-105	85-105	90-110
Aggregate of Actual demand		157-193	251-309	237-293	175-215

The organization follows multi sourcing policy which means that order quantity of raw material for these products can be split amongst the set of previously identified suppliers. This split or distribution of order is influenced by supplier performance indicator like cost, quality rating etc.

Table 5: Discount Window.

	Order Quantity	RM1	RM2	RM3	RM4
		Percentage Discount for per unit cost			
Supplier 1	0 to 176	0	0		
	177 to 235	9	10		
	above 235	15	16		
Supplier 2	0 to 179		0		0
	180 to 239		10		9
	above 240		16		17
Supplier 3	0 to 158	0	0	0	
	159 to 211	7	7	7	
	above 212	12	12	12	
Supplier 4	0 to 170			0	0
	171 to 227			6	6
	above 227			11	12

Table 6: Supplier Details.

		Raw Material			
		RM 1	RM 2	RM 3	RM 4
1 = Can Supply	Supplier 1	1	1	0	0
	Supplier 2	0	1	0	1
0= Cannot supply	Supplier 3	1	1	1	0
	Supplier 4	0	0	1	1
Cost/ Unit Ordered	Supplier 1	1.5	1.6		
	Supplier 2		1.7		1.7
	Supplier 3	1.75	1.75	1.75	
	Supplier 4			1.6	1.6
Maximum Order Quantity	Supplier 1	300	295		
	Supplier 2		300		300
	Supplier 3	265	265	265	
	Supplier 4			285	285
Average Quality Rating (%)	Supplier 1	0.96	0.96		
	Supplier 2		0.97		0.95
	Supplier 3	0.94	0.94	0.93	
	Supplier 4			0.97	0.99

Also, to attract large orders, suppliers provides discounted price for larger ordered quantities. Such supplier characteristics are as mentioned in table 5 and table 6.

6 SOLUTION METHOD

In general, conventional "M Job-1 Machine" production scheduling problem have M! feasible solution. Likewise, maintenance decision for a particular component is binary in nature – PM or No PM. Thus, for a machine with "k" components, PM activity leads to 2^k possible decisions. This maintenance decision is repeated after each of the "M" production run for "m" months, which leads to total no. of solutions as $[(M!)(2^k)^M]^m$. For the example mentioned above, M=4, k=5 and m=3, which leads to total number of feasible solution equal to 1.5^{22} approximately. This number excludes the decision variable related to, production lot size, supplier selection and order quantity which manifolds the number of possible solutions. Such combinatorial situations, makes it complex to use any exact algorithm.

In addition, present models also incorporate uncertainties in machine yield, actual demand, supplier quality rating and other parameters. Such considerations are accommodated to closely replicate real world complexities. This is achieved using probability distributions for value of specific parameters mentioned above. Therefore a simulation based Genetic algorithm approach is used to solve this optimization problem. "@ RISK" optimizer" software is used for the same in this research.

7 RESULTS

The model was simulated for over one lakh trials, each having 50 iterations, for generating optimized results. A part of optimization log is as mentioned in table 7. The table shows that minimum cost is obtained in trial no. 88780. No further reduction in cost was observed after this trial and thus log is truncated at this trial number.

Table 7: Log of Progress Steps.

Trial	Goal Cell Statistics			
	Min.	Max.	Std. Dev.	Result (Mean)
23259	123874	140410	6522	134221
28414	123874	139423	6140	133862
88780	123960	138952	5894	**133455**

Table 8: Integrated Operations Plan (IOP).

<table>
<tr><td colspan="2" rowspan="5">Monthly Procurement Decision</td><td colspan="2">Supplier</td><td>S1</td><td>S2</td><td>S3</td><td>S4</td></tr>
<tr><td rowspan="4">Order Quantity</td><td>P1</td><td>100</td><td></td><td>100</td><td></td></tr>
<tr><td>P2</td><td>100</td><td>100</td><td>0</td><td></td></tr>
<tr><td>P3</td><td></td><td></td><td>121</td><td>169</td></tr>
<tr><td>P4</td><td></td><td>202</td><td></td><td>0</td></tr>
<tr><td rowspan="16">PRODUCTION RUN</td><td rowspan="4">RUN 1</td><td colspan="2">Product to be Manufactured</td><td><u>P2</u></td><td colspan="2">Lot Size</td><td><u>193</u></td></tr>
<tr><td rowspan="3">Preventive Maintenance Decision (1=Execute PM, 0=No PM)</td><td colspan="5">Component</td></tr>
<tr><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">RUN 2</td><td colspan="2">Product to be Manufactured</td><td><u>P1</u></td><td colspan="2">Lot Size</td><td><u>182</u></td></tr>
<tr><td rowspan="3">Preventive Maintenance Decision (1=Execute PM, 0=No PM)</td><td colspan="5">Component</td></tr>
<tr><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">RUN 3</td><td colspan="2">Product to be Manufactured</td><td><u>P3</u></td><td colspan="2">Lot Size</td><td><u>275</u></td></tr>
<tr><td rowspan="3">Preventive Maintenance Decision (1=Execute PM, 0=No PM)</td><td colspan="5">Component</td></tr>
<tr><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">RUN 4</td><td colspan="2">Product to be Manufactured</td><td><u>P4</u></td><td colspan="2">Lot Size</td><td><u>191</u></td></tr>
<tr><td rowspan="3">Preventive Maintenance Decision (1=Execute PM, 0=No PM)</td><td colspan="5">Component</td></tr>
<tr><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>C5</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
</table>

The decisions corresponding to this optimal solution are represented in the form of a unified operations plan as summarized in table 8.

From the table it can be noted that, in order to have minimum total cost of operation, for the month of January, the schedule proposes total order quantity as 200, 302, 221 and 169 from S1, S2, S3 and S4 respectively. Simultaneously, it also proposes the production sequence as P2, P1, P3, and P4 with respective manufacturing quantities as 193, 182, 275 and 191 as highlighted in the table. It also integrates optimized preventive maintenance plan as mentioned under column "Individual component maintenance decision" by showing "1" for components which needs to go for preventive maintenance after each production run.

To summarize, this integrated operations plan precisely communicates decisions related to:

1. Production
   - Job sequencing
   - Manufacturing lot size
2. Maintenance
   - PM schedule for individual components
3. Procurement
   - Supplier Selection

Order Quantity

8 CONCLUSIONS

Functions like production, maintenance, inventory etc. have already been combinatorialy considered for integration. However, with addition of each function, complexity of formulating an integrated model manifolds which apprehends the integration of more functions for operations planning. Current work successfully fills this gap by exhaustive integration of multiple functions viz. production, maintenance, inventory and procurement. In addition, it incorporates stochastic nature of the processes like imperfect machining and maintenance process which brings it closer to real manufacturing environment. Consequently, current work can be looked upon as a step towards development over existing models which lacks integration to a detailed level where parameters and constraints related to processes, equipment etc. are also taken into account for integration.

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