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Contiguous-cells transportation model for multi-objective non-pre-emptive production and maintenance scheduling

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Abstract

The long-standing issue of non-pre-emption in 'multi-period' production/maintenance (P/M) scheduling has always been a challenge and this has been the focus of many researchers. Recently, the Contiguous-Cells Transportation Model (CCTM) was proposed to address this problem. However, the CCTM is limited to non-pre-emptive P/M scheduling decision situations where only one objective is of concern. The multiple objective non-pre-emptive P/M scheduling are encountered more frequently in the real world than the single objective case. This study proposed the Multi-Objective Contiguous-Cells Transportation Model (MOCCTM) and the solution procedure for handling multi-objective cases of non-pre-emptive production/maintenance scheduling. The variables and parameters of the CCTM were adopted with modifications to cater for the multi-objective requirements. A composite multiple-objective function was formulated by employing multi-objective optimisation techniques of assigning weights to objectives and normalisation of objectives. An algorithm similar to the conventional least cost method was developed for the solution of the MOCCTM. A bi-objective non-pre-emptive maintenance scheduling problem of 5 production machines across an operation and maintenance planning horizon of 10 periods was used to demonstrate the application of the MOCCTM. The MOCCTM is a good approach to solving multi-objective P/M scheduling problems in a non-pre-emptive environment.

Keywords: Non-pre-emption; Multi-objective Contiguous-Cells Transportation Model; Production Scheduling; Maintenance Scheduling

1. Introduction

One of the earliest problems faced by man is the problem of allocation of limited resources. This problem exists in different forms, ranging from production of goods (where there is need to adequately schedule jobs to machines), inventory control, product mix and employment scheduling to rendering of services such as transportation of items from warehouses to customers. Researchers have invested efforts to address this long-standing issue with several models and approaches developed to handle the problem. The model that best describes this multi-dimensional problem is the well-known Transportation model (TM). The Transportation Problem is a special class of linear programs that has to do with shipping of commodities from sources to destination, with the objective of determining the shipping schedule that minimize the total shipping cost while satisfying supply and demand limits [1, 2]. The TM is not limited to shipment of commodities due to the fact that the nature of some real-life problems can be described within the context of the TM. As a result, the flexibility of the model has prompted researchers to extend the application of the TM to solve problems of transshipment, inventory control, personnel assignment, production scheduling, etc. Several extensions of the TM are given in [2-6].

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One area of application of the TM which is of interest is in Production/Maintenance (P/M) scheduling. The P/M scheduling poses the problem of allocation of periods of time to execute multiple tasks which can either be pre-emptive or non-pre-emptive. Pre-emption means to temporarily suspend an on-going task for another task of more importance, with the intention of resuming the suspended task later. Non-pre-emptive scheduling on the other hand has to do with completing series of activities without any form of interruption (i.e once the activity begins, it must run to completion without interruption) [7]. Pre-emptive scheduling can occur for reasons such as unavailability of materials and P/M facility breakdown among others. While pre-emption of tasks is the case in many real-life scenarios, there exist situations of P/M scheduling where it is not favourable to pre-empt tasks. A practical case such as petroleum refining is a production situation where pre-emption is not feasible as interrupting any of the production processes might impact greatly on factors such as; set-up cost, set-up time and product quality. Maintenance of a fleet of vehicles (such as; aircrafts, buses, etc.) and maintenance of certain facilities (e.g. steam turbine maintenance) are activities carried out without pre-emption due to the high set-up cost and set-up time associated with them.

While researchers have focused on developing models to handle cases of pre-emption in P/M scheduling, not much is known about cases where pre-emption of tasks is not favourable. This issue of non-pre-emption in P/M scheduling was addressed by the proposition of the Contiguous-Cells Transportation Model (CCTM) [7]. The CCTM was formulated with the aim of determining the set of contiguous periods for preventive maintenance that minimizes total maintenance cost. The CCTM has so far been applied to solve a non-pre-emptive maintenance scheduling problem of a fleet of ships and aircrafts, yielding feasible results. Charles-Owaba et al [7] modelled situations where cost minimisation was the sole objective. Multiple objective decision situations are more common in many real-life scenarios [5, 8-11]. A practical case is with the maintenance of a fleet of aircrafts. Asides being interested in minimizing the total maintenance cost of the aircrafts, it is also important to ensure that the aircrafts are ready as at when due, in order to reduce the contract penalty associated with tardiness of any aircraft, which imparts negatively on meeting customer demands. A similar situation is the maintenance of a fleet of ambulances in which availability of the ambulances is an important objective to be considered in order to have them available to respond to cases of emergency. These practical situations draw attention to the existence of a multiple-objective case in non-pre-emptive maintenance scheduling which is yet to be addressed by the CCTM. The focus of this study is the development of Multi-Objective Contiguous-Cells Transportation Model (MOCCTM) and solution procedure for non-pre-emptive decision situations in production and maintenance scheduling. The review of literature is presented in the next section followed by model development. Next, numerical example is given followed by the results and discussion and finally, the conclusion is presented.

2. Literature review

The TM, being a special class of linear program associated with resource allocation has been the interest of many researchers because the model has been found useful in solving real-life problems. Although the TM was initially formulated and applied to finding an optimal schedule for transportation of items with the aim of minimizing cost, researchers have explored the extent to which the model can be applied including practical cases that involve multiple and conflicting objectives as reported in [12, 13]. The existence of such problems led to the development of the Multi-Objective Transportation Problem (MOTM). The MOTM is given by [14-16] and described as follows:

$$Optimize\ F(Z_\alpha(x_{gl}))\sum_{g=1}^{G}\sum_{l=1}^{L} C_{gl}^{\alpha} x_{gl}\ ;\ \ where, \alpha = 1,2,3,\ldots\ldots K$$

Subject to; (1)

$$\sum_{g=1}^{G} x_{gl} = a_g\ ; \qquad (\ l = 1,2,3,\ldots\ldots L)$$

$$\sum_{l=1}^{L} x_{gl} = b_l\ ; \quad (\ g = 1,2,3,\ldots\ldots G)$$

$$x_{ij}\ \geq 0;$$

Where;

A_{gl} = supply amount at source g

b_{gl} = demand at destination $Z_1, Z_2, Z_3 .... Z_k$ = Objectives of interest to Decision Maker. Scheduling has a wide range of definitions depending on the context in which it is used. In [7], the scheduling problem was defined from a production perspective to be the case of finding the feasible and optimal sequence in which jobs pass through machines. Maintenance scheduling was explained in [16] as the process of developing the sequence in which items are to be maintained as well as defining the methods and procedures to accomplish maintenance tasks. One underlying fact behind scheduling is that it has to do with the allocation of one form of resource or the other. Scheduling is associated with allocation of maintenance resources, plan production processes, etc. which in many practical cases, are just a few of many issues that have to be addressed. With the TM associated with the systematic allocation of resources, the scheduling problem situation can be modelled within the framework of the TM making the TM a useful decision-making tool for P/M scheduling.

In many practical situations of P/M scheduling, two or more objectives are relevant as a broad class of P/M scheduling objectives were identified in [7, 8]. In these cases of multi-objective P/M scheduling, the problem is that of minimizing, maximizing, or a combination of minimizing and maximizing all the objectives simultaneously. The solution to such problems relies on multi-objective optimisation techniques which can only provide "compromise solutions" as against "optimal solutions" due to the conflict associated with the objectives. In most cases, the objectives in question are of different dimensions which cannot be evaluated over different scales. This inconsistency in dimensions of objectives also brings about the issue of skewness in computations which calls for scaling of the objectives by the process of normalisation. Various normalisation techniques and the effect of these various techniques in a multi-criteria decision making (MCDM) environment were studied by [2, 17-19]. Mathematical models for expressing the multi-objective scheduling problem are presented in [4, 20]. The approach presented in [20] follows multi-objective optimisation principles which has to do with assignment of relative weights to each objective and aggregating all the objectives into a single function called the Linear Composite Objective Function (LCOF). The LCOF is as in equation (1)

Over the years, it has been the concern of researchers to apply different optimisation approaches to solve P/M scheduling problems. Some of the approaches adopted to solve the problems are presented in [21, 22, 23].

The first attempt at formulating the scheduling problem as a TM was proposed in [24] by identifying the problems of balancing production overtime and inventory storage costs associated with production scheduling, so as to yield the least cost of production. An extension of the TM to maintenance scheduling is presented in [25]. By defining a gantt charting problem of scheduling machines on periods, Charles-Owaba [25] developed an extension of the TM for preventive maintenance scheduling of mass transit vehicles, with the objective of minimizing total preventive maintenance cost. Advanced works on the approach in [25] focused on optimisation of preventive maintenance cost and operational activities using fuzzy linguistic approach [26] and evaluation methods for preventive maintenance cost [27]. Although the situations in [25-27] expressed and solved the maintenance scheduling problem as a TM, the models developed were based on the assumption of pre-emption. The existing extensions of the TM also depict structures that can only handle pre-emption which renders them unfit to solve the long-standing issue of non-pre-emption of tasks in P/M scheduling. To address this issue, the contiguous-cells transportation model (CCTM) was proposed in [7]. However, the CCTM considers a single objective, as against multiple and conflicting objectives which is obtainable in many practical cases. This limitation of the CCTM is addressed by the development of the MOCCTM

3. Model formulation

3.1. Problem definition

3.1.1. Problem definition

The Multi-Objective Contiguous-Cells Transportation Problem is stated mathematically as follows:

Given Q objectives to be considered, with a relative weight of importance assigned to a specific objective; M distinct items for processing; T periods available for alternate operations and processing, (in which processing is carried out without pre-emption); determine the set of contiguous periods y_{ij} (i.e. contiguous-cells) required for processing each item, which provides a compromise solution for the Q objectives.

3.1.2. Notations

Notations of parameters and variables of the MOCCTM are similar to those from the contiguous-cells transportation model, as presented by Charles-Owaba et al [7]. However, considerations are given to cater for the multi-objective situation of the problem. Notations used in the model formulation are as follows;

i : Index indicating the item to be processed

j : Index indicating the time period of contiguous-cells

α: Index indicating a particular objective

M : Total number of items to be processed

T : Total number of periods in planning horizon

B_i : Number of periods required to process item i

t_i : Number of periods item i stays in the system

H_i : Period in which processing was completed on item i

k_i : Period in which item i is ready for processing

s_i : Period at which activities commence on item i

I_i : Number of periods item i waited before being attended to

A_j : Available processing capacity at period j

Q: Total number of decision objectives of interest

w: Weight representing the relative importance of a particular objective

Observe that $s_i = k_i$ if activities or processing commence in item i as soon as it is ready or arrives and $s_i \geq k_i$ if activities commence on i at a later period.

y_{ij} : A contiguous variable defined as;

$$y_{ij} = \begin{cases} B_i, & number\ of\ contiguous - cells\ commencing\ from \\ & (j - B_i + 1)th, \quad if\ cell\ j\ is\ the\ last\ cell\ among \\ & contiguous - cells\ assigned\ for\ the\ task \\ 0, & otherwise \end{cases} \quad (1)$$

3.1.3. Model Assumptions

Assumptions for the MOCCTM general formulation for preventive maintenance scheduling are adopted from the contiguous-cells transportation model, as presented in [7], with inclusions to cater for multi-objective situation of the problem. The assumptions of the model are as stated below:

The total numbers of periods (T) are fixed and contiguous.

An item is either on queue or in for processing at any moment.

The time (period) in which an item is ready for processing is known.

An item visits the processing facility only once within a planning horizon.

An item that is ready for processing has its activities commencing only when resources are available. Otherwise, it waits.

The problem parameters are known.

Many objectives are considered and span over the contiguous period.

The length of a period may be in any unit of time (i.e. seconds, minutes, hours, days, weeks, month etc.).

When an item is ready, activities commence at the beginning of the period while completion is at the end of the period.

Pre-emption is not allowed (i.e. once processing begins on an item, it remains until completion without interruption).

A member in the set of objectives considered has to be independent.

3.1.4. General MOCCTM formulation

Let Q be the set of objectives considered; α be a decision objective and $U_{ij\alpha}$ be the expression for objective α, with known dimensions. {where α = 1, 2, 3, 4…. Q}

For any specific situation, the expression for $U_{ij\alpha}$ must be known. Let $V_{ij\alpha}$ be the dimensionless equivalent of $U_{ij\alpha}$.

Then:

$$V_{ij\alpha} = f_\alpha(U_{ij\alpha}, r_\alpha) \tag{2}$$

Where r_α connotes normalisation factor of α^{th} objective. Adopting the Linear Min-Max normalisation method in [20], $V_{ij\alpha}$ in equation (2) is defined as:

$$V_{ij\alpha} = \begin{cases} \dfrac{U_{ij\alpha(max)} - U_{ij\alpha}}{U_{ij\alpha(max)} - U_{ij\alpha(min)}} \; ; \; if \;\; \alpha \; is \; to \; be \; minimised \\ \\ \dfrac{U_{ij\alpha} - U_{ij\alpha(min)}}{U_{ij\alpha(max)} - U_{ij\alpha(min)}} \; ; if \; \alpha \; is \; to \; be \; maximised \end{cases} \tag{3}$$

Also, let w_α be the relative weight of importance of objective α, as decided by the model user and $V_{ij\bullet}$ be the total value of all the K objectives considered.

Then:

$$V_{ij\bullet} = \sum_{\alpha=1}^{Q} w_\alpha f_\alpha(U_{ij\alpha}, r_\alpha) = \sum_{\alpha=1}^{Q} w_\alpha V_{ij\alpha} \tag{4}$$

Where;

$$\sum_{\alpha=1}^{Q} w_\alpha = 1 \tag{5}$$

Since the contiguous-cells concept is that of completing the processing of items without pre-emption, then the objectives are evaluated as ‘cumulative’ over the set of contiguous periods. For contiguity, if k_i is the period item i is ready for processing and H is any period in which processing is completed on item i (where k_i and H are members of T); and $\tilde{V}_{ij\bullet}$ is the cumulative value of all Q objectives, from the beginning of period k_i to the end of period H.

Then:

$$\tilde{V}_{ij\bullet} = \begin{cases} \sum_{j=k}^{H} V_{ij\bullet} \quad ; \quad if \ j \ \geq \ H \\ \\ - \quad ; \quad if \ j \ < \ H \end{cases} \tag{6}$$

'-' in the equation implies that the period is not contiguous with other periods.

Table 1 Transportation Tableau for Multi-Objective Contiguous-Cells Case

J / I	1	2	3	4	---	T	Supply
1	–	$\tilde{V}_{12\bullet}$	$\tilde{V}_{13\bullet}$	$\tilde{V}_{14\bullet}$		$\tilde{V}_{1T\bullet}$	
2	—	—	—	$\tilde{V}_{24\bullet}$		$\tilde{V}_{2T\bullet}$	
3	—	—	$\tilde{V}_{33\bullet}$	$\tilde{V}_{34\bullet}$		$\tilde{V}_{3T\bullet}$	
⋮							
⋮							
M	—	—	—	—		$\tilde{V}_{MT\bullet}$	
Demand							

From Transportation Tableau (1), the items i (where i = 1, 2, 3…M) are represented vertically while periods j (i.e. the periods for contiguous-cells), (where j = 1, 2, 3…T) are represented horizontally. $\tilde{V}_{ij\bullet}$ is the cumulative value of all Q objectives across the contiguous periods (i.e, the summation of the weighted normalised values of all objectives from the 'beginning of start period' to the 'end of finish period'). By applying equation 5 to Table 1 above, expressions for $\tilde{V}_{13\bullet}$, $\tilde{V}_{24\bullet}$, $\tilde{V}_{33\bullet}$ and $\tilde{V}_{MT\bullet}$, as illustrations for obtaining values of cumulative dimensionless objectives are as follows:

$$\tilde{V}_{13\bullet} = \sum_{j=1}^{3} V_{1j\bullet} \ ; \ \tilde{V}_{24\bullet} = \sum_{j=1}^{4} V_{2j\bullet} \ ; \ \tilde{V}_{MT\bullet} = \sum_{j=1}^{T} \tilde{V}_{Mj\bullet} \tag{7}$$

3.1.5. Development of objective function and constraints

For the objective function, the actual period for processing item i is considered since processing of the item may not start at the beginning of the arrival period.

Now let $Ɣ_{ij}$ be the value of the combined objectives for item i from the beginning of the start period (i.e k_i or s_i) to the end of finish period H. Then $Ɣ_{ij}$ is defined as follows:

$$Ɣ_{ij} = \begin{cases} \sum_{j=si}^{H} V_{ij\bullet} \quad ; \quad if \ \ si > ki \\ \\ \sum_{j=ki}^{H} V_{ij\bullet} \quad ; \quad if \ \ si = ki \end{cases} \tag{8}$$

Note that V_{ij} represent the value of the combined Q objectives for processing item i in any period j within the set of contiguous periods for item i. Since $Ɣ_{ij}$ is for all B_i contiguous-cells, then V_{ij} is given by the expression:

$$\mathrm{V}_{ij} = \frac{\mathrm{Y}_{ij}}{B_i} = \frac{1}{B_i}\left(\sum_{j=s}^{H} V_{ij\bullet}\right) \quad (9)$$

For item i across T periods, the 'actual' cumulative value of the objectives becomes:

$$Z(T, y_{ij}) = \sum_{j=1}^{T} \mathrm{V}_{ij}\, y_{ij} \quad (10)$$

For all M items, the cumulative value of the objectives across T periods (i.e. the objective function) is given by:

$$Z(T, M, y_{ij}) = \sum_{i=1}^{M}\sum_{j=1}^{T} \mathrm{V}_{ij}\, y_{ij} \quad (11)$$

The demand and supply constraints are given in equations (12) and (13) respectively as expressed by [10]:

$$\sum_{i=1}^{M} \frac{y_{ij}}{B_i} \le A_j \quad (12)$$

The supply constraint which caters for pre-emption is given by:

$$\sum_{j=1}^{T} y_{ij} = B_i \quad (13)$$

Re-writing equation (11) from equations (8) and (9); and combining equations (4), (5), (12) and (13), the general MOCCTM is given by:

$$Optimize \quad Z(w_\alpha, T, M, y_{ij}) = \sum_{i=1}^{M}\sum_{j=1}^{T} \frac{y_{ij}}{B_i}\left(\sum_{j=s}^{H} V_{ij\bullet}\right)$$

Subject to: (14)

$$\sum_{i=1}^{M} \frac{y_{ij}}{B_i} \le A_j; \quad and \quad \sum_{j=1}^{T} y_{ij} = B_i$$

where;

$V_{ij\propto}, V_{ij\bullet}$ *and* $w_\propto$ *are as given in equations* (3), (4) *and* (5) and $U_{ij\alpha}$, r_α, M, w_α, T are as earlier defined.

3.2. The Multi-Objective Contiguous-Cells Transportation Algorithm (MOCCTA)

The algorithm to be employed for solving the MOCCTM is similar to the conventional 'least cost' method of solving transportation problems. This algorithm will make use of allocation by maximum/minimum combined objectives ($\tilde{V}ij\bullet$) and is stated as follows:

Step 1 For each item, select the $\tilde{V}ij\bullet$ value in the last (Tth) period on the contiguous-cells transportation tableau, and divide the $\tilde{V}ij\bullet$ value by the total number of contiguous cells to obtain the average $\tilde{V}ij\bullet$ value.

Step 2 Start with the item having the lowest/highest average $\tilde{V}ij\bullet$ for maximize/minimize cases respectively.

Step 3 Allocate all the supply in that row (to satisfy the contiguity condition) whilst simultaneously meeting the demand constraint.

Step 4 Repeat the procedure from step 1 if the duration in the row and capacity in the column are satisfied for the scheduled item. But in case there is no capacity to accommodate the duration for the item, move to the next available period that can accommodate he capacity constraint for the duration on that row and schedule the item. (Note that moving to the next period for any item connotes re-scheduling of the item, thereby changing the start period from ki to si).

3.3. Solution procedure for the MOCCTM

Step 1 Obtain the values of the parameters of the problem (Q, T, M, , Bi, Aj, ki,).

Step 2 Convert the values of all Q objectives into dimensionless (i.e. normalised) values, using the linear min-max normalisation method in equation (3).

Step 3 Assign relative weights of importance to all Q objectives (as perceived by the model user), such that the sum of weights for all objectives must be equal to 1.

Step 4 Compute Vij● (i.e the total value of all the Q objectives) to be the value in each cell using equation (4), and by computing Ṽij● using equation (6), develop the MOCCTM transportation tableau as depicted in Table (1).

Step 5 Apply the MOCCTA to the tableau to determine the optimal yij for the contiguous perio, d. The optimal yij gives the optimal schedule considering all the Q objectives.

Step 6 Using the optimal yij obtained from the MOCCTM transportation tableau, determine the compromise solution to the Q objectives independently.

4. Numerical example

The proposed MOCCTM approach is illustrated with a hypothetical bi-objective non-pre-emptive maintenance scheduling problem of 5 production machines, across an operation and maintenance planning horizon of 10 periods with the objective of minimizing the total preventive maintenance cost and total production losses. The capacity of the maintenance facility is 2 machines per period.

4.1. Step1 Identify all Problem Parameters

The problem parameters are given in Tables 2, 3 and 4 below.

Number of objectives (Q) = 2;

Table 2 Machine arrival period and maintenance duration

Machine	Arrival period	Periods required for maintenance
1	3	3
2	1	4
3	4	3
4	7	2
5	5	3

Note that the ‘demand per period’ is taken as ‘available maintenance capacity per period’, and the ‘supply per machine’ is taken as ‘maintenance duration per machine.

The preventive maintenance cost (Uij1) and units produced (Uij2) per machine for each period respectively, are given in Tables 3 and 4.

Table 3 Maintenance cost for each machine for each period (in million)

	1	2	3	4	5	6	7	8	9	10
1			15	21	9	13	25	15	10	18
2	17	20	11	8	10	14	22	15	9	13
3				12	16	13	14	9	24	10
4							12	16	21	14
5					10	12	8	19	10	9

Table 4 Units produced per period for each machine

	1	2	3	4	5	6	7	8	9	10
1			70	159	110	98	196	147	50	87
2	68	120	145	200	185	136	85	153	94	130
3				106	95	174	158	90	124	100
4							75	200	175	140
5					95	185	88	102	100	90

4.2. Step 2 Normalization of the objectives

The normalized maintenance cost for machine 1 in period 9 (U_{191}) is given by equation (3). From Table 3 $U_{ij1(max)}$ = 25, $U_{ij1(min)}$ = 9 and $U_{ij\alpha}$ = 10. Using equation (3), the normalized = 0.94. Similarly, the normalized value for the second objective which production quantity for machine 3 for period 7 is 0.19. The normalized value of the maintenance cost and production for all the machines and periods are shown in Tables 5 and 6 as follows:

Table 5 Normalized maintenance cost for all machines and period

	1	2	3	4	5	6	7	8	9	10
1			0.63	0.25	1	0.75	0	0.63	0.94	0.44
2	0.36	0.14	0.79	1	0.86	0.57	0	0.5	0.93	0.64
3				0.8	0.53	0.73	0.67	1	0	0.93
4							1	0.56	0	0.78
5					0.82	0.64	1	0	0.82	0.91

Table 6 Normalized production loss for all machines and period

	1	2	3	4	5	6	7	8	9	10
1			0.86	0.25	0.59	0.67	0	0.34	1	0.75
2	1	0.61	0.42	0	0.11	0.48	0.87	0.36	0.8	0.53
3				0.81	0.94	0	0.19	1	0.6	0.88
4							1	0	0.2	0.48

4.3. Step 3 Assign Weights Objectives For the purpose of illustration

A weight of 0.6 is assigned to maintenance cost and 0.4 is assigned to production loss and each entry in Tables 5 and 6 were multiplied by 0.6 and 0.4 respectively, as shown in Tables 7 and 8. Observe that weights may be elicited from the Decision Maker or use any of methods mentioned in [20].

Table 7 Weighted maintenance cost per period

	1	2	3	4	5	6	7	8	9	10
1			0.38	0.15	0.6	0.45	0	0.38	0.56	0.26
2	0.21	0.09	0.47	0.6	0.51	0.34	0	0.3	0.56	0.39
3				0.48	0.32	0.44	0.4	0.6	0	0.56
4							0.6	0.33	0	0.47
5					0.49	0.38	0.6	0	0.49	0.55

Table 8 Weighted production loss per period

	1	2	3	4	5	6	7	8	9	10
1			0.35	0.1	0.24	0.27	0	0.13	0.4	0.3
2	0.4	0.24	0.17	0	0.05	0.19	0.35	0.14	0.32	0.21
3				0.32	0.38	0	0.08	0.4	0.24	0.35
4							0.4	0	0.08	0.19
5					0.37	0	0.4	0.34	0.35	0.39

4.4. Step 4 (Computation of $V_{ij\bullet}$, $\tilde{V}_{ij\bullet}$ and the MOCCT Tableau)

$V_{ij}\bullet$ is computed using equation (4), by adding the corresponding entries in Tables 7 and 8. The $V_{ij}\bullet$ values are computed and shown in Table 9.

Table 9 Sum of weighted objectives ($V_{ij\bullet}$)

	1	2	3	4	5	6	7	8		9	10
1			0.72	0.25	0.84	0.72	0	0.51		0.96	0.56
2	0.61	0.33	0.64	0.6	0.56	0.54	0.35	0.44		0.88	0.6
3				0.8	0.7	0.44	0.48	1		0.24	0.91
4							1	0.33		0.08	0.66
5					0.86	0.38	1	0.34		0.84	0.94

The value for $\tilde{V}_{ij}\bullet$ is obtained using equation (6). For illustration, the first $\tilde{V}_{ij}\bullet$ entry for machine 1 = (0.72 + 0.25 + 0.84) = 1.81. The $\tilde{V}_{ij}\bullet$ entries are as shown in MOCCT Tableau 10.

Table 10 MOCCT tableau

	1	2	3	4	5	6	7	8	9	10	B_i
1			---	---	1.81	2.53	2.53	3.03	4	4.56	3
2	---	---	---	2.18	2.74	3.28	3.63	4.07	4.95	5.54	4
3				---	---	1.94	2.42	3.42	3.65	4.57	3
4							---	1.33	1.41	2.07	2
5					---	---	2.24	2.59	3.43	4.36	3
A_j	2	2	2	2	2	2	2	2	2	2	

4.5. Step 5 Application of MOCCTA

On applying the MOCCTA to Table 10, the order of schedule from the first machine to the last machine is obtained as follows:

Machine 1 = (4.56÷8) = 0.57

Machine 2 = (5.54÷10) = 0.554

Machine 3 = (4.57÷7) = 0.653

Machine 4 = (2.07÷4) = 0.518

Machine 5 = (4.36÷6) = 0.727

Since the case under study is a minimisation problem, we start allocation of cells with the machine with the highest average $\tilde{\mathbf{V}}_{\mathbf{ij\bullet}}$ value and continue in descending order (i.e. machine, 5 – 3 – 1 – 2 – 4) as shown in Table 11:

Table 11 Final Schedule

	1	2	3	4	5	6	7	8	9	10	B_i
1			---	---	1.81	2.53	2.53	3.03	4	4.56	3
2	---	---	---	2.18	2.74	3.28	3.63	4.07	4.95	5.54	4
3				---	---	1.94	2.42	3.42	3.65	4.57	3
4							---	1.33	1.41	2.07	2
5					---	---	2.24	2.59	3.43	4.36	3
A_j Capacity	2	2	2	2	2	2	2	2	2	2	

4.6. Step 6 Determination of compromise values of maintenance cost and production loss

Given the final schedule in Table 11, the respective values of maintenance cost and production loss are obtained from Tables 3 and 4 as presented in Table 12. The relevant parameters are defined as follows;

MC_i: Maintenance cost of i^{th} machine over the B_i periods

PL_i: Production loss of i^{th} over the B_i periods when it was under maintenance

PLI_i: Production loss of i^{th} machine due to idleness. While waiting for maintenance work to commence on it.

OP_i: Number of periods i^{th} machine spent in operation producing units of products. Note that $OP_i = T - B_i$.

IP_i: Number of periods, the i^{th} machine stayed in the maintenance facility while waiting for maintenance to commence. Observe that $IP_i = s_i - k_i$

TPL_i: Total production loss due to waiting time on queue and maintenance (i.e. total time in the maintenance system). That is, $TPL_i = PL_i + PLI_i$

5. Results and discussion

The maintenance costs, production losses due to waiting time before maintenance, production losses due to time taken to actually carry out the maintenance and their respective durations are presented in Table 12.

Table 12 Costs and Production Losses Associated with Maintenance schedule

Machine (i)	**MC_i in (million)**	**PLi (units)**	**PLI_i (units)**	**OP_i (periods)**	**IP_i (periods)**	**TPL_i (units)**
1	50	393	437	3	4	830
2	56	533	-	6	0	533
3	41	375	-	7	0	375
4	37	375	75	7	1	450
5	30	368	-	7	0	368
Total for all machines	214	2,044	512	30	5	2,556

Table 12 shows that the algorithm gives total operations period {3, 6, 7, 7, 7} with idle periods {4, 0, 0, 1, 0} for machines {1, 2, 3, 4, 5} respectively. The production loss for machines 2, 3 and 5 are losses accrued across the contiguous periods of maintenance. However, there is an additional production loss of 437 units for machine 1; and 75 units for machine 4 due to the idleness across periods 3 to 6; and 7 respectively on Table 11. The idleness is as a result of unavailable maintenance capacity on arrival of machine 1 and 4, leading to a re-scheduling. This takes the total production loss of machine 1 and 4 to 830 and 450 units respectively. The total preventive maintenance cost and production loss over the planning horizon are 214 million and 2,556 units respectively.

The merit of the proposed approach is the ability to give the best compromise preventive maintenance schedule in a multiple objective decision situation under the existing conditions. The computed values provide insight for management on areas requiring improvement for the system to be more efficient. For instance, in real world situations, attention of management would be how to reduce production loss due to time spent on queue at the maintenance facility.

6. Conclusion

This study proposed the Multi-Objective Contiguous-Cells Transportation Model as an extension of the Contiguous-Cells Transportation Model, to cater for cases where more than one objective is of interest in non-pre-emptive scheduling. The model was developed by adequately identifying and defining the variables and parameters of the problem. An efficient solution procedure of was also proposed, with a numerical example to illustrate the application of the model. The results obtained from the numerical example show that the model is a good approach that researchers can employ to solve multi-objective preventive maintenance scheduling problems in a non-pre-emptive environment. A proposition for further research is to apply the model to a real-life problem and to study the behaviour of the model in response to varying the parameters of the model.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors have seen and approved the article in the form presented for publication, and declare that there are no potential conflicts of interest with respect to the research, authorship and publication of this article

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