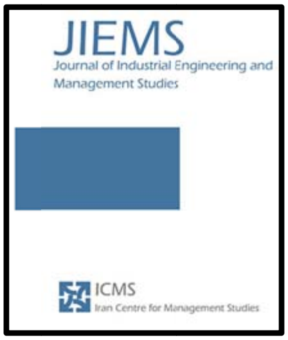
JIEMS

Journal of Industrial Engineering and Management Studies

Vol. 2, No. 1, pp. 61-73

www.jiems.icms.ac.ir



Virtual manufacturing cells scheduling considering lot-streaming and sequence dependent setup times

A.Ayough[1]*, A. Alem Tabriz[2], A. Javani [3]

Abstract

In this paper, a new mathematical model for the problem of job scheduling in virtual manufacturing cells (VMC) is presented to minimizing the completion time of all jobs. Sequence dependent setup times of machines is considered and lot-streaming is possible. In Virtual manufacturing cells, each job has a different processing path and there is a set of machines for processing each operation. There are multiple machine types with several identical machines in each type locating in different locations in the shop floor. In this type of system, the cells are not physical and Machines can be shared between the cells. In Mixed-integer nonlinear programming model presented, the scheduling decisions involve assigning a machine to each operation, the start time at each operation, the start time of machines and sub-lot sizes of each job. Some test problems have been generated to demonstrate the implementation of the model and solved by Lingo.

Keywords: virtual manufacturing cells; Scheduling; lot-streaming; Mathematical model; integer programming.

Received: March 2014-30

Revised: May 2014-17

Accepted: August 2014-09

1. Introduction

Today's competitive market has led the manufacturing companies to improve their production capabilities. This competitive and turbulent market conditions have resulted in a new generation of companies that are dynamically linked to production needs. In a dynamic environment, composition and volume of product demand are variant from a period to another period that this variability needs decision-making and planning in a dynamic environment and flexibility. Therefore, cellular manufacturing system (CMS) was introduced.

In CMSs, shop floor is divided into more manageable units by physically grouping the machines. In the cell formation Phase, it is assumed that demand is constant throughout the product lifecycle. If demand is unstable, CMS is not able to meet changes in demand. In such a case, dynamic cellular manufacturing system (DCMS) can be used based on multi-period planning horizon. In a way that

---

[1] Management Department, Caspian institute, Qazvin, Iran.

* Corresponding Author

[2] Department of Industrial Management, Shahid Beheshti University, Tehran, Iran.

[3] Department of Industrial Management, Kar Higher Institute, Qazvin, Iran

at the start of each period, cells are reconfigured. When the demand change is high, replacement equipment will cost a lot. Some researchers suggested, virtual manufacturing cell (VMC) to overcome the defects of traditional CMS. In this type of system, the cells are not physical and we can have shared machines between cells. Logical grouping of jobs and machines are only in the production control system and the imagination of workers. A new approach to layout at VMC, is the scattered arrangement in which for increasing the availability, similar machines are scattered throughout the shop floor. This paper addresses the VMC problem with lot-streaming tactic.

Researches have done on the scheduling of virtual manufacturing cells. If, due to performing various operations by each vehicle (machines sharing between cells), at no one, preparation time sequence dependent machinery is not considered. While this can lead to the calculation of real and direct impact on the completion of all jobs. In this study, we focus on the scheduling of operations in VMC with scattered layout and consider sequence dependent setup time to thereby minimize the completion time of all jobs and the distance traveled by the work. We also consider lot streaming strategy that provides the ability to split the jobs.

2. Literature review

MacLean et al. for the first time in 1982 introduced the concept of virtual manufacturing cells. According to them virtual cell is not as a physical grouping of machinery, but it is as data files and processes on a controller computer (MacLean et al. 1982). Irani et al. developed a two-stage flow based approach for formation of VMCs with an objective of minimizing traveling distances (Irani et al. 1993). Kannan and Ghosh in 1996, Kannan in 1997 and 1998 explored the many part-family based scheduling rules in process layout (Kannan VR. 1997). In 2003, Ko and Egbelu presented a methodology for designing VMCs. They carried out a comparative study of dynamic and static manufacturing systems at the intent of examining the influence of variations in the product mix on the shop performance. The total preparation time and total distance transport components were considered as a measure of performance (Ko K-C and Egbelu PC. 2003). Mak et al. provided a non-linear programming for scheduling VMCs and ant colony optimization algorithm is presented (Mak et al. 2007). Kesen et al. in 2009 compared three types of cell systems, processes and virtual cells using simulation (Kesen et al. 2009). Kesen et al. gave mixed integer linear programming model with objective function for minimizing job completion time and distance jobs profiting (Kesen et al. 2010). In 2012 its previous models developed so that the job could be divided into smaller tasks (lot streaming) (Kesen SE. and Gungor Z. 2012).

3. Problem description and model formulation

3.1. Virtual manufacturing cells

The main difference between VMC system and CMS systems is how they respond to changes in demand. In cellular manufacturing system due to the use of physical constant groups of the machine, there is a limitation to respond appropriately to changes in demand. But in virtual manufacturing cells, the cells are not physical and logical grouping of tasks, machines and workers are only in the production control system and the perceptions of workers. As a result, these cells can easily change to respond to changes in demand at the beginning of each period. In VMC systems, from any machine more than one machine is unique. Unique machines spread throughout the shop floor (Sort distributed) and each can have a different speed. In these systems a machine can belong to more than one cell at the same time.

Given the above assumptions, a VMC system can be shown in Figure 1.

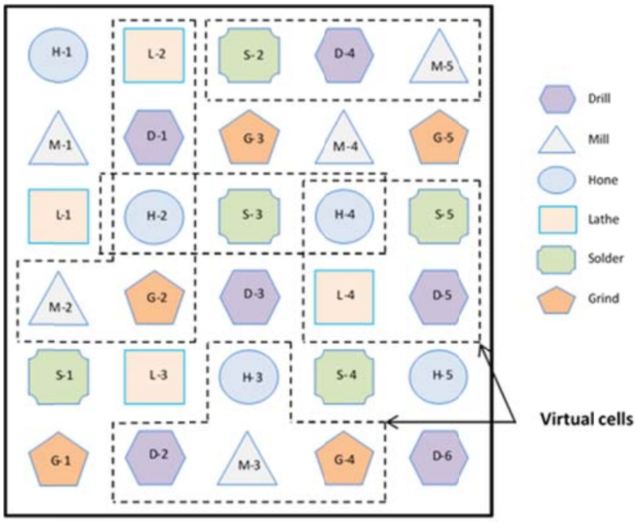


Figure 1. Schematic representation of VMCs layout

Because VMCs are proposed for small-sized and medium-sized companies that perform batch production, lot-streaming strategy has to be considered in the VMC scheduling problem. The majority of the aforementioned papers have assumed that set-up times are sequence-independent and are either negligible or included in processing times. While this assumption simplifies the analysis and/or reflects certain applications, it adversely affects the solution quality of many applications of scheduling that require an explicit treatment of set-up times (Allahverdi et al. 2010). In many manufacturing systems, the sequence of jobs processed on a machine affects set-up times. Changing production plan from a part into another one can spend a significant set-up time and effort. Therefore, sequence-dependent set-up times can be considered as an important factor in the operations scheduling.

3.2. Problem description

In this study, a model is proposed for the scheduling of virtual manufacturing cells. The mixed integer linear programming model will be a single objective, which is also the goal of minimizing.

Model inputs include the time of each operation, the number of jobs, batch size, operations for each job and sequence of them. Also the number of machine types and the number of each type of machine, sequence dependent setup time and travelling time between machines are needed.

In the problem of virtual manufacturing cells scheduling, we have m machines and n jobs so that each job involves h_j successive operations. o_{jh} is hth operation of job j and P_{ijh} shows the unit processing time of operation o_{jh} on machine i. jobs are produced in Groups that lot size of job j is shown by N_j. Lot-streaming is allowed since there are alternative machines for operation o_{jh}. So, successive operations can be overlapped. Since machines are positioned in different locations in the layout, after the operation o_{jh} is completed on machine i and before the operation $o_{j,h+1}$ is started on machine k, d_{ik} unit of travelling time occurs for job j. S_{ifj} is setup time for machine i while it is working for job *f* and now it wants to do job *j*. so s_{ij} is setup time for machine i while it is standby and now it wants to do job *j*. As a result, according to the amount of operations S_{ifj} or S_{ij}, setup time between two sequence for machine i must be considered.

Problem of VMC scheduling includes:

- Assigning proper machine to each operation
- Obtain the sub lot size for each job
- Calculated the starting time of each operation
- Determine the time to start the job in any order

All of the above should be selected so that all jobs will be done in the shortest time possible.

The following assumptions should be considered:

- Operations must be performed one after another according to the problem input
- Each machine can only perform one operation at a single time.
- Sequence of operations, setup time depends on the sequence, process time, batch size and the travelling time between the machines are pre-determined.
- The machines are fixed and do not change their location.
- Number of sub-lot for all jobs is fixed and known in advance.
- All job must be available at time zero and is not acceptable in any new work.
- Each job can visit any machine at most once.
- There is no preference for doing Jobs.
- Machine Breakdown and maintenance activities are not considered.

Parameters:

i,k: indices for machine (i, k=1, . . . ,m) where m is the number of machines in the system

j,f: indices for job (j=1, . . . , n) where n is the number of jobs in the system

h,r: indices for operation (h=1, . . . , hj) where h_j is the number of operations to be performed for job j

p,q: indices for sub-lot (p=1, . . . ,L) where L is the number of sub-lots

l: indices for order on each machine (l=1, . . . , li) where li is the number of operations assigned to machine i

N_j: lot size for job j

P_{ijh}: unit processing time of operation o_{jh} on machine i

d_{ik}: travelling time between machine i and k

S_{ij}: machine i setup time for doing job j while machine i was standby

S_{ifj}: machine i setup time for doing job j while machine i was do job f in previous order.

SQ_{jhi}: 1 if machine i capable of doing *j*th operation of job j to be, 0 otherwise.

M: sufficiently big number

Decision variables

C_{max}: makespan or maximum completion time of jobs to leave the system

V_{jp}: number of parts to be produced for job j in lot p

Y_{ijhp}: 1 if machine i is selected for the *p*th lot of operation o_{jh}, 0 otherwise

X_{ijhlp}: 1 if operation o_{jh} for lot p is performed on machine i in order l, 0 otherwise
Z_{ikjhp}: 1 if operation o_{jh} is performed on machine i and operation $o_{j,h+1}$ is performed on machine k, 0 otherwise.
t_{jhp}: starting time of operation o_{jh} for the *p*th lot
Tm_{il}: starting time of work on machine i in order l

Minimize $C_{\max}$
Subject to

$$C_{\max} \geq t_{jhp} + V_{jp}P_{ijh} - M(1 - Y_{ijhp}) \quad \forall i,j,h,p \qquad (1$$

$$\sum_p V_{jp} = N_j \quad \forall j \qquad (2$$

$$t_{jhp} + V_{jp}P_{ijh} - M(1 - Y_{ijhp}) + \sum_k d_{ik} Z_{ikjhp} \leq t_{j,h+1,p} \qquad \forall i,j,p,h : i \neq k, h \neq h_j \qquad (3$$

$$Tm_{il} + S_{ij}X_{ijhlp} + V_{jp}P_{ijh} \leq Tm_{i,l+1} + M(1 - X_{ijhlp}) \qquad \forall i,j,h,l,p : l = 1 \qquad (4$$

$$Tm_{il} + \sum_f \sum_r \sum_q S_{ifj}(X_{ifr,l-1,q})(X_{ijhlp}) + V_{jp}P_{ijh} \leq Tm_{i,l+1} + M(1 - X_{ijhlp})$$
$$\forall i,j,h,l,p : l \neq l_i, l \geq 2 \qquad (5$$

$$Tm_{il} + S_{ij}X_{ijhlp} \leq t_{jhp} + M(1 - X_{ijhlp}) \quad \forall i,j,h,l,p : l = 1 \qquad (6$$

$$Tm_{il} + \sum_f \sum_r \sum_q S_{ifj}(X_{ifr,l-1,q})(X_{ijhlp}) \leq t_{jhp} + M(1 - X_{ijhlp}) \quad \forall i,j,h,l,p : l \geq 2 \qquad (7$$

$$Tm_{il} + S_{ij}X_{ijhlp} \geq t_{jhp} - M(1 - X_{ijhlp}) \quad \forall i,j,h,l,p : l = 1 \qquad (8$$

$$Tm_{il} + \sum_f \sum_r \sum_q S_{ifj}(X_{ifr,l-1,q})(X_{ijhlp}) \geq t_{jhp} - M(1 - X_{ijhlp}) \quad \forall i,j,h,l,p : l \geq 2 \qquad (9$$

$$\sum_j \sum_h \sum_p X_{ijhlp} \leq 1 \quad \forall i,l \qquad (10$$

$$\sum_j \sum_h \sum_p X_{ijh,l+1,p} \leq \sum_j \sum_h \sum_p X_{ijhlp} \quad \forall i,l : l \neq l_i \qquad (11$$

$$\sum_i Y_{ijhp} \geq 1 \quad \forall j,h,p \qquad (12$$

$$Y_{ijhp} \leq SQ_{jhi} \quad \forall i,j,h,p \qquad (13$$

$$\sum_l X_{ijhlp} = Y_{ijhp} \quad \forall i,j,h,p \qquad (14$$

$$2Z_{ikjhp} \leq Y_{ijhp} + Y_{kj,h+1,p} \quad \forall i,k,j,h,p : h \neq h_j, i \neq k \qquad (15$$

$$Z_{ikjhp} \geq Y_{ijhp} + Y_{kj,h+1,p} - 1 \quad \forall i,k,j,h,p : h \neq h_j, i \neq k \qquad (16$$

$$V_{jp} \geq \sum_i Y_{ijhp} \quad \forall j,h,p \qquad (17$$

$$Z_{ikjhp} = 0 \quad \forall i,k,j,h,p : i = k \qquad (18$$

$$Z_{ikjhp} = 0 \quad \forall i,k,j,h,p : h = h_i \qquad (19$$

$$C_{\max} \geq 0 \qquad (20$$

$$V_{jp} \geq 0 \text{ and integer} \quad \forall \mathrm{j,p} \qquad (21$$

$$t_{jhp} \geq 0 \quad \forall j,h,p \qquad (22$$

$$Tm_{il} \geq 0 \quad \forall i,l \qquad (23$$

$$Y_{ijhp} \in \{0,1\} \quad \forall i,j,h,p \qquad (24$$

$$X_{ijhlp} \in \{0,1\} \quad \forall i,j,h,l,p \qquad (25$$

$$X_{ifrlq} \in \{0,1\} \quad \forall i,f,r,l,q \qquad (26$$

$$Z_{ikjhp} \in \{0,1\} \quad \forall i,k,j,h,p \qquad (27$$

Objective function is to minimize the make span value that is used in order to minimize the total completion time of jobs. Constraint (1) ensures that the make span is greater or equal to the completion of all jobs. Constraint number (2) shows that summation of sub-lot size is equal to lot size for each job. Constraint set (3) guarantees that the succeeding operation of any job for any sub-lot can be started only after the preceding operation is completed and transported between respective machines. Constraint set (4 & 5) enforces that between the consecutive operations to be executed on any machine; the succeeding one can only be started after the preceding one is completed and setup time is spend. Constraint sets (6 & 7 & 8 & 9) guarantee that if X_{ijhlp} is equal to 1 , the starting time of o_{jh} for sub-lot p and the starting time of the work on machine i in order l plus setup time are the same. Constraints number (10) ensures that at most one operation will be done on every machine in order l. Also limits the number (11) shows that for machine i until l has not accepted its operation, it will not be able to get it another operation for order l + 1. Constraint (12) ensures that the o_{jh} for the sub-lot *p* must be assigned to only one machine (Also, it should be allocated to one of the machines). On the constraint number (13) we can say that if machine i has the ability to perform o_{jh}, it can select it. Constraint set (14) makes sure that if operation o_{jh} for sub-lot p is performed on machine i, this operation must be performed on machine i in any order. Constraint sets (15) and (16) ensure that if operation o_{jh} and operation oj,hþ1 for sub-lot p are performed on machine i and k respectively, Z_{ikjhp} can only be equal to 1, 0 otherwise. Constraint set (17) ensures that if operation o_{jh} for sub-lot p is performed on machine i, the number of items to be processed in job j for sub-lot p (ie, sub-lot size) must be greater than zero. The constraints (18) and (19) show that if the machine does not change or is ongoing on the last operation, Z_{ikjhp} value is zero. Constraint numbers (20), (21), (22), (23), (24), (25), (26) and (27) indicate that the variables are non-negative.

Kesen and Gunger in 2012 VMC developed a model for the VMC system scheduling so that the work could be divided into smaller tasks (lot streaming). This model has the following problems:

- ✓ The main problems are the lack of a parameter that indicates the machine is able to perform which operations. To solve this problem we define the parameter SQ_{jhi} and we resolve this problem by taking the Constraints 13.
- ✓ Also there is not suitable Constraints that covers all states of Z_{ikjhp} and For this purpose, Constraints of 18 and 19 were considered.
- ✓ In this model $X_{ijh.l+1,p}$ can be 1 while X_{ijhlp} was 0, that This had a negative impact on Tm_{il}. For example, Tm_{il} value in the first and second order was zero, but in third order, it starts to get value. To solve this problem, Constraint 11 was considered.

4. Numerical examples

To better understand the model, two illustrative examples will be described in the following that the first example is simpler than the second one. These examples are solved by Lingo software Version 14. Also a computer with Intel core i5-4200M 2.50 GHz up to 3.10 GHz processor and 6 GB Ram memory is used.

Example 1: In this example, there are three types of machine A, B and C that for each type, there are two unique machines. Machines number is available in Table 1. The number of sub-lot is 2 and 4 is the maximum number of order in machine.

In this system, there are two jobs that you can see in Table 2. The sequence and process time for each operation and batch size are given in this table. For example, each lot of job 1 meets Type B machine and then Type C machine. However, for type B machine, machine 3 at 25 units and machine 4 at 23 units of time do the operation. Also batch size to produce job 1 is 20 time units. Table 3 represents the setup time of standby mode for different machines (s_{ij}). Table 4 shows sequence dependent setup time for each type of machine. According to the sequence of jobs operation if machine i could not get a job transfer to another job, the sequence dependent setup time can be considered zero. For example, in the case of machine type C, if the machine has finished job 2 and wants to start job 1, setup time will be 8 time units. Table 5 shows the SQ_{jhi} values for each job separately. For example, only machines 3 and 4 can perform a second operation of job 2, they have received amounts 1. Table 6 shows the travelling time between machines.

Table 1: Machine types and individual machines belonging to each machine type

machine type	machine number
A	1 , 2
B	3 , 4
C	5 , 6

Table 2: Lot sizes, operation sequences and process time of the jobs

job j	sequence operation and process time	lot size
1	B(25,23)→C(18,17)	20
2	A(32,35)→B(12,11)→C(15,14)	17

Table 3: Machine setup time from standby mode (S_{ij})

j i	1	2
1 , 2	0	10
3 , 4	5	7
5 , 6	7	3

Table 4: Sequence dependent setup time (S_{ifj})

	A: i=1,2		B: i=3,4		C: i=5,6	
To j From f	1	2	1	2	1	2
1	0	0	0	10	0	10
2	0	0	20	0	8	0

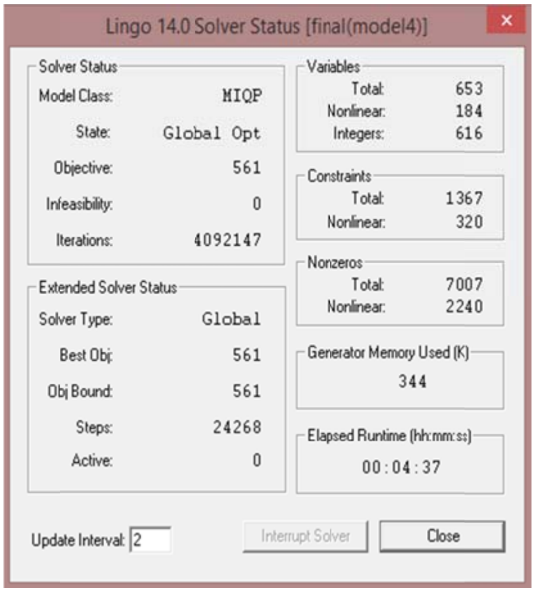
Table 5: the ability of machine i to produce *h*th operation for each job

	i h	1	2	3	4	5	6
j=1	1	0	0	1	1	0	0
	2	0	0	0	0	1	1
	3	0	0	0	0	0	0
J=2	1	1	1	0	0	0	0
	2	0	0	1	1	0	0
	3	0	0	0	0	1	1

Table 6: Travelling time between machines

machine	1	2	3	4	5	6
1	0	3	2	1	2	3
2	3	0	1	4	1	2
3	2	1	0	2	3	1
4	1	4	2	0	1	3
5	2	1	3	1	0	4
6	3	2	1	3	4	0

After coding the above example in lingo and solving it, model outputs that are answers to the example, are shown by figure 3. Also sub-lot 1 and 2 of job 1 include 10 lot for them and sub-lot 1 and 2 of job 2 include 8 and 9 items respectively. As the shortest possible time to complete all the Jobs is 561 time units that is global optimum for this example. The example above was dissolved in 4 minutes and 37 seconds (See Figure 2 in the status window output Lingo). It should be noted that the value of M, is intended one hundred million.



Lingo 14.0 Solver Status [final(model4)]

Solver Status
Model Class: MIQP
State: Global Opt
Objective: 561
Infeasibility: 0
Iterations: 4092147

Extended Solver Status
Solver Type: Global
Best Obj: 561
Obj Bound: 561
Steps: 24268
Active: 0

Variables
Total: 653
Nonlinear: 184
Integers: 616

Constraints
Total: 1367
Nonlinear: 320

Nonzeros
Total: 7007
Nonlinear: 2240

Generator Memory Used (K)
344

Elapsed Runtime (hh:mm:ss)
00:04:37

Update Interval: 2

Figure 2: Lingo status window output in Example 1

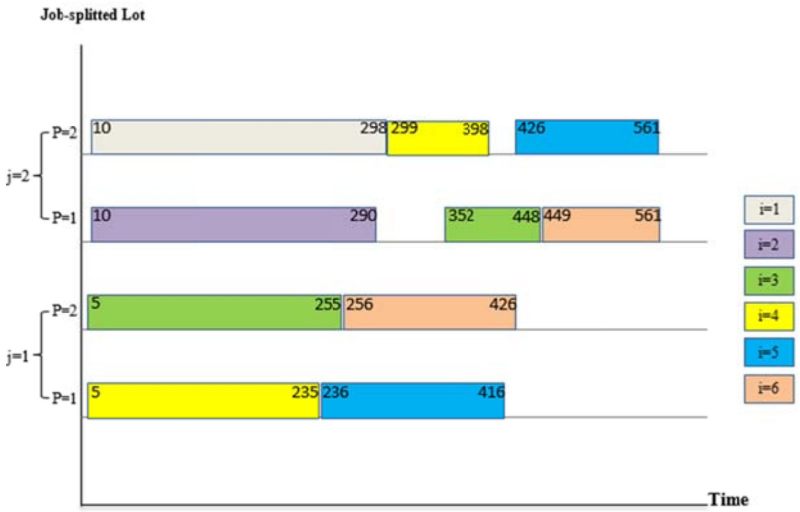


Figure 3: Gantt chart for Test Problem No. 1

As can be seen, all the hypotheses are considered, For example, no machine is working two different jobs at a time and the sequence of operations are involved in doing jobs strictly and sequence dependent setup time is considered.

According to Figure 2, operation o_{21} process starts at 10 by machine 2 and completes in 290. The next operation will start at 352 and end at 448 and finally, the first sub-lot of job 2 after the last operation in the machine 6, the 561 times is ready for delivery.

Lags that occur between the various operations of a job, are Due to the following:

- Time of travelling between machines
- sequence dependent setup time for change job allocated to each machine
- Lack of appropriate machine for the allocation of the next operation

If the setup time was not considered, Completion time of Jobs is reduced to 546. So in order to gain a more realistic calculation, sequence dependent setup time should also be considered. If we do not consider lot streaming and solve above example (p=1), we witness the completion time of the Jobs (make span) increased to 983 times. Thus lot streaming is leading to a reduction of make span, But this does not mean that the number of sub-lot will be further reduced completion time of Jobs, But according to the setup times and travelling time and number of machines, the amount of make span will increase or decrease. In the above example, for P = 3 make span value increased to 578.

Example 2: This example is developed in the previous example, there were 2 jobs in the previous example, but in this example, we are planning to have 3 jobs. Machines Number is available in Table 1. Also, P = 2 and L = 3 is considered. Table 7, shows jobs and sequence operations of them and process time by the appropriate machine. Table 8 and Table 9 show (S_{ij}) and (S_{ifj}) values respectively. SQ_{jhi} values for jobs 1 and 2 is given in Table 6 and for job 3 in Table 10. Time interval between machines is given in Table 5.

Table 7: Lot sizes, operation sequences and process time of the jobs

job j	sequence operation and process time	lot size
1	B(25,23)→C(18,17)	20
2	A(32,35)→B(12,11)→C(15,14)	17
3	C(21,24)→A(25,22)	27

Table 8: Machine setup time from standby mode (S_{ij})

i \ j	1	2	3
1 , 2	0	10	8
3 , 4	5	7	0
5 , 6	7	3	4

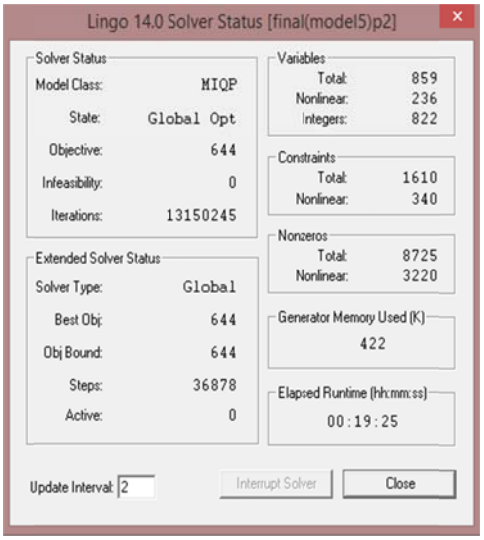
Table 9: Sequence dependent setup time (S_{ifj})

machine type	A : i = 1,2			B: i=3,4			C: i=5,6		
from f \ to j	1	2	3	1	2	3	1	2	3
1	0	0	0	0	10	0	0	10	14
2	0	0	12	20	0	0	8	0	7
3	0	11	0	0	0	0	16	12	0

Table 10: The ability of machine i to produce *h*th operation for each job (SQ_{jhi})

	h \ i	1	2	3	4	5	6
j = 3	1	0	0	0	0	1	1
	2	1	1	0	0	0	0
	3	0	0	0	0	0	0

After the example code in Lingo, optimum solution (global optimum) within 19 minutes and 25 seconds was obtained (Refer to Figure 4). The minimum time for completion of Jobs, 644 time units was achieved. Also V_{11} = 10, V_{12} = 10, V_{21} = 9, V_{22} = 8, V_{31} = 14, V_{32} = 13 was calculated.



Solver Status
Model Class: MIQP
State: Global Opt
Objective: 644
Infeasibility: 0
Iterations: 13150245

Extended Solver Status
Solver Type: Global
Best Obj: 644
Obj Bound: 644
Steps: 36878
Active: 0

Variables
Total: 859
Nonlinear: 236
Integers: 822

Constraints
Total: 1610
Nonlinear: 340

Nonzeros
Total: 8725
Nonlinear: 3220

Generator Memory Used (K)
422

Elapsed Runtime (hh:mm:ss)
00:19:25

Update Interval: 2

Figure 4: Lingo status window output in Example 2

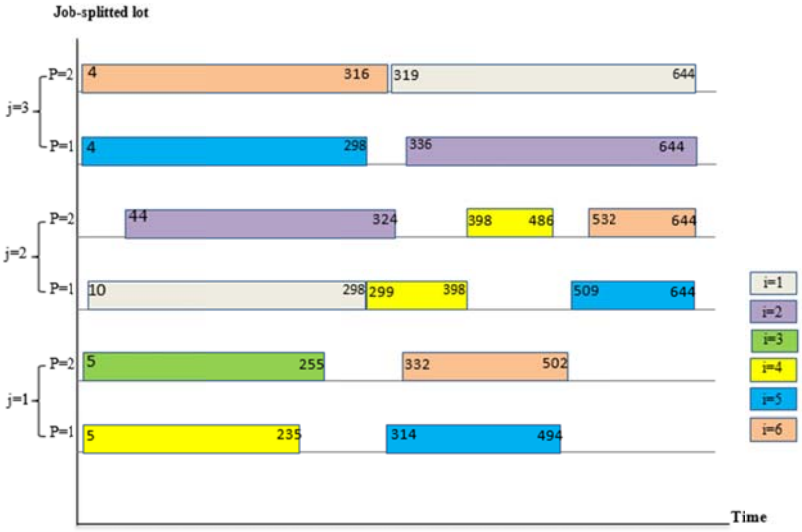


Figure 5: Gantt chart for Test Problem No. 2

5. Discussion and conclusions

Virtual manufacturing cell is mentioned as a future layout. This system places in it both CMS and FMS (flexible manufacturing system) benefits. The main issue addressed in this paper, includes the problem of VMC system scheduling with considering sequence dependent setup time and lot streaming strategy that has not been studied. We have considered the case that there are several jobs and each job is composed of successive operations. There are several types of machine to perform jobs, each of them is composed of multiple machines with different processing times. The machines are scattered throughout the workshop. Travelling time between machines is also considered. We have offered a mixed integer nonlinear programming model in order to calculate minimum completion time of jobs. The most important model outputs are machines assignment, the start time of each operation and the sub-lot size for each job. The size of the make span is very sensitive to the number of sub-lot. This study expansion is in some ways. To solve the large size, Time solution is increased highly by methods exact solution. Hence, the use of meta-heuristic algorithms can be useful for this purpose. Also monitor machine Breakdown and maintenance of a system can lead to the development of models and create new research.

References

1. Allahverdi, A., C. T. Ng, T. C. E. Cheng, & Kovalyov M., 2010. "A Survey of Scheduling Problems with Setup Times or Costs". European Journal of Operational Research 187 (3): 985–1032.
2. Arkat J. & Ghahve H., 2014. "Scheduling of virtual manufacturing cells with outsourcing allowed". International Journal of Computer Integrated Manufacturing: 1079-1089.
3. Baker K.R. 1995. "Lot streaming in the two-machine flow shop with setup times". Annals of Operations Research 57, 1-11.
4. Chen J., & Steiner G. 1998. "Lot streaming with attached setups in three-machine flow shops". IIE Trans 30: 1075–1084.
5. Drolet JR., 1989. "Scheduling virtual cellular manufacturing systems". PhD thesis, Purdue University.
6. Glass C. & Potts C., 1998. "Structural properties of lot streaming in a flow shop". Mathematics of operation research.
7. Hamedi M., Esmaeilian G., Ismail N., Ariffin M., 2012. "Capability-based virtual cellular manufacturing systems formation in dual-resource constrained settings using Tabu Search". Computers & Industrial Engineering: 953–971.
8. Irani SA., Cavalier TM., & Cohen PH. 1993. "Virtual manufacturing cells: Exploiting layout design and intercell flows for the machine sharing problem". Int J Prod Res 31(4): 791–810.
9. Kalir A., Sarin S., 2002. "Constructing Near Optimal Schedules for the Flow-Shop Lot Streaming Problem with Sublot-Attached Setups". Journal of Combinatorial Optimization: 23–44.
10. Kannan VR., Ghosh S., 1996. "Cellular manufacturing using virtual cells". International Journal of Operations and Production Management.
11. Kannan VR., 1997. "A simulation analysis of the impact of family configuration on virtual cellular manufacturing". Production Planning and Control: 14–24.
12. Kesen SE., Toksari MD., Gungor Z., & Guner E. 2009. "Analyzing the behaviors of virtual cells (VCs) and traditional manufacturing systems: Ant colony optimization (ACO)-based metamodels". Comput Opns Res 36(7): 2275–2285.
13. Kesen SE., Das SK., & Gungor Z. 2010. "A mixed integer programming formulation for scheduling of virtual manufacturing cells (VMCs)". Int J Adv Manuf Technol 43(5–8): 665–678.
14. Kesen SE., Das SK., & Gungor Z. 2010. "A genetic algorithm based heuristic for scheduling of virtual manufacturing cells (VMCs)". Comput Opns Res 37(6): 1148–1156.
15. Kesen E. & Gungor Z., 2011. "How important is the batch splitting activity in scheduling of virtual manufacturing cells (VMCs)?" International Journal of Production Research: 1645-1667.
16. Kesen SE., & Gungor Z. 2012. "Job scheduling in virtual manufacturing cells with lot-streaming strategy a new mathematical model formulation and a genetic algorithm approach". Journal of the Operational Research Society, 63, 683–695.
17. Ko K-C , Egbelu PC., 2003. "Performance comparison of static and dynamic cellular manufacturing system". In: Proceedings of the first group technology / cellular manufacturing world symposium.p.1–6.
18. Mak K., Lau J., & Wang X. 2002. "Production Scheduling and Cell Formation for Virtual Cellular Manufacturing Systems". Int J Adv Manuf Technol:144–152.
19. Mak K., Lau J., & Wang X. 2005. "A genetic scheduling methodology for virtual cellular manufacturing systems: an industrial application". International Journal of Production Research: 2423-2450.

20. Mak K., Lau J., & Wang X. 2007. “An ant colony optimization algorithm for scheduling virtual cellular manufacturing systems”. International Journal of Computer Integrated Manufacturing: 524-537.
21. McLean CR, Bloom HM, & Hopp TH. 1982. “The virtual manufacturing cell”.
22. Rezazadeh H., Mahini R., & Zarei M. 2010. “Solving a dynamic virtual cell formation problem by linear programming embedded particle swarm optimization algorithm”. Applied Soft Computing: 3160-3169
23. Mak K., Ma J. & Cui X., 2011. “Integrated Multi-period Production Scheduling and Cell Formation for Virtual Cellular Manufacturing Systems”. Engineering Letters.
24. Nomden G. & Zee D., 2008. “Virtual cellular manufacturing: Configuring routing flexibility”, Int. J. Production Economics: 439–451.
25. Nomden G., Slomp J., Suresh c., 2006. “Virtual manufacturing cells A taxonomy of past research and identification of future research issues”, Int J Flex Manuf Syst: 71–92.
26. Rezazadeh H., Ghazanfari M., Sadjadi S., Aryanejad B. & Makui A., 2009. “Linear programming embedded particle swarm optimization for solving an extended model of dynamic virtual cellular manufacturing systems”. Journal of Applied Research and Technology: 83-108.
27. Saad SM., Baykasoglu A., GindyN NZ., 2002. “An integrated frame work for reconfiguration of cellular manufacturing systems using virtual cells”. Production Planning & Control:381–93.
28. Slomp J., Chowdary V., Suresh C., 2005. “Design of virtual manufacturing cells a mathematical programming approach”. Robotics and Computer-Integrated Manufacturing: 273–288.
29. Vakharia AJ., MoilyJP., HuangY.,1999. “Evaluating virtual cell sand multi stage flow shops”. International Journal of Flexible Manufacturing Systems:291–314.