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Simultaneous Scheduling of Machines, Tool Transporter and Tools in a Multi Machine Flexible Manufacturing System Without Tool Delay Using Crow Search Algorithm

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Abstract

This paper deals with machines, tool transporter (TT) and tools simultaneous scheduling in multi machine flexible manufacturing system (FMS) with the lowest possible number of copies of every tool type without tool delay taking into account tool transfer times to minimize makespan (MSN). The tools are stored in a central tool magazine (CTM) that shares with and serves for several machines. The problem is to determine the lowest possible number of copies of every tool variety, allocation of copies of tools to job-operations, job-operations' sequencing on machines and corresponding trip operations of TT, including the dead heading trip and loaded trip times of TT without tool delay for MSN minimization. This paper proposes nonlinear mixed integer programming (MIP) formulation to model this simultaneous scheduling problem and crow search algorithm (CSA) built on the crows' intelligent behavior to solve this problem. The results have been tabulated, analyzed and compared.

Keywords: Scheduling of machines, tool transporter and tools; FMS; no tool delay; crow search algorithm; makespan; optimization techniques.

1. Introduction

Manufacturing companies are expected to handle growing product complexities, shorter market time, new technologies, global competition threats, and quickly changing situation. FMS is setup to deal with manufacturing competition. FMS is an integrated production system consisting of multipurpose machine tools which are computer numerical controlled (CNC), linked to an automated material handling system (MHS) [1]. FMS aims to be flexible in manufacture without undermining the product quality. The flexibility of the FMS relies on the flexibilities of CNC machines, automated MHS, and control software. FMSs have been categorized into distinct kinds as per their workflow patterns, size, or manufacturing type. Four kinds of FMS are described from the planning and control point of perspective: single flexible machines (SFM), flexible manufacturing cells (FMC), multi-machine FMS (MMFMS), and multi-cell FMS (MCFMS) [2]. Advantages, such as reductions in cost, enhanced utilizations, decreased work-in-process, etc have already been proved by existing FMS implementations [3]. Use of resources is improved by scheduling tasks so as to reduce the MSN [4]. One way to achieve high productivity in FMS is to solve scheduling problems optimally or near optimally.

Tool loading is a complicating issue in scheduling problems since the number of tool copies are limited and may be smaller than the number of machines due to economic restrictions. Job and tool scheduling is an important problem for production systems. Inefficient planning of job scheduling and tool loading may lead to under utilization of capital intensive machines, and high level of machine idle time [5]. Therefore, efficient scheduling of jobs and the tools enables a manufacturing system to increase machines' utilization and decrease their idle times. There are a number of studies on the machines and tools scheduling. Tang and Denardo [6] solved the problem of determining job sequence and tools which are placed before every job is processed on machine for minimization of tool switches. Chandra et al [7] proposed a practical approach for deciding the sequence of jobs and tools for minimization of the total set up and processing times to make sure that jobs are completed before their delivery dates. Song et al [8] mentioned heuristic algorithm for allocating tools and parts for minimization of tool switches between machines where every part needs to visit only one machine for its complete processing. Roh and Kim [9] examined allotment of part and tool, and scheduling issues for entire tardiness minimization under

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its tool movement plan where every part needs to visit only one machine for its complete processing in FMS. Agnetis et al [1] addressed combined part and tool scheduling in FMC by placing tools in a CTM which are shared by machines using TT to minimize MSN and maximum delay. When two machines are in need of the same tool, the Tabu search algorithm is applied to address the disagreement. Tsukada and Shin [10] recommended distributed artificial intelligence approach for problems of tool scheduling and borrowing along with an approach to share the tool in FMS to deal the unexpected jobs' introduction in the dynamic situation. It is demonstrated that sharing of tool among distinct FMS cells helps to reduce tooling costs and improves the tools usage. Jun, Kim and Suh [11] recommended Greedy Search Algorithm for scheduling and supplying of tools, and determining the amount of additional tools required when FMS setup changes due to change in the product mix for MSN minimization in FMS. Keung, Ip and Lee [12] investigated machine allocation and job shop scheduling on the parallel machining workstation in tandem with different machines where tools are shared for minimization of tool switching cases and tool switches by means of GA approach. Ecker and Gupta [13] proposed an algorithm to task precedence relationships with the intend of sequencing tasks in order to minimize the overall time required for the tool changes on the SFM equipped with tool magazine, where every job requires one of the tools. Prabhaharan et al [14] addressed joint scheduling of operation and tool for MSN minimization by using preference dispatching rule and simulated annealing algorithms in the FMC with "m" indistinguishable work cells and the CTM. Karzan and Azizoğlu [15] addressed job sequencing and tool transporter movements problem on SFM with a limited tool magazine capacity. Branch-Bound algorithm and beam search technique are employed to obtain optimal or near optimal solutions for minimizing tool transporter movements between machine and tool crib area. Suresh Kumar and Sridharan [16] discussed simulation study conducted to analyze the impact of scheduling rules controlling part launch and tool request selection decisions of FMS. FMS was operating under tool movement along with part movement policy. Simulation study is employed to identify the best possible scheduling rule combinations for part launch and tool request selection to minimize mean flow time, tardiness and conditional mean tardiness. Ant Colony Optimization Algorithm was suggested by Udhay kumar and Kumanan [17] to produce optimal job and tool sequences to minimize makepan for FMS, and extended GT algorithms were used for active schedule creation. Udhaya Kumar and Kumanan [18] suggested un-traditional optimization algorithms like SA, ACO, PSO, and GA to produce the optimum jobs and tools sequence for tardiness minimization in FMS, and modified GT algorithms were used to generate efficient schedules. Aldrin Raj, et al [19] suggested 4 heuristics, including preference shipment rules, revised non-delay schedule generation algorithms with 6 dissimilar rules, revised GTA and Artificial Immune System algorithms for resolving machine and tools combined scheduling in FMS which consists of 4 machines and one CTM to minimize MSN. Özpeynirci [20] introduced a time-indexed mathematical model for machines and tools scheduling in FMS to minimize MSN. Costa, et al [21] have developed a hybrid GA that implements a local search enhancement scheme to resolve ' p ' parts on ' q ' machines scheduling undertaking tool change activity triggered by tool wear. Sivarami Reddy et al [22] presented symbiotic organisms search algorithm (SOSA) to deal with machines and tools joint scheduling to produce best optimal sequences with a copy of every type of tools in a MMFMS that minimize MSN, and it is shown that SOSA outperforms the existing algorithms. Beezao et al [23] modeled and addressed the identical parallel machines problem with tooling constraints for minimizing MSN using an adaptive large neighborhood search metaheuristic(ALNS). It is demonstrated that ALNS outperformed other existing algorithms. Baykasoğlu and Ozsoydan [24] addressed automatic tool changer (ATC) indexing problem and tool changing problem concurrently in order to reduce non machining times in automatic machining centers using simulated annealing algorithm. Paiva and Carvalho [25] addressed job ordering and tool changing problem (SSP) to find out the jobs order and the tool loading order so as to minimize the tool changes. A methodology which employs graph representation, heuristic methods and local search methods is used for solving sequencing problem. Such techniques are integrated along with classical tooling approach to solve SSP in an algorithmic local search scheme. Gökgür et al [26] addressed constraint programming models in environments of parallel machines to solve tools scheduling and allotment problems with prearranged tools quantity in system due to financial limitations to minimize MSN. Job transport times and tool switch times among machines are not taken into account in the references reviewed above.

Sivarami Reddy et al [27] and Sivarami Reddy et al [28] solved machines and tools simultaneous scheduling problems without considering job transfer times and considering tool switch times among machines with a copy of every tool type ***(*****SMTTATWACT*****)*** for minimum MSN as an objective and shown that tool transfer times have significant effect on MSN.

Sivarami Reddy et al [29], Sivarami Reddy et al [30],and Sivarami Reddy et al. [31] addressed machines, AGVs and tools simultaneous scheduling with one copy of every tool type considering job transport times among machines, with and without considering tool transfer times among machines respectively to find out optimal sequences for MSN minimization in MMFMS.

Sivarami Reddy et al. [32] and Sivarami Reddy et al. [33] addressed concurrent scheduling of MCs and tools with a replica of each tool kind and alternate machines for minimization of MKSN.

The following are the other scheduling problems addressed in the literature. Al-Refaie et al. [34] devised a mathematical model for concurrent optimal patients' scheduling and sequencing in newly opened operating rooms under emergency events for maximization of patient's assignment over the empty available rooms. Abbas and Hala [35] proposed an optimization model to deal with quay crane assignment and scheduling problem considering multiple objective functions, such as minimization of handling makespan, maximization of number of containers being handled by each quay crane and maximization of satisfaction levels on handling completion times.

When operations of different jobs require the same tool at the same time, tool would be allocated for only one operation that causes other operations to wait for the tool in SMTTATWACT. This increases the MSN. Therefore it is important to address machines, TT and tools simultaneous scheduling with the lowest number of copies of each tool kind which are much less than the number of machines without tool delay (SMATLNTC) by sharing the tools among machines to minimize MKSN in an FMS. As it causes no tool delay which in turn reduces MKSN with few additional copies for few tool types. The novelty of the research is addressing the SMATLNTC for minimization of MKSN first time, presenting nonlinear MIP model. CSA is employed to minimize MKSN of SMATLNTC and demonstrate its difference from other studies.

Automated tool sharing system presents technical solution to tools' high cost where different machines are able to employ same tool by dynamically moving the tool from machine to machine as tooling needs evolve. Because FMS is an interconnected manufacturing facility, it is important to concurrently schedule different components of FMS.

The job shop's scheduling problem [36], and the TT scheduling problem which are analogous to a problem of pick-up and delivery [37] are NP-hard problems. Combining them is a double interlinked NP-hard problem. Determining the lowest possible number of copies of every tool type for no tool delay and allocating them to the operations increases the scheduling problem complexity further, and it is also expected to improve the utilization of machines, TT and tools.

CSA is a metaheuristic developed by Askarzadeh [38]. It attempts to simulate the intelligent behavior of the crows to find the solution of optimization problems. It has been successfully applied to cope with engineering optimization problems [38-40, 27, 41-44, 29]. The advantages of the CSA over most other metaheuristic algorithms are that algorithm operations require two algorithm parameters, simple and easy to implement.

2. Problemand model formulation

Setup varies in FMS types and operations. Because having a common configuration is not feasible, the majority research focuses on defined production systems. Specification of the system, assumptions, criteria for objective and the problem addressed in this work are offered in the subsequent sections.

2.1. FMS Environment

Using common tool storage is typically followed in several manufacturing systems through one CTM serving multiple machines to cut down tool stocks. During the part's machining, demanded tool is shared from different machines or shipped from CTM by TT. CTM cuts down the tools copies required in system, and therefore cuts down tooling cost. Switching of tools and jobs between the machines will be carried out by TT and AGVs respectively. The FMS in this work is assumed to consist of four CNC machines, CTM with necessary tool types for all the machines and one copy of every type, a TT, two indistinguishable AGVs and each machine with ATC. There are loading and unloading (LU) stations where FMS releases parts for manufacturing and the completed parts are deposited and transported to the final storage facility respectively. To stock up the work-in-progress, an automatic storage and retrieval system (AS/RS) is available. Figure 1 shows its configuration.

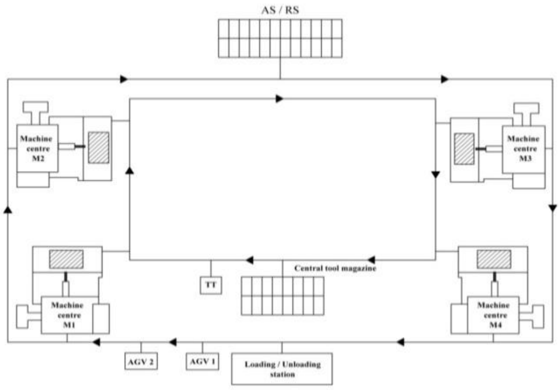

Figure 1. FMS environment

2.2. Assumptions

The following assumptions are made for the problem being studied

Initially all jobs, machines and TT are available for use.

Tool/ machine can perform one job only at any given time.

Operation's pre-emption on machine is barred.

The necessary machines and tools are identified before scheduling every operation.

Every job has operations' set with its own order and known processing times that also include setup times.

Initially, tools are stored in a CTM.

Transportation time of parts among machines is not taken into account.

At the time of jobs' arrival, the service life given to the tools will be sufficient to perform the operations allocated to the respective tools.

There is only one TT which moves the tools all through the system and tool switch times among machines are taken into account. A flow path layout for TT is given, travel times on each path segment are known and it moves along shortest predetermined paths.

TT starts from CTM initially, returns to CTM after all their assignments have been done and holds a single unit at a time.

The process planning information for determining the sequence of operations for optimizing tolerance stack-up is provided in terms of precedence constraints for each job. Thus, we assume that each job has prearranged operations order that cannot be altered.

2.3. Problem definition

Consider an FMS with a job set J of j job types $\{J_1, J_2, J_3 ... , J_j\}$, m machines $\{M_1, M_2, M_3 ... , M_m\}$, and total operations of job set {1,2,3.......N} and k types of tools $\{t_1,t_2, t_3....t_k\}$with few copies of every type. A job's operations have a predetermined order of processing, and the order is known in advance. At most one operation at a time can be processed by a machine. Until its predecessor operation is complete, an operation cannot begin. The order of operations on a machine determines the setup requirements for a machine. The simultaneous scheduling problem is defined as determining the lowest possible number of copies of every variety of tools, allocation of copies of tools to job-operations and job-operations' sequencing on machines without tool delay, in addition to determining each job's beginning and finishing times on every machine and tool copy and corresponding trip operations of TT, including the dead heading trip and loaded trip times of TT for MSN minimization in a MMFMS. The problem is stated in crisp, so unambiguous mathematical form is given in section 2.4.

2.4. Model formulation

In this section, nonlinear MIP model is introduced to clearly specify the crucial parameters and their effect on the FMS scheduling problem.

2.4.1. Notations

Decision variables

$$q_{rs} = \begin{cases} 1 & \text{if } c_r \text{ is less than } c_s, \text{ where } r \text{ and } s \text{ are operations of different jobs} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{hi} = \begin{cases} 1 & \text{if the TT is assigned for dead heading trip between trip 'h' and trip 'i' where the demanded tool is available} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{oi} = \begin{cases} 1 & \text{if the TT starts from CTM to accomplish trip 'i' as its first assignment} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ho} = \begin{cases} 1 & \text{if TT returns to the CTM after completing trip 'h' as its last assignment} \\ 0 & \text{otherwise} \end{cases}$$

$$ttw = \begin{cases} tttd_{o,u} & \text{if the TT starts from CTM to accomplish trip 'i' as its first accomplishment,} \\ 0 & \text{otherwise} \end{cases}$$

2.4.2. Mathematical model

In the formulation, machine and tool indices are not employed specifically as each job routing is available; the machine and tool indices are known for each operation index in I. Among operations and loaded trips there is one-to- one association. TT loaded trip for operation *i* is associated for every operation *i*. The destination of TT loaded trip' *i*' is a machine for which operation *i* is allocated and its origin is either a machine which is performing the operation using the tool required for operation i or a CTM. The tool needs to follow operations precedence constraints for the operations that belong to the same tool copy and same job i.e. RT_{kj} .The objective function for minimization of MSN is

Subscripts

j	index for a job
i, h,r,s	indices for operations
k	index for a tool
J	job set on hand for processing.
n_j	operations in job j.
N	$\sum_{j\in J} n_j$, total operations in job set J.
I	{1,2,-------N}, index set for operations.
I_j	$\{J_j+1, J_j+2, \text{------} J_j+n_j\}$, the indices' set in 'I' linked with job 'j', where 'J_j'is jobs' operations listed before job 'j' and J_1=0.
IS_i	$I-\{h; h\ge i, i, h\in I_j\}$ operations' index set without operation 'i' and same job's following operations to operation 'i'.
IP_h	$I-\{i; i\le h, i, h\in I_j\}$ operations' index set without operation 'h' and same job's preceding operations to operation 'h'.
pt_i	operation 'i' processing time.
ct_i	operation 'i' completion time.
TL	the set of tool types to carry out the jobs' operations
TLCopy	set of copies of each tool variety.
R_k	indices set in I linked with tool type k in TL , $\forall k\in TL$
RT_{kj} :	$I_j \cap R_k$ the index set of operations in I common for tool k and job j $\forall k\in TL, \forall j\in J$
b_{kci}	Set of ready times of copies of tool type \`k\` at a machine for operation \`i\`, including tool copies\` transfer time from other machines or CTM to this machine.
$TLRM_i$	$\min\{b_{kci}\}, \forall k\in TL, \forall c\in TLCopy, \forall i\in R_k$
ct_{ick}	operation i's completion time using copy c of tool type k , $\forall i\in I$, $\forall c\in TLCopy$, and $\forall k\in R_k$
u	first operation that uses tool k, $u\in R_k, \forall k\in TL$
v	preceding operation of i, $i, v\in R_k, \forall k\in TL$
L	number of TTs
a_j	job j ready time
TM_i	machine ready time for operation i
$tttl_i$	TT loaded trip 'i' travel time including load and unload times.
$tttd_{hi}$	TT empty trip 'i' travel time, trip commencing at a machine processing operation \`h\` and concluding at the machine processing operation \`i\` with the demanded tool.
$CTTTL_i$	TT loaded trip 'i' completion time
Q_i :	$\max(ct_{i-1}, TM_i), \quad \forall i\in I$

$Z = \min\ (\max\ (ct_i)), \quad \forall\, i \in I$ subject to	
$Z \geq ct_{N_j+n_j} \quad \forall\, j \in J$	(1)
$ct_i - ct_{i-1} \geq pt_i + tttl_i\,, \quad \forall\, i-1, i \in I_j\,, \forall j \in J$	(2a)
$ct_{N_j+1} \geq pt_{N_j+1} + tttl_{N_j+1}, \quad \forall j \in J$	(2b)
$ct_{ick} \neq ct_{hck}\ , i \neq h,\ \forall\ i, h \in R_{k,}\,, \forall c \in TLCopy\ , and\ \forall k \in TL$	(2c)
$(1 + H\ tagd_{rs})\, ct_r \geq ct_s + pt_r - H\, q_{rs}$ $(1 + H\, tagd_{rs})\, ct_s \geq ct_r + pt_s - H(1 - q_{rs})$ $\forall r \in I_j\ , and\ \ \forall s \in I_l\ \ where\ j, l \in J,\ j < l$	(3)
$TM_{i} < TLRM_{i}\ \ ,\ i \in I$ i\` is the first scheduled operation on the machine	(4)
$Q_i - TLRM_i\ \geq 0 \quad \forall i \in I$	(5)
$y_{oi} + \sum_h y_{hi} = 1\ h \neq i, \quad i, h \in R_k\ ,\ \forall k \in TL$	(6)
$y_{ho} + \sum_i y_{hi} = 1\ i \neq h,\ i, h \in R_k, \forall\, k \in TL$	(7)
$\sum_{i \in R_k} y_{oi} \leq L \qquad \forall k \in TL$	(8)
$\sum_{i \in R_k} y_{oi} - \sum_{h \in R_k} y_{ho} = 0,\ \forall k \in TL$	(9)
$CTTTL_i - tttl_i \geq ct_v\,,\ \forall i, v \in R_k\,, i \neq u,\ \ \forall k \in TL$	(10)
$CTTTL_i - tttl_i \geq\ y_{oi}\ ttw + \sum_{h \in R_k, h \neq i} y_{hi} (CTTTL_h + tttd_{h,v})$ $\forall\, i \in R_k\ , \forall k \in TL, \quad if\ h, i \in RT_{kj}\ then\ \ i < h$	(11)
$CTTTL_u - tttl_u\ \geq \sum_{h,u \in R_k\,, h \neq u} y_{h,u} (CTTTL_h + tttd_{ho}),\ \ \forall k \in TL$	(12)
$\max(\, TM_i\ , CTTTL_i) \leq ct_i - pt_i\ ,\ \forall\, i \in I$	(13)
$ct_i \geq 0,\ \forall i \in I$ $y_{hi} = 0{,}1 \quad i \neq h \quad i, h \in R_k\ \ , \forall\, i \in I$	

The 1st constraint specifies that MSN is greater than or equal to the completion time of last operation of all the jobs. The constraint 2a is the operations precedence constraints. The constraint 2b is the constraint for the completion time of first operations of jobs. The constraint 2c is the constraint for the operations that belong to the same tool copy.

H is a large positive integer in the 3rd constraint which ensures that no two operations allocated to the same machine can be concurrently performed. If operations 'r' and 's' that belong to distinct jobs need the same machine, then $tagd_{rs}$ is zero by definition. The 4th constraint defines that the machine ready time should be less than the $TLRM_i$ as the tool is to be shifted either from other machine or CTM if operation 'i' is the first scheduled operation on the machine. The 5th constraint defines that there will not be tool delay for operation i.

The 6th and 7th constraints express that tools are loaded and unloaded once for every operation respectively. The 8th constraint assures that every TT goes into the system at most one time. The 9th constraint keeps total TTs consistent in the system.

The 10th constraint states that TT loaded trip i can begin only when the preceding operation v is completed. The 11th constraint states that TT loaded trip i can begin only after TT dead heading trip is completed, and it is applicable if it is the first loaded trip of TT or TT loaded trips for operations other than the first operation of the tools. The 12thconstraint states that TT loaded trip 'u' i.e. for first operation of a tool can begin only after completion of TT dead heading trip.

The 10th, 11th, and 12th constraints are connected to the starting times of TT loaded trips. Collectively, they declare that the TT loaded trip i cannot commence before the maximum of dead heading trip to the preceding operation and the finish time of the preceding operation.

The 13th constraint specifies that the operation i cannot begin before maximum of the machine ready time and the TT loaded trip. However, this formulation is intractable due to its size and nonlinearity, thus meta-heuristic algorithm namely CSA is used to obtain near optimal or optimal solutions.

Since the MSN needs to be minimized, calculation of MSN and lowest possible number of tool copies for a given schedule needs to be developed. Flow-chart for such a computation is shown in Figure 2.

2.4.3. Input data

Since the FMS configurations differ from one to the other topologically, four different layout configurations shown in Figure 3 are considered as reported in Bilge and Ulusoy [45]. Job sets employed for this problem are the 1st ten job sets

employed by Aldrin Raj et al [19], which are also the standard problems provided by Bilge and Ulusoy [45] but with the additional information, such as tools to carry out the operations. These problems were developed for various levels of travel times to processing times' ratio (t/p). The 82 test problems were designed with 10 job sets, 2 AGVs and 4 layouts, 40 problems with t / p greater than 0.25 and 42 problems with t / p less than 0.25. Four separate layouts (LAOT 1, LAOT 2, LAOT 3 and LAOT 4) with three cases were taken into account for the estimation of the MSN with the growing processing times. The original processing times (OPT), twice the OPT and thrice the OPT had been used in case 1, case 2 and case 3 respectively. Case 1 and case 2 are taken into account for LAOT 1, LAOT 2 and LAOT 3 and all the cases are taken into account for LAOT 4. The three cases are classified into 2 sets with relatively high t / p ratio greater than 0.25(case 1) and relatively small t / p less than 0.25(case 2 and case 3).The above test problems with original travel times of TT are used for this problem.

The following data is offered as an input.

It is assumed that the flow path of tool transporter closely resembles flow path of the AGVs for any given layout, the average speed of tool transporter is 57 m/min, and travel time matrix of tool transporter including load and unload times of tool for various layouts is given in Table 1.

Number of jobs, each job's operations and job's maximum operations in job set.

Machine needed for every job operation (machine matrix),

Time needed to perform every job-operation on the machine (process time matrix), and

Tool for processing every job-operation (Tool matrix)

3. CSA

The crow flock behavior has many similarities with the process of optimization [38]. Crows conceal their surplus food in the environment's hiding places and get stored food when necessary. Crows are voracious to get better food sources, and they go after each other. If the crow notices another one is behind it, the crow attempts to deceive that crow by heading to a different location in the vicinity. The crows are searchers from an optimization view point, the environment is a search space. Every hiding place in environment is a corresponding viable solution, the food source's quality is an objective function, and the problem's global solution is the best food source. CSA tries to simulate crows ' behavior to get a solution to the problem of optimization

3.1. Implementation of CSA.

In this problem of simultaneous scheduling, CSA is employed to minimize MSN. In the suggested CSA, every parameter of solution vector has to represent job-operation, and the machine and tool that are allocated for job-operation. Therefore, job-operation, machine, and tool encoding is employed. The parameter's first item represents the job number and location in the order in which it happens in vector showing operation number. The parameter's second item indicates the machine allocated to process that operation, selected from machine matrix, and the parameter's third item represents tool allocated to perform the operation selected from tool matrix. Parameters in vector are same as job set's total operations. This coding is useful in checking precedent relationships between job's operations in the vector.

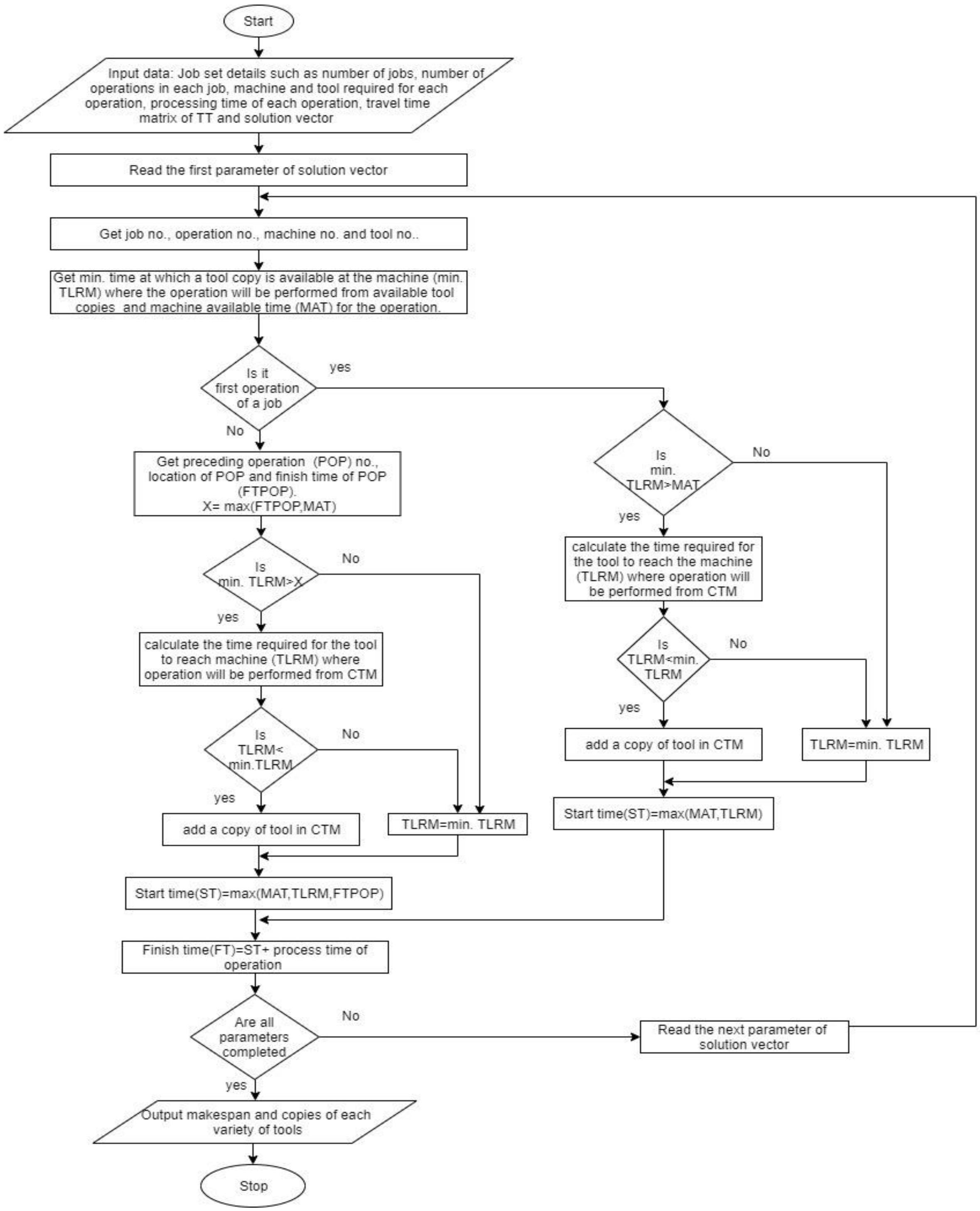

Figure 2. Flow chart for calculation of MSN and lowest possible number of tool copies for a given schedule.

Table 1. Travel time matrix of TT

Layout 1						Layout 2					
	To						To				
From	CTM	M1	M2	M3	M4	From	CTM	M1	M2	M3	M4
CTM	0	4	6	7	8	CTM	0	3	4	6	4
M1	8	0	4	6	7	M1	4	0	1	3	1
M2	7	4	0	4	6	M2	6	8	0	1	3
M3	6	6	4	0	4	M3	4	7	8	0	1
M4	4	7	6	4	0	M4	3	6	7	8	0
Layout 3						Layout 4					
	To						To				
From	CTM	M1	M2	M3	M4	From	CTM	M1	M2	M3	M4
CTM	0	1	3	7	8	CTM	0	3	6	7	10
M1	8	0	1	6	7	M1	13	0	3	4	7
M2	7	8	0	4	6	M2	14	10	0	6	4
M3	3	4	6	0	1	M3	8	6	4	0	4
M4	1	3	4	8	0	M4	10	10	8	4	0

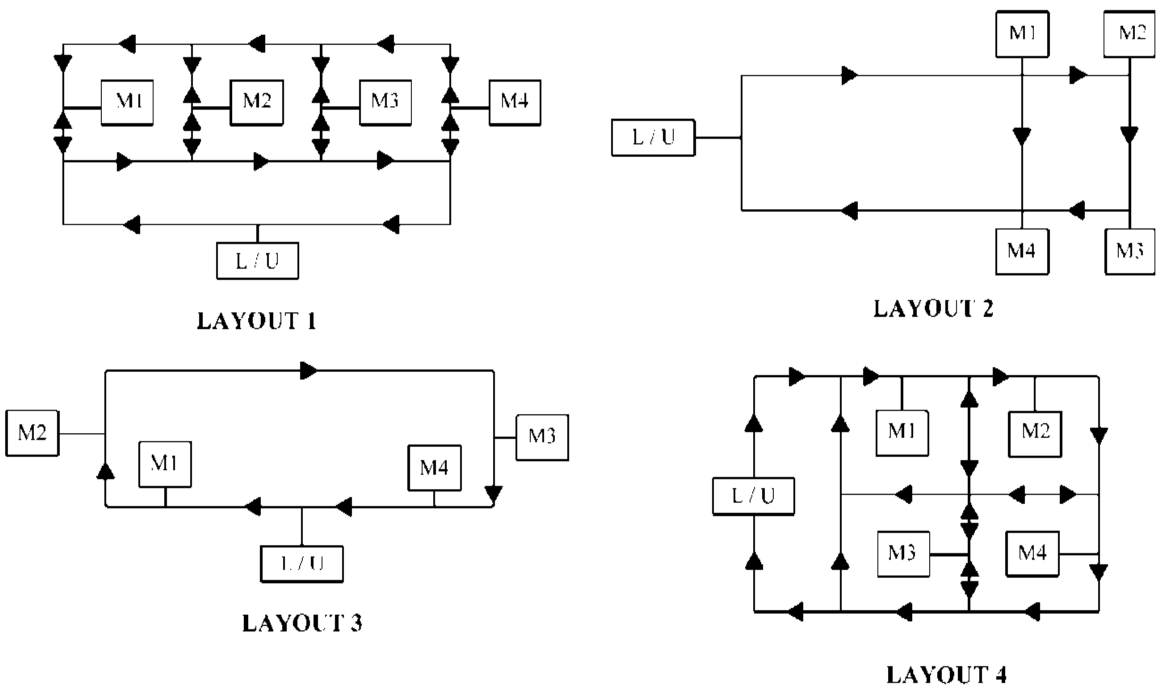

Figure 3. The layout configurations

3.1.1. Random solution generator (RSG)

RSG is devised to offer solutions for initial population. A solution vector is constructed parameter after parameter by this generator. An operation must be eligible for assigning to a parameter. An operation is said to be qualified once all of its predecessors are allocated. Qualifying operations are placed in a set for scheduling next. In the beginning, this set is made up by the first operations of each job. At every iteration one among the operations in the set is chosen arbitrarily and put next to the parameter in the vector. Then, machine and tool are picked up from machine matrix and tool matrix for the operation respectively and both are allotted to a parameter to end the vector. The set is kept up to date, and if the solution vector is not yet finished, the process will continue.

3.1.2. Limits function

It is used to ensure that the produced operations in a new solution are compatible with the precedence constraints requirement. If the precedence requirement constraints are not observed, the new solution will be corrected by the limits function so that the operations of the new solution vector will observe the precedence constraints requirement.

CSA's step-by-step implementation procedure is outlined below.

Step1: The problem and adjustable parameters be initialized.

MSN minimization is specified as an objective function. The decision variables are job-operations, machines, tools. The constraints are job-operations precedence requirements, copies of each tool variety and number of TTs. The CSA parameters, such as flock size (size of population), flight length(fl), probability of awareness (AP) and maximum iterations ($iter_{max}$) are set. Initialize iteration no to zero.

Step 2: Initialize positions.

N crows are arbitrarily situated as group mates in the search space.

This implies that N solutions are produced arbitrarily (located) through the use of RSG in the search space known as initial population.

$$\text{Initial population} = \begin{bmatrix} x_1^{\ 1} & x_2^{\ 1} & x_3^{\ 1} \\ x_1^{\ 2} & x_2^{\ 2} & x_3^{\ 2} \\ - & - & - \\ x_1^{\ N} & x_2^{\ N} & x_3^{\ N} \end{bmatrix}$$

where $x_1^{\ i}$ is sequence of operations and $x_2^{\ i}$ and $x_3^{\ i}$ are machines and tools allocation to the corresponding job-operations respectively.

Step 3 : Assess objective function and initialize crows memory.

Each crow's position quality i,e MSN is computed by means of flow chart given in figure 2. The memory of every crow is initialized and crows are believed to have concealed their food in their original positions. That is solutions of the population and associated MSNs are recorded in memory.

Step 4: Crows make a fresh location in the search space as given below.

Crow i would like to make a new location, then it arbitrarily selects one among the crows, say the crow j, and pursues it to locate hidden food from the crow j. Crow i uses the following equation (14) to obtain new position.

$$x^{i,iter+1} = \begin{cases} x^{i,iter} + r_j X\, fl^{i,iter} X\left(m^{j,iter} - x^{i,iter}\right) & r_j \geq AP^{i,iter} \\ a\ random\ position & otherwise \end{cases} \quad (14)$$

where r_j is a uniformly distributed random number between 0 and 1.

Fresh solution (new position) is obtained as per equation (14) for solution i (present position) in the population.

Step 5: Test if new positions (new solutions) are feasible.

If the new solution is infeasible, the use of limit functions will make it feasible. The crow modifies its location. That is the new solution of i (new location), which is to replace solution of i (present location).

Step 6: Update memory.

If the fresh solution MSN (fresh position of crow) is superior to the old solution MSN recorded in memory (crow's memory), fresh solution along with its MSN replaces the old solution and its MSN.

Repeat steps 4 to 6 for all members of the population.

Step 7: verify termination criterion.

Increment the iteration one by one. Repeat steps 4-6 till iteration no reaches $iter_{max}$. The best MSN position in the memory is identified as the optimization problem's solution when the termination requirement is met.

The initial population is generated arbitrarily by the use of RSG in the proposed methodology. Every vector of the solution consists of parameters equal to the job set operations. The data mentioned in section 2.4.3 is offered as an input. The code is written in MATLAB and offers a schedule for job-operations together with allocation of machines and tools to the corresponding job-operations for minimum MSN.

At every generation, all candidates of population are selected for replacement. Thus, NP competitions are provided to decide members for next generation.

Example: Job set 5 is considered that has five jobs and operations in job set are 13. Therefore, the solution vector with 13 parameters along with its job-operation, machine and tool based coding is given below.

333	114	141	324	532	322	232	442	433	511	221	114	233

Randomly generated solution vector for the initial population is shown below.

114	333	522	442	121	232	144	413	231	344	233	521	312

The generated solutions for initial population observe precedence constraints, therefore, they are feasible solutions.

Assessment: Each vector's MSN value in initial population is calculated and recorded together with vector in memory matrix.

Next generation: First vector in the population is considered as input vector and given below.

333 212 344 114 121 532 511 442 144 423 231 312 223

The above vector MSN is 66 and lowest possible tool copies are [3 2 1 1]

Generated random Value is 0.2059.Since the random value generated is lower than the probability of awareness (0.3), number other than 1 is produced at random and it is 200. The best of the 200th crow recorded in memory is taken and given below to generate new vector.

333 442 344 532 212 511 231 114 121 223 144 312 423

whose MSN is 75 and lowest possible tool copies are [2 2 1 1]

According to equation 14 new solution vector is generated and its feasibility is checked employing the Limit function. The fresh feasible vector generated is given below.

333 442 344 532 212 511 231 114 121 223 423 312 144

The new vector fitness value is assessed, and if it is superior than the input vector best fitness value in memory matrix, then the vector in the memory matrix is substituted by new vector. MSN of this vector is 70 and lowest possible tool copies are [2 2 1 1]

specified generations have been completed, the best sequence until now is given below.

114 532 333 212 344 121 442 521 144 423 231 312 223

whose MSN is 51 and lowest possible tool copies are [2 2 1 1]

First tool copy is represented with A, second tool copy is represented with B and so on. The above vector can be represented in the Job-operation, machine and tool copy form given below.

114A 532A 333A 212A 344A 212A 344A 121A 442B 511A 144A 423A231B 312B 223A

4. Results and discussions

The proposed approach has been applied on different population sizes varying from 2 to 12 times of operations in the job set, and it is found that when population size is 10 times of operations, better results are noticed. Different combinations of probability of awareness (AP) and flight length (fl) are employed, but a combination of 0.3 and 2 provided good results. Good results are obtained between 200 and 250 generations for most of the problems, so 250 generations are taken into account as the stopping criteria. The code written in MATLAB for ***SMTTATWLNTC*** is run on each job set discussed in section 2.4.3 for 20 times for MSN minimization. The best MSN from 20 runs is provided for every layout and job set, along with mean and standard deviation (SDV) for various cases in Table 2.

In Table 2, the non zero SDV in case 1 vary for LAOT 1 in the range [0.8127, 2.9105], for LAOT 2 in the range [0.5501, 2.0417], for LAOT 3 in the range[1.0501, 2.5644] and for LAOT 4 in the range [1.6051, 3.1473]; the non zero SDV in case 2 varies for LAOT 1 in the range [0.2236, 3.2911], for LAOT 2 in the range [1.2085, 3.4622], for LAOT 3 in the range [0.4474, 3.6158] and for LAOT 4 in the range [1.5761, 3.1289] and the non zero SDV in case 3 varies for LAOT 4 in the range [1.2732, 3.5700]. From Table 2 one interesting finding is that the SDV values are extremely small compared with the magnitude of the mean values. In fact, the coefficient of variation for non zero standard deviation varies in the range [0.001746, 0.3445]. Furthermore, the SDV is zero for 13 out of 85 problems. If one looks closer to the final solutions of 20 simulation experiments for these problems, one finds that distinct solutions with the same MSN value exist. It means many optima alternatives are there, and the suggested CSA is able to find them.

4.1. Gantt chart

The Gantt chart shows the feasibility of the job set 1 LAOT 2 of case 1 optimal solution for minimum MSN obtained by CSA. Below is given the job set 1 LAOT 2 of case 1 optimal solution vector.

113A 124A 212A 443A 532B 233B 424A 331A 511B 344A 221C 312A 141A

The solution above is given as Table 3 in the table form.

The operations assigned for every tool copy and machines are indicated in Gantt chart together with each operation's start and end times. The Gantt chart also shows empty trips, loaded trips and waiting time of TT. Figure 4 shows the above solution vector’s Gantt chart. A five character word represents an operation. For instance, in operation 5132B, the 1st character '4' specifies the job number, the 2nd character '1' denotes the job-operation, the 3rd character '3' indicates the required machine, the 4^{th} and 5^{th} characters ' 2B ' denotes tool copy i,e tool type 2 and copy ‘A’ allocated to the job-operation.

In Figure 4, M4, M3, M2 and M1 denotes machines, T4A, T3A, T3B, T2A, T2B, T1A,T1B and T1C indicate tool copies and TT indicates tool transporter.

LTT xxxxx corresponds to TT loaded trips for operation xxxxx .

ETT xxxxx corresponds to TT empty trips for operation xxxxx.

WT xxxxx denotes TT waiting time to pick up the tool for operation xxxxx from machine.

Table 2. Best MSN of SMTTATWLNTC with mean and SDV for various job sets, layouts and cases

Job set number	Case 1											
	LAOT 1			LAOT 2			LAOT 3			LAOT 4		
	Best MSN	mean	SDV	Best MSN	mean	SDV	Best MSN	mean	SDV	Best MSN	mean	SDV
1	110	112.35	0.8127	87	87.75	0.5501	90	91.45	1.0501	123	125.75	1.2085
2	114	118.65	1.6944	94	95.7	1.3803	98	100.15	1.5985	135	137.3	1.7199
3	112	113.45	1.572	91	94.45	1.4318	95	98.75	1.5517	125	125.55	1.7614
4	109	111.65	1.4965	86	87.2	0.8335	85	86.95	1.4318	129	133.05	1.6051
5	96	96.85	1.0500	74	74.95	0.2286	74	75.95	2.5644	112	112.4	0.6806
6	107	107	0.0000	99	99	0.0000	100	100	0.0000	117	117	0.0000
7	107	112.95	2.6651	89	91.6	1.818	89	93.7	2.1546	121	128.6	4.4296
8	148	151.9	2.7511	135	137.25	1.2513	138	140.3	1.6575	167	173.6	2.6328
9	107	190.45	2.9105	104	106.2	1.3611	106	108.5	1.3955	135	138.3	1.6255
10	136	164.85	2.5808	141	144.8	2.0417	143	148.55	2.1879	179	183.85	2.5397
Job set number	case 2											
	LAOT 1			LAOT 2			LAOT 3			LAOT 4		
	Best MSN	mean	SDV	Best MSN	mean	SDV	Best MSN	mean	SDV	Best MSN	mean	SDV
1	149	150	0.5620	132	120	0.0000	135	135.4	0.5982	165	166.8	1.5761
2	166	169.8	2.6077	145	152.25	3.3067	147	153.75	3.3541	185	188.25	2.1491
3	162	168.95	2.9285	157	159.5	1.6702	152	159.1	2.5935	172	182.85	4.4636
4	144	146.25	1.7733	128	129.75	1.2085	128	130.35	0.8751	168	170.8	2.2804
5	128	128.05	0.2236	96	96	0.0000	105	105	0.0000	141	144.2	2.7067
6	188	188	0.0000	181	181	0.0000	182	182	0.0000	195	195	0.0000
7	160	163.75	2.0474	146	149.75	1.7733	132	132.2	0.4474	176	182	2.9558
8	268	266	0.0000	266	262	0.0000	265	265.15	0.4894	268	271	2.6557
9	186	191.5	2.7625	180	182.9	1.9708	181	183.4	1.818	200	204.3	2.3193
10	262	269.1	3.2911	249	259.75	3.4622	252	259.6	4.6158	273	284.9	5.1289
Job set number	case 3			-			-			-		
	LAOT 4			-			-			-		
	Best MSN	mean	SDV	-	-	-	-	-	-	-	-	-
2	241	248.3	3.57	-	-	-	-	-	-	-	-	-
3	241	245.1	2.0749	-	-	-	-	-	-	-	-	-
4	208	210.1	2.2455	-	-	-	-	-	-	-	-	-
5	177	177.4	1.2732	-	-	-	-	-	-	-	-	-
7	234	238.25	2.8447	-	-	-	-	-	-	-	-	-

Table 3. Optimal solution vector for job set 1 LAOT 2 of case 1

Job-operation	1-1	1-2	2-1	4-1	5-1	2-2	4-2	3-1	5-2	3-2	2-3	3-3	1-3
Machine number	1	2	1	4	3	3	2	3	1	4	2	1	4
Tool copy	3A	4A	2A	3A	2B	3B	4A	1A	1B	4A	1C	2A	1A

Jaya algorithm reported in Venkata Rao [46] is also applied on the above mentioned problems for various cases and layouts, and the results obtained are recorded along with the results obtained by employing CSA in Tables 4 and 5. When the MSN of both algorithms given in tables 4 and 5 are compared, it is observed that CSA is outperforming the Jaya algorithm.

The best MSN of **SMTTATWLNTC** with the best MSN of simultaneous scheduling of machines and tools with a copy of every tool type considering tool transfer time (**SMTTATWACT)** as reported in Sivarami Reddy et al [27] obtained by CSA and % reduction in MSN of former over later for various cases and layouts are given in Table 6. From Table 6, it is noticed that the % reduction in MSN of **SMTTATWLNTC** over **SMTTATWACT** varies in case1 for LAOT 1 from 0.00 to 20.74, for LAOT 2 from 0.00 to 19.38, for LAOT 3 from 0.00 to 18.46, for LAOT 4 from 0.00 to 4.26; in case 2 for LAOT 1 from 0.00 to 31.72, for LAOT 2 from 0.00 to 26.83, for LAOT 3 from 0.00 to 26.12 and for LAOT 4 from 0.00 to 19.35; and in case 3 for LAOT 4 from 5.85 to 13.

4.2. Convergence characterstics

Figure 5 shows CSA convergence characterstics for job set 4 LAOT 2 of case 1. The best value is 86, observed at 214 iteration and time per iteration is 0.429882 seconds.

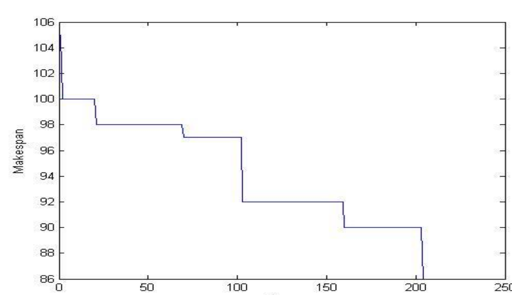

Figure 5. Convergence characteristics of CSA for job set 4, LAOT 2 of case 1

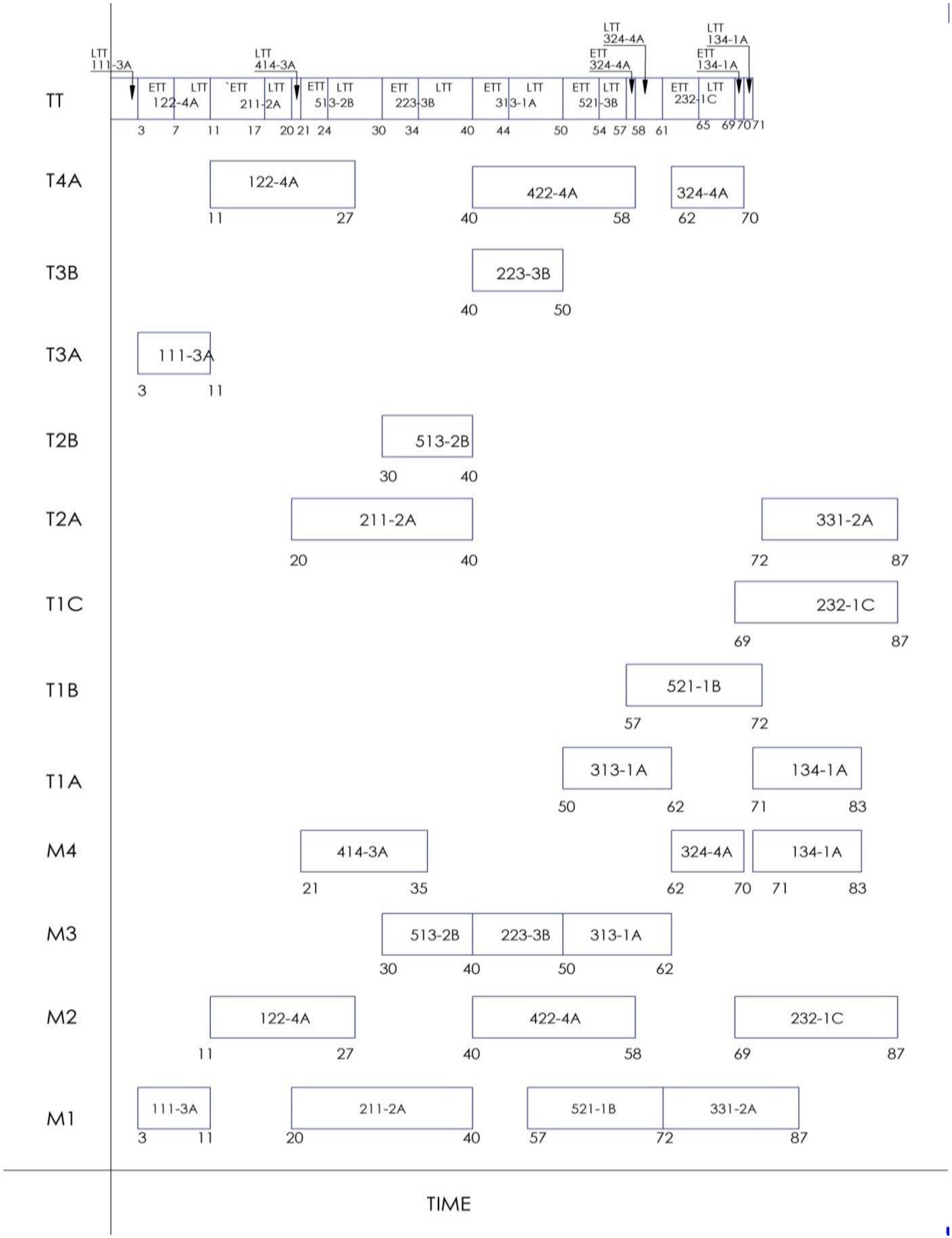

Figure 4. Gantt chart for job set 1, LAOT 2 of case1.

Table 4. Best MSN of SMTTATWLNTC obtained by CSA and Jaya algorithm for various layouts of case 1

Job set number	case 1									
	LAOT 1									
	Best MSN obtained by CSA	Lowest copies for each typeof tool for minimum MSN				Best MSN obtained by Jaya	Lowest copies for each typeof tool for minimum MSN			
		T1	T2	T3	T4		T1	T2	T3	T4
1	110	2	1	1	1	113	2	1	1	2
2	114	2	1	2	1	119	2	2	1	2
3	112	1	2	2	1	116	1	1	2	2
4	109	2	2	2	1	112	2	2	2	1
5	96	1	1	1	1	96	1	1	1	1
6	107	1	1	1	1	108	1	1	1	1
7	107	1	1	2	1	113	1	2	1	1
8	148	1	3	2	1	155	1	3	2	2
9	107	1	2	2	2	121	1	1	1	2
10	136	2	2	2	2	164	2	2	2	2
Job set number	LAOT 2									
	Best MSN obtained by CSA	Lowest copies for each typeof tool for minimum MSN				Best MSN obtained by Jaya	Lowest copies for each typeof tool for minimum MSN			
		T1	T2	T3	T4		T1	T2	T3	T4
1	87	3	2	2	1	88	2	1	1	2
2	94	2	2	1	2	97	2	2	2	1
3	91	2	2	3	2	95	2	2	2	2
4	86	2	2	2	1	88	2	3	2	1
5	74	2	1	2	1	75	1	2	2	1
6	99	1	1	1	1	99	1	1	1	1
7	89	2	1	3	2	94	1	2	2	2
8	135	1	2	3	1	137	2	2	3	2
9	104	2	2	2	3	108	2	3	1	3
10	141	2	2	3	2	147	1	2	3	2
Job set number	LAOT 3									
	Best MSN obtained by CSA	Lowest copies for each typeof tool for minimum MSN				Best MSN obtained by Jaya	Lowest copies for each typeof tool for minimum MSN			
		T1	T2	T3	T4		T1	T2	T3	T4
1	90	3	2	2	1	92	2	1	2	2
2	98	2	1	2	2	101	3	2	1	2
3	95	2	2	2	2	100	2	2	2	2
4	85	2	3	2	1	89	2	3	2	1
5	74	1	2	2	1	79	1	2	2	1
6	100	1	1	1	1	100	1	1	1	1
7	89	1	2	1	2	94	1	2	2	2
8	138	2	2	3	2	140	1	2	2	1
9	106	1	2	2	2	109	1	3	1	3
10	143	1	3	3	2	151	2	2	2	1
Job set number	LAOT 4									
	Best MSN obtained by CSA	Lowest copies for each typeof tool for minimum MSN				Best MSN obtained by Jaya	Lowest copies for each typeof tool for minimum MSN			
		T1	T2	T3	T4		T1	T2	T3	T4
1	123	1	1	1	1	128	2	1	1	1
2	135	2	1	1	1	137	1	1	1	1
3	125	1	1	1	2	129	1	1	2	1
4	129	1	2	1	1	134	1	1	2	1
5	112	1	1	1	1	113	1	1	1	1
6	117	1	1	1	1	117	1	1	1	1
7	121	1	1	1	1	130	1	1	1	1
8	167	1	1	2	1	174	1	2	2	1
9	135	1	1	1	2	139	1	1	1	2
10	179	1	1	1	1	183	2	2	2	2

Table 5. Best MSN of SMTTATWLNTC obtained by CSA and Jaya algorithm for various job sets, layouts of case 2 and case 3

Job set number	Best MSN obtained by CSA	Lowest copies for each typeof tool for minimum MSN				Best MSN obtained by Jaya	Lowest copies for each typeof tool for minimum MSN			
	case 2									
	LAOT 1									
		T1	T2	T3	T4		T1	T2	T3	T4
1	149	2	2	1	2	150	3	2	1	2
2	166	2	2	1	2	170	1	2	1	2
3	162	1	1	2	2	170	2	2	3	2
4	144	2	2	2	2	146	2	2	2	2
5	128	2	2	1	1	128	2	2	1	1
6	188	1	1	1	1	188	1	1	1	1
7	160	1	2	3	2	166	1	2	2	2
8	268	1	2	1	1	270	1	3	3	1
9	186	1	2	2	2	191	2	2	2	3
10	262	2	3	3	3	267	2	2	2	2
	LAOT 2									
Job set number	Best MSN obtained by CSA	T1	T2	T3	T4	Best MSN obtained by Jaya	T1	T2	T3	T4
1	132	2	2	1	2	132	2	2	1	2
2	145	2	2	2	2	152	2	2	2	2
3	157	2	2	3	2	158	2	2	3	2
4	128	2	2	2	2	129	1	2	2	2
5	96	1	2	1	1	107	1	2	2	1
6	181	1	1	1	1	181	1	1	1	1
7	146	2	2	2	3	151	2	2	2	2
8	266	1	2	2	1	266	1	3	3	2
9	180	2	2	2	3	184	2	3	2	3
10	249	2	3	3	2	262	2	3	2	2
	LAOT 3									
Job set number	Best MSN obtained by CSA	T1	T2	T3	T4	Best MSN obtained by Jaya	T1	T2	T3	T4
1	135	3	2	1	2	135	3	2	1	2
2	147	2	2	1	2	154	2	2	2	2
3	152	2	2	3	2	160	2	2	4	2
4	128	2	3	2	1	130	2	3	2	2
5	105	1	2	2	1	114	1	2	2	1
6	182	1	1	1	1	182	1	1	1	1
7	132	2	2	3	2	151	2	2	3	2
8	265	1	3	2	2	265	2	2	3	1
9	181	2	3	1	3	187	2	2	2	3
10	252	2	3	3	3	264	2	3	3	2
	LAOT 4									
Job set number	Best MSN obtained by CSA	T1	T2	T3	T4	Best MSN obtained by Jaya	T1	T2	T3	T4
1	165	2	1	1	2	167	2	1	1	2
2	185	2	2	1	2	187	1	3	2	2
3	172	1	1	2	2	186	1	1	2	2
4	168	2	2	1	1	170	1	1	2	1
5	141	2	1	1	1	146	2	2	1	1
6	195	1	1	1	1	196	1	1	1	1
7	176	2	2	1	2	184	1	2	1	1
8	268	1	2	2	2	272	1	2	3	2
9	200	2	3	1	2	209	1	2	2	3
10	273	2	2	2	2	265	2	2	2	2
	case 3									
	LAOT 4									
Job set number	Best MSN obtained by CSA	T1	T2	T3	T4	Best MSN obtained by Jaya	T1	T2	T3	T4
2	241	2	2	1	2	249	2	2	1	2
3	241	1	2	3	2	282	1	1	2	1
4	208	2	2	1	1	212	1	2	2	2
5	177	2	2	1	1	182	2	2	1	1
7	234	1	2	2	2	241	1	2	2	2

Table 6. Best MSN values of SMTTATWLNTC, SMTTATWACT and % reduction in MSN of former over later for various job sets, layouts and cases.

Job set number	case 1											
	LAOT 1			LAOT 2			LAOT 3			LAOT 4		
	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction
1	110	116	5.17	87	95	8.42	90	95	5.26	123	123	0.00
2	114	120	5.00	94	100	6.00	98	104	5.77	135	137	1.46
3	112	118	5.08	91	102	10.78	95	106	10.38	125	131	4.58
4	109	116	6.03	86	98	12.24	85	99	14.14	129	131	1.53
5	96	96	0.00	74	77	3.90	74	82	9.76	112	112	0.00
6	107	107	0.00	99	99	0.00	100	100	0.00	117	117	0.00
7	107	113	5.31	89	95	6.32	89	99	10.10	121	126	3.97
8	148	160	7.50	135	151	10.60	138	149	7.38	167	172	2.91
9	107	135	20.74	104	129	19.38	106	130	18.46	135	141	4.26
10	136	171	20.47	141	165	14.55	143	166	13.86	179	182	1.65
Job set number	case 2											
	LAOT 1			LAOT 2			LAOT 3			LAOT 4		
	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction
1	149	170	14.09	132	159	16.98	135	158	14.56	165	175	5.71
2	166	185	11.45	145	174	16.67	147	180	18.33	185	192	3.65
3	162	188	16.05	157	178	11.80	152	180	15.56	172	189	8.99
4	144	160	11.11	128	148	13.51	128	153	16.34	168	180	6.67
5	128	133	3.91	96	119	19.33	105	120	12.50	141	147	4.08
6	188	188	0.00	181	181	0.00	182	182	0.00	195	195	0.00
7	160	183	14.38	146	170	14.12	132	173	23.70	176	193	8.81
8	268	272	1.49	266	270	1.48	265	269	1.49	268	281	4.63
9	186	245	31.72	180	246	26.83	181	245	26.12	200	248	19.35
10	262	303	15.65	249	293	15.02	252	302	16.56	273	310	11.94
Job set number	case 3			-			-			-		
	LAOT 4			-			-			-		
	MSN of SMTTATWLNTC	MSN of SMTTATWACT	% reduction	-	-	-	-	-	-	-	-	-
2	241	275	12.36	-	-	-	-	-	-	-	-	-
3	241	277	13.00	-	-	-	-	-	-	-	-	-
4	208	225	7.56	-	-	-	-	-	-	-	-	-
5	177	188	5.85	-	-	-	-	-	-	-	-	-
7	234	261	10.34	-	-	-	-	-	-	-	-	-

Conclusions

This paper introduces a nonlinear MIP model for machines, TT and tools simultaneous scheduling in MMFMS to minimize MSN with the lowest possible number of copies of every tool type without tool delay considering tool switch times between machines in MMFMS. This scheduling problem involves determining the lowest possible number of copies of every tool type for no tool delay, assigning of suitable tool copy for every job-operation, ordering and synchronization of those job-operations and associated trip operations of TT including the dead heading trip and loaded trip times of TT for minimum MSN. An algorithm for computation of MS and lowest possible number of copies of every variety of tools without tool delay is developed for a given schedule and Figure 2 shows its flow chart. The proposed algorithm is tested on the job sets mentioned in section 2.4.3. From the tables 2, it is quite evident that CSA is robust and able to find many optimal alternatives for the problems. From tables 4 and 5, it is noticed that CSA is outperforming Jaya algorithm. From Table 6, it is observed that impact of SMAATWLNTC on reduction in MSN over SMTTATWACT is significant. In future work with machines and tool scheduling, subsystems such as robots and automated storage and retrieval systems (AS/RS) may be integrated.

References

[1] Agnetis,Alessandro.Arianna Alfieri, Paolo, Brandimarte. Prinsecchi, Paolo. (1997). Joint Job/Tool Scheduling in a Flexible Manufacturing Cell with No On-Board Tool Magazine. Computer Integrated Manufacturing System, 10 (1), 61–68. https://doi.org/10.1016/S0951-5240(96)00023-7

[2] Saravanan, M., A,. Noorul Haq. (2008). Evaluation of scatter-search approach for scheduling optimization of flexible manufacturing systems. Int J Adv Manuf Technol, 38, 978–986. https://doi.org/10.1007/s00170-007-1134-5

[3] Chen, F. Frank. and Everett, E. AdamJr. (1991),The Impact of Flexible Manufacturing Systemson Productivity and Quality. IEEE Transactions on Engineering Management, 38(1)1, 33-45.

[4] Jyothi, S. D. (2012) Scheduling Flexible Manufacturing System Using Petri-nets and Genetic Algorithm. Project Report Indian Institute of Space Science and Technology, Thiruvananthapuram, https://www.semanticscholar.org › paper › SCHEDULING-FLEXIBLE-MAN...

[5] Shirazi, Rabia.& G. D. M. Frizelle. (2001). Minimizing the number of tool switches on a flexible machine: An empirical study. International Journal of Production Research, 39(15), 3547-3560, DOI: 10.1080/00207540110060888

[6] Tang, Christopher S. Eric V, Denardo. (1988). Models Arising from a Flexible Manufacturing Machine, Part I: Minimization of the Number of Tool Switches. Operations Research, 36(5), 767–777. https://doi.org/10.1287/opre.36.5.767

[7] Chandra, P. S. Li & M. Stan. (1993). Jobs and tool sequencing in an automated manufacturing environment. International Journal of Production Research, 31 (12), 2911-2925 .https:// doi.org/ 10.1080/00207549308956907

[8] Song, Chang-Yong. Hark, Hwang. and Yeong-Daekim. (1995). Heuristic algorithm for the tool movment policy in Flexible Manufacturing systems. Journal of Manufacturing Systems, 14(3), 160-168. https://doi.org/10.1016/0278-6125(95)98884-9

[9] Roh, H.-K. and Y-D, Kim. (1997).Due-date based loading and scheduling methods for a flexible manufacturing system with an automatic tool transporter. International Journal of Production Research, 35 (11), 2989-3004, https:// doi.org/ 10.1080/ 002075497194255

[10] Tsukada,T.K. Kang. G. Shin. (1998). Distributed Tool Sharing in Flexible Manufacturing Systems. IEEE Transactions on Robotics and Automation, 14 (3), 379–389. DOI: 10.1109/70.678448

[11] Jun,Hong-Bae. Yeong-Dae, Kim. Hyo-Won, Suh. (1999). Heuristics for a Tool Provisioning Problem in a Flexible Manufacturing System with an Automatic Tool Transporter. IEEE Transactions on Robotics and Automation, 15(3), 488–496. DOI: 10.1109/70.768181

[12] Keung, K. W. W. H, Ip. and T. C. Lee. (2001). A genetic algorithm approach to the multiple machine tool selection problem. Journal of Intelligent Manufacturing, 12, 331–342. https://doi.org/10.1023/A:1011215416734

[13] Ecker, K.H. and J.N.D,Gupta. (2005). Scheduling tasks on a flexible manufacturing machine to minimize tool change delays. European Journal of Operational Research, 164, 627–638. https://doi.org/10.1016/j.ejor.2003.12.025

[14] Prabaharan,T. P. R,Nakkeeran, and N,Jawahar. (2006). Sequencing and Scheduling of Job and Tool in Flexible Manufacturing Cell. International Journal of Advanced Manufacturing Technology, 29 (3), 729–745. https:// doi.org/10.1007/s00170-005-2567-3

[15] Karzan, Fatma KilinÇ. and Meral, Azizoğlu.(2008). The tool transporter movements problem in flexible manufacturing systems. International Journal of Production Research,46(11), 3059–3084. https://doi.org/10.1080/00207540601070135

[16] Sureshkumar, N., and R.Sridharan.(2009). Simulation Modeling and Analysis of Tool Flow Control Decisions in a Flexible Manufacturing System. Robotics and Computer Integrated Manufacturing, 25, 829–838. https:// doi.org/ 10.1016/ j.rcim. 2008.12.004

[17] Udhayakumar, P. and S, Kumanan. (2010). Sequencing and scheduling of job and tool in a flexible manufacturing system using ant colony optimization algorithm. Int J Adv Manuf Technol, 50, 1075–1084. https://doi.org/10.1007/s00170-010-2583-9

[18] Udhayakumar, P. and S, Kumanan. (2012). Some metaheuristic approaches for optimising tardiness of job and tool in a flexible manufacturing system. Int. J. Advanced Operations Management, 4(3) , 219-252.https://doi.org/10.1504/IJAOM. 2012 .047683

[19] Aldrin Raj, J. Ravindran, D. Saravanan, M. and Prabaharan, T. (2014). Simultaneous scheduling of machines and tools in multimachine flexible manufacturing system using artificial immune system algorithm. International Journal of Computer Integrated Manufaturing, 27(5), 401–414. https://doi.org/ 10.1080/0951192X. 2013.834461

[20] Özpeynirci, Selin. (2015).A heuristic approach based on time-indexed modelling for scheduling and tool loading in flexibl manufacturing systems. Int J Adv Manuf Technol, 77, 1269–1274. https://doi.org/10.1007/s00170-014-6564-2

[21] Costa, A. F.A, Cappadonna, S, Fichera. (2016). Minimizing the total completion time on a parallel machine system with tool changes. Computers & Industrial Engineering, 91, 290–301.. https://doi.org/10.1016/j.cie.2015.11.015

[22] Sivarami Reddy, Narapu Reddy. Dwivedula, Venkata Ramamurthy. K, Prahlada Rao. M,Padma Lalitha. (2016). A Novel metaheuristic method for simultaneous scheduling of machines and tools in multi machine FMS. IET Digital Library International Conference on Recent Trends in Engineering, Science & Technology 2016, 1–6. ISBN-978-1-78561-785-0 DOI: 10.1049/cp.2016.1489

[23] Beezao, Andreza Cristina. Jean-Francüois, Cordeau. Gilbert Laporte,Horacio. Hidek, Yanasse. (2017).Scheduling identical parallel machines with tooling constraints. EuropeanJournal of Operational Research, 257(3), 834-844. doi: 10.1016/j.ejor.2 016.08.008

[24] Baykasoğlu, Adil. and Fehmi, Burcin Ozsoydan. (2017). Minimizing tool switching and indexing times with tool duplications in automatic machines. International Journal of Advanced Manufacturing Technology , 89,1775–1789.DOI 10.1007/s00170-016-9194-z

[25] Paiva Gustavo Silva. Marco Antonio M, Carvalho. (2017). Improved Heuristic Algorithms for the Job Sequencing and Tool Switching Problem. 88, 208-219. Computers and Operations Research, doi: 10.1016/j.cor.2017.07.013

[26] Gökgür, Burak.Brahim, Hnich. &Selin, Özpeynirci.(2018). Parallel machine scheduling with tool loading: a constraintprogramming approach. International Journal of Production Research. https://doi.org/10.1080/ 00207543. 2017. 1421781

[27] Sivarami Reddy, N. D.V,Ramamurthy. K, Prahlada Rao. (2018a).SimultaneousScheduling of Machines and Tools Considering Tool Transfer Times in Multimachine FMS Using CSA. International Conference on Intelligent Computing and Applications, Advances in Intelligent Systems and Computing 632, 421–432.

[28] Sivarami Reddy, N. D.V, Ramamurthy. and K, Prahlada Rao. (2018b). Simultaneous scheduling of jobs, machines and tools considering tool transfer times in multi-machine FMS using new nature-inspired algorithms. Int. J. Intelligent Systems Technologies and Applications, 17(1/2), , 70–88.

[29] Sivarami Reddy, N. D V, Ramamurthy. K, Prahlada Rao. & M. Padma Lalitha. (2019).Integrated scheduling of machines, AGVs and tools in multi-machine FMS using crow search algorithm, International Journal of Computer Integrated Manufacturing. DOI:10.1080/0951192X.2019.1686171 https:// doi.org/10.1080/0951192X.2019.1686171

[30] Sivarami Reddy, N. D. V, Ramamurthy. K, Prahlada Rao.& M, Padma Lalitha. (2021).Practical simultaneous scheduling of machines, AGVs, tool transporter and tools in a multi machine FMS using symbiotic organisms search algorithm. International

Journal of Computer Integrated Manufacturing, DOI: 10.1080/ 0951192X.2020.1858503 https://doi.org/10.1080/0951192X. 2020. 1858503

[31] Sivarami Reddy, N. D V,. Ramamurthy. M, Padma Lalitha.& K, Prahlada Rao.(2021b).Integrated simultaneous scheduling of machines, automated guided vehicles and tools in multi machine flexible manufacturing system using symbiotic organisms search algorithm.Journal of Industrial and Production Engineering.https://doi.org/10.1080/21681015.2021.1991014

[32] Sivarami Reddy N., Padma Lalitha M., S.P.Pandey, Venkatesh G.S.(2021c). Simultaneous scheduling of machines and tools in a multi machine FMS with alternative routing using symbiotic organisms search algorithm. Journal of Engg. ResearchDOI : 10.36909/jer.10653

[33] Sivarami Reddy N., Padma Lalitha M., D V. Ramamurthy, K Prahlada Rao. (2022). Simultaneous scheduling of machines and tools in a multi machine FMS with alternate machines using crow search algorithm., Journal of Advanced Manufacturing Systems https://doi.org/10.1142/S0219686722500305

[34] Al-Refaie et al. (2017).Optimal Scheduling and Sequencing of Operating Room Under Emergency Cases. Jordan Journal of Mechanical and Industrial Engineering 11(1), 21-26.

[35] Abbas, Al-Refaie. and Hala, Abedalqader. (2021). Optimal Quay Crane Assignment and Scheduling in Port's Container Terminals. Jordan Journal of Mechanical and Industrial Engineering, 15(2), 153-167.

[36] Lenstra, J.K.A.H.G,Rinnooy Kan. (1979).Computational complexity of discrete optimization problems. Ann. Discrete Math., vol. 4, 121–140. https://doi.org/10.1016/S0167-5060(08)70821-5

[37] Lenstra, J.K. A.H.G,.Rinnooy Kan. (1981). Complexity of vehicle routing and scheduling problems. Networks, vol. 11, No. 2, 221–227. https://doi.org/10.1002/net.3230110211

[38] Askarzadeh,Alireza. (2016). A novel metaheuristic method for solving constrained engineering optimization problems. Computers and Structures.169, 1– 12. https://doi.org/10.1016/j. compstruc.2016.03.001

[39] Oliva, Diego. , Salvador, Hinojosa. Erik, Cuevas. Gonzalo, Pajares. Omar, Avalos. Jorge, G«alvez. (2017). Cross entropy based thresholding for magnetic resonance brain images using Crow Search Algorithm. Expert Systems With Applications,79, 164-180. doi:10.1016/j.eswa.2017.02.042

[40] Sivarami Reddy, N. Dr.D.V,Ramamurthy. Dr. K, Prahlada Rao. and Dr. M, Padma Lalitha. (2017). Simultaneous Scheduling of Machines and Tools in Multi Machine FMS Using Crow Search Algorithm. International Journal of Engineering Science and Technology, 9(09S), 66–73.

[41] Sivarami Reddy,N. D.V,Ramamurthy. K,Prahlada Rao. (2018c). Simultaneous Scheduling of Machines and AGVs using Crow Search Algorithm. Manufacturing Technology Today, 17(09) ,12–22. ISSN: 0972-7396. www.i-scholar.in › index.php › MTT › search › authors › view › country=...

[42] Pankaj, Upadhyay. J.K, Chhabra.(2019). Kapur's entropy based optimal multilevel image segmentation using Crow Search Algorithm. Applied Soft Computing Journal105522, https://doi.org/10.1016/j.asoc.2019.105522.

[43] Anter Ahmed, M. Aboul Ella, Hassenian. Diego, Oliva.(2019).An improved fast fuzzy c-means using crow search optimization algorithm for crop identification in agricultural. Expert Systems With Applications, 118,340-354 doi: https://doi.org/10.1016/j.eswa.2018.10.009

[44] Spea Shaimaa, R. (2020). Solving practical economic load dispatch problem using crow search algorithm. International Journal of Electrical and Computer Engineering (IJECE) , 10(4), 3431-3440

[45] Bilge,Ümit.Gündüz, Ulusoy.(1995).A time window approach to simultaneous scheduling of machines and material handling system in FMS. Operations Research, 43, 1058−1070. https://doi.org/10.1287/opre.43.6.1058

[46] Venkata Rao, R.(2016). Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. International Journal of Industrial Engineering Computations , 7, 19–34.