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OPTIMISATION OF PRODUCTION MACHINE SCHEDULING USING A TWO LEVEL MIXED OPTIMISATION METHOD

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Abstract: This paper presents an application of a two level mixed optimization method on a machine scheduling problem of a government owned machine shop. Where evolutionary algorithm methods are suitable for solving complex, discrete space, and non-linear, discontinuous optimization problems; classical direct-search optimization methods are suitable and efficient in handling simple unimodal problems requiring less computation. Both methods are used at two levels, the first level decides which machines to be used for the machining operations and how much overtime (at extra cost) to be allotted to each work order, the second level decides for which operation and on which day the overtime should be allotted so as to attain its maximum benefit. A sample problem has been solved by using the above methods and a range of non-dominated solutions have been presented in a tabular form to enable the production manager to choose his options based on the given criticality of the work order.

Keywords: Multi-objective optimization, Genetic algorithm.

AMS Subject Classification: 90C29, 90C59

1. INTRODUCTION

Government owned (Public sector) machine shops are inherently inefficient. In such a machine shop it was observed by the author that a "component" (work piece) to be machined is to be shifted between different types of machines (viz. lathe, shaper, milling machine etc) for performing different operations on it. Furthermore, because of worker union compulsions, no work is performed for more than 08 hours per day and there was no arrangement for workers to work in shifts. In case a work order is critical and is to be finished in the earliest possible time, workers are to be allowed to work on overtime (OT) beyond the normal 08 working hours per day. This overtime comes at a cost which is at double the rate that is admissible to the rate for normal (08 hours) working time. A manager appointed to such an in-efficient production shop set up has very little choice, but to play within the given set of rules. However, even the above mentioned set up has a scope for implementation of optimization techniques.

Understanding the Problem

The paper presents a solution of a practical problem faced in a Government owned machine shop. But before we go on to solve the problem; a basic understanding is required about the terminologies used in a production workshop.

A 'machining operation' is the kind of work carried out on a piece of raw material by a particular machine. Different machines are meant for carrying out different types of machining operations. For example, turning is carried out on a lathe machine, slotting can be carried out on a milling machine and so on. To manufacture a finished product, various types of machining operations may be required to be carried out on the raw material.

A 'work order' or a 'job' is described as a group of instructions given in a sheet of paper that gives details of machining operations required to be carried out sequentially on a raw piece of metal. The instructions give the dimensional details such as sizes, machining tolerances, surface finish etc to be achieved on the work piece.

A 'work piece' is a piece of raw material (metals like steel, brass, etc) of required dimensions which is issued to the worker along with the work order. Various machining operations are carried out on this work piece according to the instructions given in the work order.

Refer to table 2 that shows a problem, the table giving types of Operations and Time required for work orders and waiting time for machines. It shows a problem of manufacture of three components. Let the manufacturing time for each machining operation and the waiting time of machines be as shown in the problem table. For example the first component requires "turning" (an operation carried out on lathe machine) for 12 hours followed by grinding of 7 hours followed by milling operation of 1 hour and then again turning of 5 hours. The waiting time table shows that there are 20 lathes which are busy and have a waiting time shown in the row matrix as [12,10,9,3,4,16,2,9,12,2,10,6,7,8,10,0,12,7,1,20] in hours. It may be noted that the 16^{th}

lathe has 0 waiting time. Waiting times are also shown for other types of machines such as grinders, milling machines etc.

Work orders are received by the manager for manufacture of certain metallic work pieces using machines such as; Lathes, milling machines, boring machines, grinding machines, shaping machines and drilling machines. Each work piece that needs to be produced requires multiple operations in the above machines. For example, a shaft for a rotary pump would need to be put through turning operation in a lathe machine, and then it would be put through a milling machine for making of a keyway slot. Since there a large number of machines and most of the machines are already busy manufacturing, the manager has to optimally select the machines where he can get the particular work piece machined as economically as possible. For example, the above-mentioned shaft for rotary pump could be machined in Lathe number1 or 2 or 3 etc…. and later put in milling machine number 1 or 2 … etc. If, for example, the work piece has been allotted lathe machine number 3 and that particular machine is busy machining some other work piece and not available for next 02 hours, then these two hours are spent by the given work piece in waiting. This is termed as "**waiting time**". The total time taken for a work piece to be manufactured is termed as "**make-span**". Obviously higher the waiting time of machines, higher will be the make-span. The manager therefore strives to select such machines which have minimum waiting time, however this situation is tricky because the machining operations to be performed on the work piece are sequential and time used for keeping track of all the machining operations are recorded on real time basis.

Furthermore, there are only 08 hours in a day for a government worker termed as "**normal working hours**" and the rate of wages applicable during this time is termed as "**normal wage rate**". If the working hours for the workers are extended beyond the normal working hours, the worker has to be paid wages at double the rate of normal wage rate. The extended working hours (beyond the normal working hours) is termed as "**OT**" or Overtime. OT is payable for full 08 hours termed as "**one OT unit**", regardless of whether the worker finishes the given job in one hour after normal working hours or two or eight hours after normal working hours. Therefore, if a worker has to work for nine hours continuously starting from 0800 hours on a day, he will work eight hours during the normal time and one hour in overtime. However, if he has to work for sixteen hours continuously starting from 0800 hours, he will end up working eight hours in normal time and then continue working for next eight hours in overtime. The wages paid however, in both the above cases will be same.

A term "**OTA**' stands for Overtime allotted and "**OTE"** stands for over time effective. For example, if the manager allots one unit OT (of 08 hours of overtime) to a worker over and above the normal working hours and the worker finishes the work in 08 hours (normal) + 03 hours (in overtime), the OTA is 08 hours(one OT unit) of overtime but the OTE is only 03 hours. In short 05 hours of OT actually get wasted. It may be noted that higher the overtime allotted for manufacture of a work piece, shorter is the make-span, but then the cost of manufacture is also higher because of higher wage rate of OT hours. Secondly, when the time required for manufacturing of a work piece extends to say for four days, and the manager decides to allot 08 hours OT, he will have to decide the day (and the machine)on which he should allot this OT so as to minimize the cost and minimize the make-span for manufacturing of the work piece.

Hence to put it briefly, once the work orders are received for a group of work pieces, the manager has to decide the following:

(a) Given the sequence of machining operations required for manufacture of the work pieces (milling, drilling etc), the length of time required for each operation and the existing waiting times on the machines, what is the most optimal selection of machines that should be allotted for undertaking manufacture of the work pieces?

(b) How much overtime to be allotted to the worker for manufacturing of the work pieces.

(c) On which day and for what machining operation should he allot the overtime?

The objectives for the manager are two folds: minimize make-span (which includes the waiting time the work piece has to wait in queue) and minimize the cost of production. The decision variables are: allocation of different machines for different operations on each of the received work orders and to decide on number of overtime (OT) hours to be allotted on each of the work order. Secondly, the overtime to be allotted is to be decided to be allotted to a specific operation or day to achieve its maximum benefit.

2. DESCRIPTION OF THE PROBLEM

It is evident from the statement of the problem that the search space for the optimal selection of machines and OT hours is discrete and non-continuous requiring un-coded real parameter decision variables (basically the serial numbers of machines and number of OT units). The interactions between the variables are complex and non-linear and the search space has many optimal solutions of which most are undesired local optimal solutions. Since GAs work well in a discrete search space with little or no auxiliary information except for the objective function values, use probabilistic rules to guide their search and use, not one, but the whole population of solutions in each iteration, they are the ideal candidate for solving the above given problem. [7 to 12]

Since the search space has discrete solutions of the order of (*number of work orders X number of operations) X* ***Π****(type of machines for operation)****!*** (not considering the allocation of overtime) evaluation of optimal set of machines and overtime is difficult using the classical optimization techniques. For solving the problem at hand the author has chosen a two level optimization technique. On the first level, an elitist GA (NSGA-II)[1] who works in a discrete and non-continuous search space requiring ***un-coded real parameter decision variables*** decides on the optimal selection of machines and OT hours. At the second level, for each solution given by the NSGA-II at first level, it decides on which day and for what operation should the overtime be allotted. For the second level a simple classical direct-search method has been employed. Notations used in mathematical formulation of the problem are shown in Table 1. The problem statement is shown in Figure 1 Certain important features unique to the subject problem are discussed in the succeeding paragraphs.

(i) <u>Variables</u> since the variables in the problem are nothing but names (or say numbers) of the machines, used purely for identification of these machines (lathe, milling etc), real variables had to be used for modeling of the problem. The variables have been used in the form of a two dimension array. The rows represent the different work orders (for different work pieces) and the columns represent the time required for each operation on the work piece. It may be noted that the last cell of each row represents the number of

OT hours allotted on each work order. This way the whole population of GA can be represented in a form of a three dimensions array where the third dimension (the sheet containing two dimension arrays each) represents the chromosomes of population. (Please refer to Figure 2)

(ii) Crossover. (Figure 3) The cross over operator creates new solutions (called children) by randomly selecting two elite solutions from the population (called parents). The operator randomly selects three points within the chromosome of the selected parents. The bits from either side of the selected points are then exchanged between the parents to give rise to two children. With this method, the cross over operation helps in searching the search space for better solutions. (Figure 3) shows the crossover operation of the GA used in this problem. It may be noted that while changing the bits from the chromosomes, only the bits between corresponding machines can be interchanged. For example a gene (or a bit) for milling operation between parent A can be crossed over with another gene of parent B only for the milling operation and not for drilling or grinding operation The bit representing the OT hours in the chromosome are not crossed over.

(iii) Mutation. Mutation operator also helps in creating new solutions; however there is one important difference. Here the bits are not interchanged between the parents, rather a chromosome is randomly selected with a small probability and then a particular bit of the selected chromosome is altered randomly. This operation helps in providing diversity to the search and it also helps in avoiding traps of local optima. OT hours of each work order number within a chromosome is mutated separately.

(iv) OT hours. Overtime hours are time for production over and above the eight normal working hours per day. These have been admissible in terms of numbers (units) where one unit is equal to eight hours. Wages for OT are paid out at double the rate of normal working hours.

In view of the characteristics of OT admissibility for work orders, the software program used has to cater for a separate function to evaluate the optimal day/machining operation for allotting the OT. In the example if OT of one unit (eight hours) has been allotted to a work order, then the OT can be allotted on the very first day of production or the next day or the next day etc. However, the usefulness of the OT (how much production work has been done in the eight hours of OT) on each day may be different. For each work order, a separate method is required to evaluate the optimal days when the allotted OT should be consumed. Since the objective function at this second level (maximizing OT benefit) is discontinuous and requires comparatively small computational effort, the same can be efficiently managed using a classical/traditional[*] direct search method. A special algorithm has been used for deciding the usefulness of the allotted overtime. The complex algorithm is not mentioned in the paper for the purpose of brevity.

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[*] *The term traditional and non-traditional optimisation methods was coined in the book by Dr Kalyanmoy Deb called "*Optimisation for Engineering* Design" published by Prentice Hall of India in 2005. Traditional direct search method here means a *classical* method. Non-traditional methods refers to methods like GA, simulated annealing etc. Direct search methods are the ones that uses only the function values to search for the minima. Examples of such methods are the Hook and Jeeves method, Nelder and Mead's method etc.

The following are constraints of the problem:

1. Overtime can be allotted in multiples of eight hours only.
2. The machining operations that are required to be carried out on a component are sequential in nature and in that sense it has a precedence constraint.
   OT time cannot be consumed waiting for a machine to be available. What this means is that a production job might continue during the OT hours but no production work should start during OT hours. This is followed in practice to allow only the operator of the machine to work on OT, and to see that OT hours are not wasted on persons in support roles needed only for commencing a particular operation.
3. Maximum OT hours cannot exceed the total production time required for a work order.

Table 1: Notations

Jn=1,2,…JN–work order number index	on = 1,2,3…….N – operation number index
$EMWT_{jn,on}$– effective machine waiting time selected for jn,on	$PTO_{jn,on}$ – Production time required for work order "jn", and operation "on"
$OTA_{jn,;}$ $OTE_{jn,x}$ – Overtime allotted for work order jn; OT effective allotted during operation x for work order jn	$MWT_{jn,on}$ – Machine waiting time of the machine selected for performing work order "jn", and operation "on" .This is accounted in real time and keeps record the time that will be spent in preceding machining operations
Cn=cost per hour for normal working hours	$MWT(i)_{jn,on}$ – initial machine waiting time (at the start of receiving the work order) for the machine selected for performing work order "jn", and operation "on"
Cot = cost per hour for overtime working hours	Make-span – Time required for finishing all the received work orders

$$OBJECTIVE \quad 1 = {}_{\min}\left[Total \quad Cost\right]$$

$$where \quad Total \quad Cost = \sum_{jn=1}^{jn=JN} \left\{ \left[\left(\sum_{on=1}^{on=N} EMWT_{jn,on} + PTO_{jn,on} \right) - OTE_{jn,x} \right].Cn + + OTA_{jn}.Cot \right\}. \qquad \ldots (1)$$

$$OBJECTIVE \quad 2 = {}_{\min}\left[Makespan\right] \vdots$$

$$where \quad Makespan = \max \left[\frac{\left[\left(\sum_{jn,on=jn,1}^{jn,on=jn,N} EMWT_{jn,on} + PTO_{jn,on} \right) - OTE_{jn} \right]}{8} \right] \quad for \quad jn = 1,2,\ldots JN \quad \ldots \ldots (2)$$

$$EMWT_{jn,on} = \left\{ \begin{array}{ll} MWT_{jn,on} & for \quad on = 1 \\ \left\langle - \left(\left[\sum_{jn,x=1}^{jn,x=on-1} \left(MWT_{jn,x} + PTO_{jn,x} \right) \right] - MWT_{jn,on} \right) \right\rangle & for \quad on \neq 1 \end{array} \right\} \quad \forall \quad jn \qquad \ldots \ldots \ldots (3)$$

$$and \quad \langle\ \rangle \quad notation \quad is \quad such \quad that \quad \langle a \rangle = a \; ; \; for \quad all \quad a < 0 \quad and \quad \langle a \rangle = 0 \quad for \quad all \quad a > 0$$

$$MWT_{jn,on} \quad on \quad selection \quad gets \quad updated \quad to \quad MWT(i)_{jn,on} + \left[\sum_{jn,x=1}^{jn,x=on-1} \left(MWT_{jn,x} + PTO_{jn,x} + OTE_{jn,x} \right) \right] \quad \ldots (4)$$

Figure 1: Objectives of the Problem – To minimize "Total cost and Make-span"

3. RESULT AND CONCLUSION

A flow chart at Figure 4 shows the algorithm used for evaluation of the optimal choice of machines and OT hours for each work order in the wake of given wait time for each machine and production time required for each machining operation given in the work orders. It may be noted that in the given problem the author has not considered the option of changing the sequence of work orders received in the machine shop. This is in line with the practical scenario in the machine shop, where the work orders may be received in a staggered manner and where the machines available for undertaking machining are in larger numbers. However, inclusion of the option of being able to change the sequence of work orders may not be such a difficult proposition, only that the chromosomes would then have a fourth dimension and the GA would need a larger population to handle the problem.

Various combinations of work orders with different operation types and times have been used to check the efficiency of GA in solving the above multi-objective problem with very encouraging results. A sample problem has been shown in the problem table (Table 2). Waiting time for various machines on shop floor with operation types and times for each work order has been shown. The problem has been solved using a NSGA-II method (with a modified cross over and optimal OT allocation technique) written in MATLAB version 6, with population strength of 400, Cross over probability is 1.0 and mutation probability is 0.01. Solutions with objective values have been shown from Figures 6 to 7 after Generations 5 and 80. A solution table at Table 3 indicates the choice of machines and OT hours for eight non-dominating solutions. If wages for normal and OT hours are Rs 30/hr and Rs 65/hr respectively, the maximum cost which will see the earliest manufacture of the 03 work orders received in the machine shop will be Rs 5050/- and all the three work orders will be completed within 4 days and 03 hours. On the other extreme if no OT hours are to be used then the work orders will be completed only after 6 days and 03 hours at an expense of Rs 3900/-. All the other non-dominated solutions fall within these two extremes.

Choice of any other machines and OT hours other than that given in the solution tables will delay the work orders and incur higher costs.

Understanding the solution

The solution is presented in a form of a table as given at Table 3. Refer to solution 1 of the solution table. The solution table states that the optimal selection for component number one would be to put on lathe number 19, (not on 16th lathe which has 0 wait time) then put on grinding machine number 7, then milling machine number 6 and then at last, again to lathe machine number 1. This solution will give a make-span of 6 days (of eight hours normal time each) and 2 hours at a cost of Rupees 4180.00 for all three components. The other 7 solutions are also presented in table 3.

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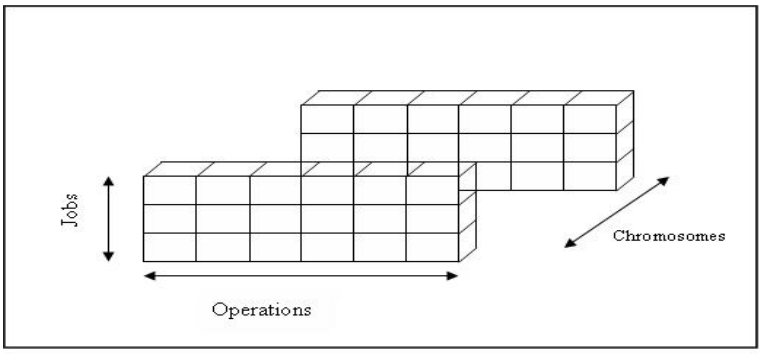

Figure 2: Chromosomes representing machines selected for production

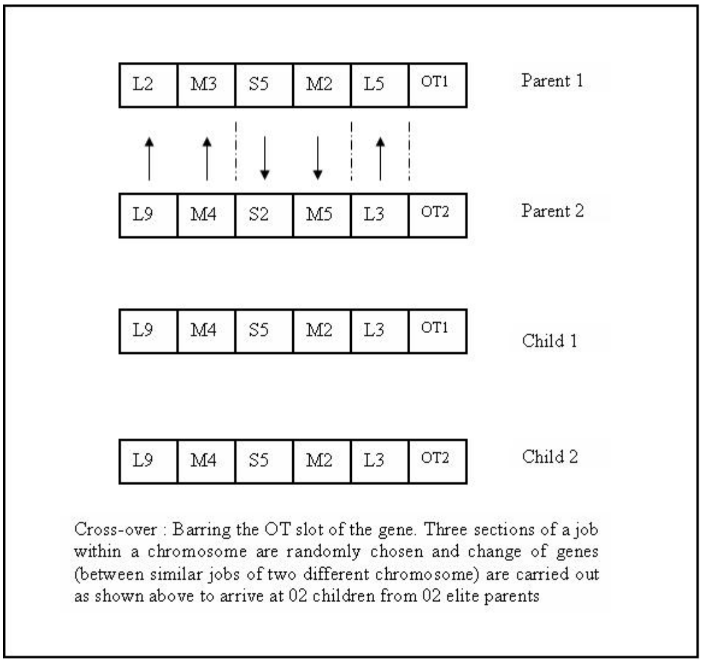

Figure 3: Chromosomes representing machines selected for production. L9, M4, S5 etc stands for Lathe machine number 9, Milling machine 4, and Shaping machine number 5 and so on

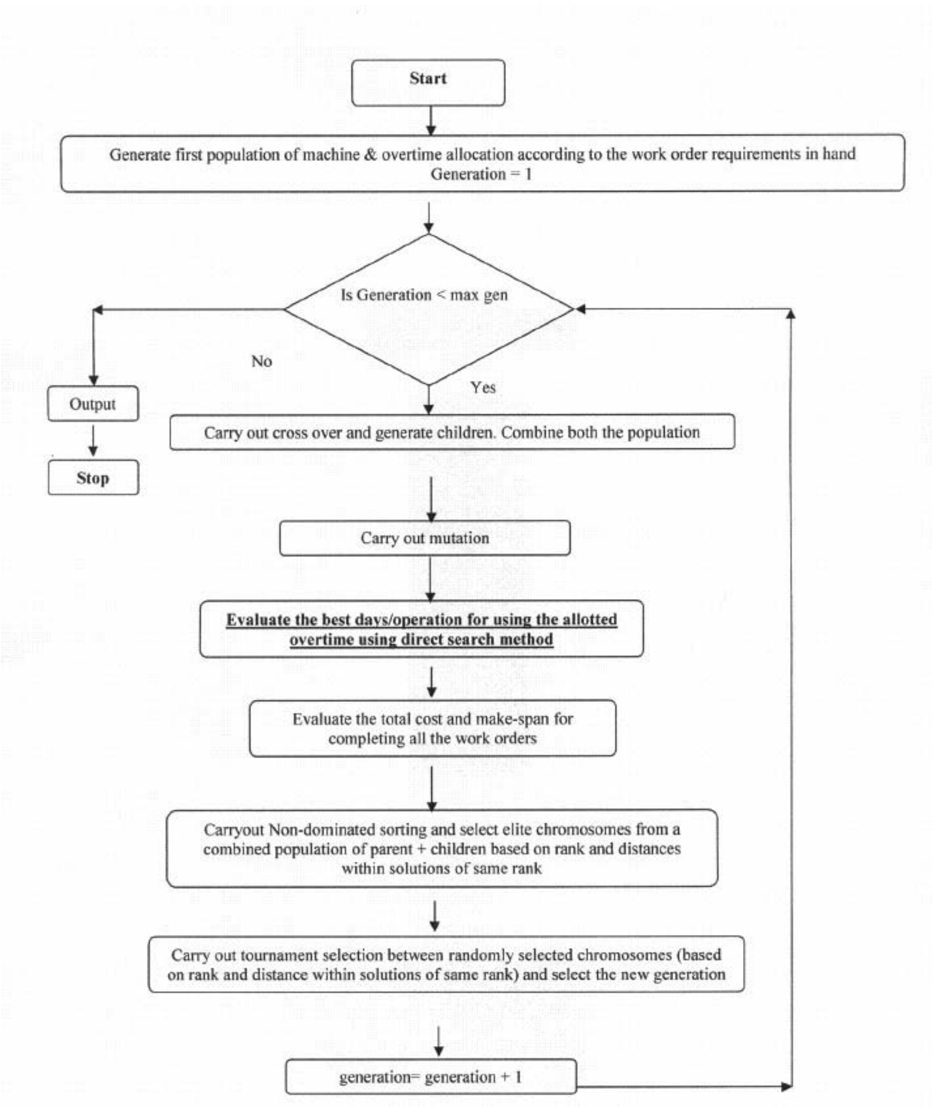

Figure 4: Flow Chart: Algorithm for evaluating optimal choice of machines and OT hours for each work order

Table 2 : Problem tables giving types of Operations and Time required for work orders and waiting time for machines

Work order Number-1				
Operations				
Turning	**Grinding**	**Milling**	**Turning**	**-**
12 hrs	**7 hrs**	**01 hr**	**5 hrs**	
Work order Number-2				
Operations				
Turning	**Milling**	**Boring**	**Shaping**	**Turning**
8 hrs	**10 hrs**	**2 hrs**	**2 hrs**	**12 hr**
Work order Number-3				
Operations				
Turning	**Shaping**	**Boring**	**Turning**	**Milling**
9 hrs	**5 hrs**	**10 hrs**	**9 hrs**	**3 hrs**

Waiting time for machines in hrs (in sequence of serial number of machines)
Lathes=[12,10,9,3,4,16,2,9,12,2,10,6,7,8,10,0,12,7,1,20] For turning operation
Grinders=[22,19,32,27,38,29,16,33,25,30,26]
Milling machines=[32,41,27,36,47,23]
Shapers=[26,32,21,49,30]
Boring machines=[46,31,29,32]
Slotting machines=[32,51,40]

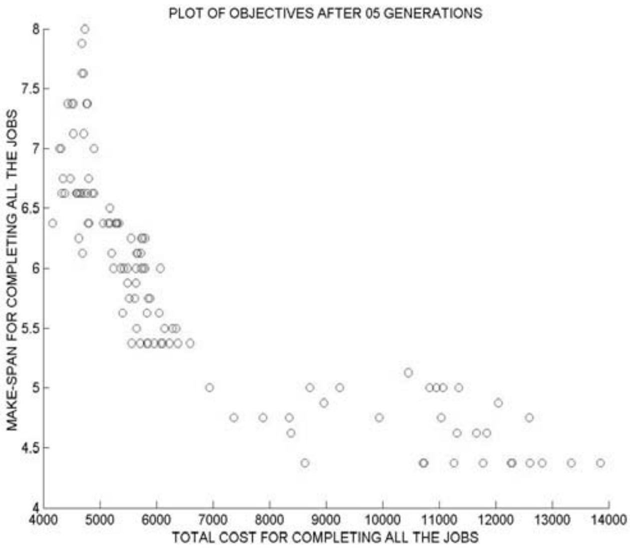

Figure 5: Solutions after 05 Generations in terms of Objective values

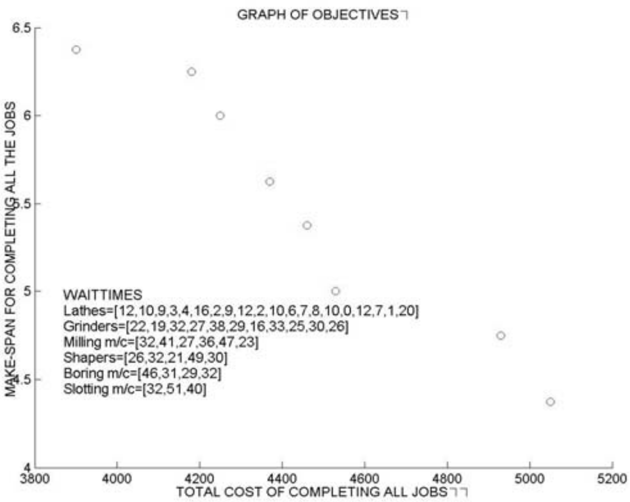

Figure 6: Depiction of Solutions after 80 Generations in terms of Objective values

Table 3: Solution tables with 08 solutions. Each solution shown as dots in Figure 6 are shown as solution numbers in the table below

SOLUTION TABLE							
SOLUTION 1							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	**6 days and 2 hrs**	**Rs 4180/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
19	7	6	1	-	0		
WORK ORDER NUMBER-2							
Machine Nos					OT		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
10	6	4	2	8	0		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
9	3	3	7	5	1		

SOLUTION TABLE							
SOLUTION 2							
WORK ORDER NUMBER-1						Make - span	Total
Machine Nos					OT hours	**5 days and 3 hrs**	**Rs 4460/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
16	7	6	2	-	0		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
19	6	4	2	4	1		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
12	3	3	14	4	1		

SOLUTION TABLE							
SOLUTION 3							
WORK ORDER NUMBER-1						Make -span	Total cost
Machine Nos					OT hours	**4 days and 6 hrs**	**Rs 4930/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
4	7	6	1	-	1		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
3	6	3	5	5	1		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
18	3	3	7	2	2		

SOLUTION TABLE							
SOLUTION 4							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	**6 days and 3 hrs**	**Rs 3900/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
19	7	6	7	-	0		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
10	6	4	2	6	0		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
9	3	3	5	5	0		

SOLUTION TABLE							
SOLUTION 5							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	4 days and 3 hrs	Rs 5050/-
Lathe	Grinder	Milling machine	Lathe	-			
16	7	6	9	-	0		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	Milling machine	Boring machine	Shaper	Lathe			
13	6	4	5	5	2		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	Shaper	Boring machine	Lathe	Milling machine			
18	3	3	13	3	2		

SOLUTION TABLE							
SOLUTION 6							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	5 days and 5 hrs	Rs 4370/-
Lathe	Grinder	Milling machine	Lathe	-			
5	7	6	1	-	1		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	Milling machine	Boring machine	Shaper	Lathe			
10	6	3	5	1	0		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	Shaper	Boring machine	Lathe	Milling machine			
9	3	3	7	5	1		

SOLUTION TABLE							
SOLUTION 7							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	**6 days**	**Rs 4250/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
5	7	6	1	-	1		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
13	6	3	5	5	1		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
18	3	3	13	2	0		

SOLUTION TABLE							
SOLUTION 8							
WORK ORDER NUMBER-1						Make - span	Total cost
Machine Nos					OT hours	**5 days**	**Rs 4530/-**
Lathe	**Grinder**	**Milling machine**	**Lathe**	**-**			
5	7	6	1	-	1		
WORK ORDER NUMBER-2							
Machine Nos					OT hours		
Lathe	**Milling machine**	**Boring machine**	**Shaper**	**Lathe**			
13	6	3	5	5	1		
WORK ORDER NUMBER-3							
Machine Nos							
Lathe	**Shaper**	**Boring machine**	**Lathe**	**Milling machine**			
18	3	3	7	2	1		