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Genetic Algorithms for Job-Shop Scheduling Problems

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1 Introduction

The $n \times m$ *minimum-makespan* general job-shop scheduling problem, hereafter referred to as the JSSP, can be described by a set of n jobs $\{J_i\}_{1\leq j\leq n}$ which is to be processed on a set of m machines $\{M_r\}_{1\leq r\leq m}$. Each job has a technological sequence of machines to be processed. The processing of job J_j on machine M_r is called the *operation* O_{jr}. Operation O_{jr} requires the exclusive use of M_r for an uninterrupted duration p_{jr}, its processing time. A *schedule* is a set of completion times for each operation $\{c_{jr}\}_{1\leq j\leq n, 1\leq r\leq m}$ that satisfies those constraints. The time required to complete all the jobs is called the *makespan* L. The objective when solving or optimizing this general problem is to determine the schedule which minimizes L. An example of a 3×3 JSSP is given in Table 1. The data includes the routing of each job through each machine and the processing time for each operation (in parentheses). Figure 1 shows a solution for the problem represented by "Gantt-Chart".

Table 1: A 3×3 problem

job	Operations routing (processing time)		
1	1 (3)	2 (3)	3 (3)
2	1 (2)	3 (3)	2 (4)
3	2 (3)	1 (2)	3 (1)

The JSSP is not only $\mathcal{NP}$-hard , but it is one of the worst members in the class. An indication of this is given by the fact that one 10×10 problem formulated by Muth and Thompson [15] remained unsolved for over 20 years.

1.1 Disjunctive graph

The JSSP can be described by a disjunctive graph $G = (V, C \cup D)$, where (1) V is a set of nodes representing operations of the jobs together with two special nodes, a *source* (0) and a *sink* $\star$, representing the beginning and end of the schedule, respectively. (2) C is a set of conjunctive arcs representing technological sequences of the operations. (3) D is

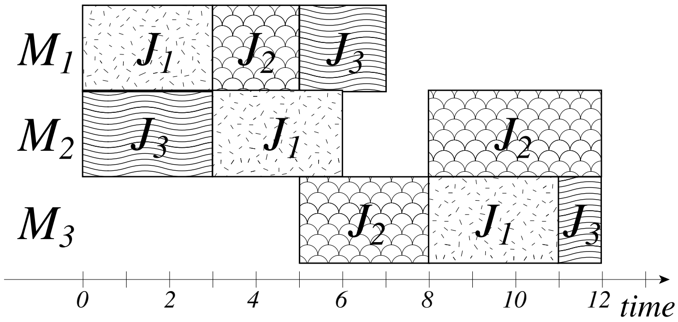

Figure 1: A Gantt-Chart representation of a solution for a 3×3 problem

a set of disjunctive arcs representing pairs of operations that must be performed on the same machines. The processing time for each operation is the weighted value attached to the corresponding nodes. Figure 2 shows this in a graph representation for the problem given in Table 1.

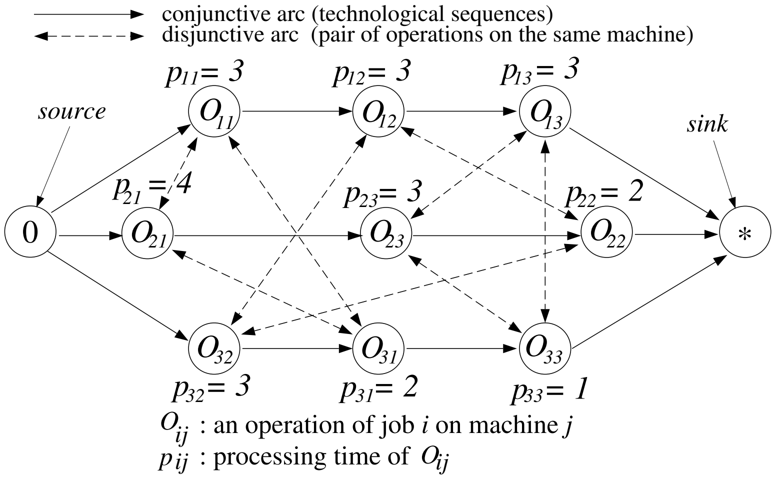

Figure 2: A disjunctive graph of a 3×3 problem

Job-shop scheduling can also be viewed as defining the ordering between all operations that must be processed on the same machine, i.e. to fix precedences between these operations. In the disjunctive graph model, this is done by turning all undirected (disjunctive) arcs into directed ones. A *selection* is a set of directed arcs selected from disjunctive arcs. By definition, a selection is *complete* if all the disjunctions are selected. It is *consistent* if the resulting directed graph is acyclic.

1.2 Semi-active schedules

A schedule uniquely obtained from a consistent complete selection by sequencing operations as early as possible is called a *semi-active* schedule. In a semi-active schedule, no operation can be started earlier without altering the machining sequences. A consistent complete selection and the corresponding semi-active schedule can be represented by the same symbol S without confusion. The makespan L is given by the length of the longest weighted path from source to sink in this graph. This path $\mathcal{P}$ is called a *critical path*

algorithm 1 GT algorithm

1. Let D be a set of all the earliest operations in a technological sequence not yet scheduled and O_{jr} be an operation with the minimum EC in D: $O_{jr} = \arg\min\{O \in D \mid EC(O)\}$.
2. Assume i–1 operations have been scheduled on M_r. A *conflict set* $C[M_r, i]$ is defined as: $C[M_r, i] = \{O_{kr} \in D \mid O_{kr} \text{ on } M_r, ES(O_{kr}) < EC(O_{jr})\}$.
3. Select an operation $O \in C[M_r, i]$ arbitrary.
4. Schedule O as the i-th operation on M_r with its completion time equal to $EC(O)$.

and is composed of a sequence of *critical operations*. A sequence of consecutive critical operations on the same machine is called a *critical block*.

The distance between two schedules S and T can be measured by the number of differences in the processing order of operations on each machine [16]. In other words, it can be calculated by summing the disjunctive arcs whose directions are different between S and T. We call this distance the *disjunctive graph* (DG) *distance*. Figure 3 shows the DG distance between two schedules. The two disjunctive arcs drawn by thick lines in schedule (b) have directions that differ from those of schedule (a), and therefore the DG distance between (a) and (b) is 2.

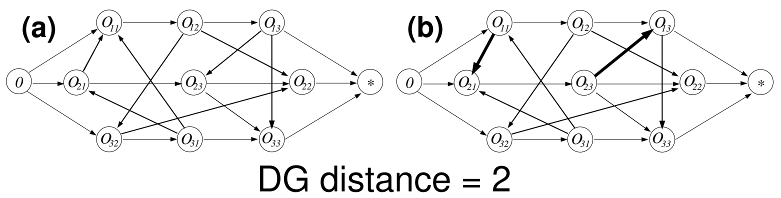

Figure 3: The DG distance between two schedules

1.3 Active schedules

The makespan of a semi-active schedule may often be reduced by shifting an operation to the left without delaying other jobs. Such reassigning is called a *permissible left shift* and a schedule with no more permissible left shifts is called an *active schedule*. An optimal schedule is always active so the search space can be safely limited to the set of all active schedules. An active schedule is generated by the *GT algorithm* proposed by Giffler and Thompson [12], which is described in Algorithm 1. In the algorithm, the *earliest starting time* $ES(O)$ and *earliest completion time* $EC(O)$ of an operation O denote its starting and completion times when processed with the highest priority among all currently schedulable operations on the same machine. An active schedule is obtained by repeating the algorithm until all operations are processed. In Step 3, if all possible choices are considered, all active schedules will be generated, but the total number will still be very large.

2 Simple GAs with binary representation

As described in the previous section, a (semi-active) schedule is obtained by turning all undirected disjunctive arcs into directed ones. Therefore, by labeling each directed disjunctive arc of a schedule as 0 or 1 according to its direction, a schedule can be represented by a binary string of length $mn(n-1)/2$. Figure 4 shows a labeling example, where an arc connecting O_{ij} and O_{kj} $(i < k)$ is labeled as 1 if the arc is directed from O_{ij} to O_{kj} (so O_{ij} is processed prior to O_{kj}) or 0, otherwise. It should be noted that the DG distance between schedules and the Hamming distance between the corresponding binary strings can be identified through this binary mapping.

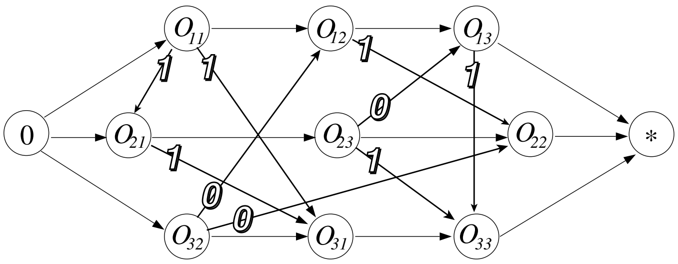

Figure 4: Labeling disjunctive arcs

A conventional GA using this binary representation was proposed by Nakano and Yamada [16]. An advantage of this approach is that conventional genetic operators, such as 1-point, 2-point and uniform crossovers can be applied without any modification. However, a resulting new bit string generated by crossover may not represent a schedule and called *illegal*.

A repairing procedure that generates a feasible bit string, as similar to an illegal one as possible, is called the *harmonization algorithm* [16]. The Hamming distance is used to assess the similarity between two bit strings. The harmonization algorithm goes through two phases: *local harmonization* and *global harmonization*. The former removes the ordering inconsistencies within each machine, while the latter removes the ordering inconsistencies between machines. An original (possibly illegal) bit string can be considered as a genotype, and a repaired feasible one as a phenotype and only used for the fitness evaluation.

The replacement of the original string with a repaired feasible one is called *Forcing*, which can be considered as the inheritance of an acquired character, although it is not widely believed that such inheritance occurs in nature. Since frequent forcing may destroy whatever potential and diversity of the population, it is limited to a small number of elites. Such limited forcing brings about at least two merits: a significant improvement in the convergence speed and the solution quality. Experiments have shown how it works [16].

3 Permutation representation

The JSSP can be viewed as an ordering problem just like the Traveling Salesman Problem (TSP). For example, a schedule can be represented by the set of permutations of jobs on each machine, in other words, m-partitioned permutations of operation numbers, which is called a *job sequence matrix*. Table 5 shows a job sequence matrix of the same solution as that given in Figure 1. The advantage of this representation is that the GA operators used to solve the TSP can be applied without further modifications, because each job sequence is equivalent to the path representation in the TSP.

$$\begin{array}{ccc} M_1 & M_2 & M_3 \\ 1\ \ 2\ \ 3 & 3\ \ 1\ \ 2 & 2\ \ 1\ \ 3 \end{array}$$

Figure 5: A job sequence matrix for a 3×3 problem

3.1 Subsequence exchange crossover

The *Subsequence Exchange Crossover* (SXX) was proposed by Kobayashi, Ono and Yamamura [14]. The SXX is a natural extension of the subtour exchange crossover for TSPs presented by the same authors [13]. Let two job sequence matrices be p_0 and p_1. A pair of subsequences, one from p_0 and the other from p_1 on the same machine, is called *exchangeable* if and only if they consist of the same set of jobs. The SXX searches for exchangeable subsequence pairs in p_0 and p_1 on each machine and interchanges each pair to produce new job sequence matrices k_0 and k_1. Figure 6 shows an example of the SXX for a 6×3 problem. Because a valid job sequence matrix does not necessarily represent a (valid) schedule, some repairing mechanism is also required. A small number of swap operations designated by the GT algorithm are applied to repair a job sequence matrix.

$$\begin{array}{cccc} & M_1 & M_2 & M_3 \\ p_0 & \underline{123}456 & 32\underline{15}64 & 2\underline{356}14 \\ p_1 & 6\underline{213}45 & 3264\underline{51} & \underline{635}421 \\ & & \Downarrow & \\ k_0 & \underline{213}456 & 32\underline{51}64 & 2\underline{635}14 \\ k_1 & 6\underline{123}45 & 3264\underline{15} & \underline{356}421 \end{array}$$

Figure 6: Subsequence Exchange Crossover (SXX)

3.2 Permutation with repetition

Instead of using an m-partitioned permutation of operation numbers like the job sequence matrix, another representation that uses an *unpartitioned permutation with m-repetitions* of job numbers was employed by Bierwirth [6]. In this permutation, each job number occurs m times. By scanning the permutation from left to right the k-th occurrence of a job number refers to the k-th operation in the technological sequence of this job (see Figure 7). In this representation, any individual is decoded to a schedule without repairing it, but still two or more different individuals can be decoded to an identical schedule.

The well used Order Crossover and Partially Mapped Crossover for TSP are naturally extended for this representation. A new *Precedence Preservative Crossover* (PPX) is also proposed in [7]. The PPX perfectly respects the absolute order of genes in parental chromosomes. A template bit string h of length mn is used to define the order in which

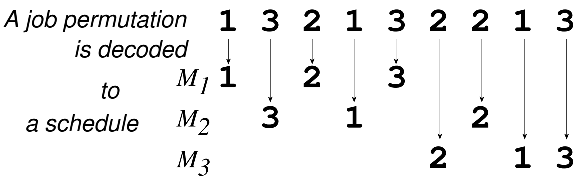

Figure 7: A job sequence (permutation with repetition) for a 3×3 problem is decoded to a schedule, which is equivalent to the one in Figure 1.

genes are drawn from p_0 and p_1. A gene is drawn from one parent and it is appended to the offspring chromosome. The corresponding gene is deleted in the other parent (See Figure 8). This step is repeated until both parent chromosomes are empty and the offspring contains all genes involved. The idea of forcing described in Section 2 is combined with the permissible left shift described in Subsection 1.3: new chromosomes are modified to active schedules by applying permissible left shifts.

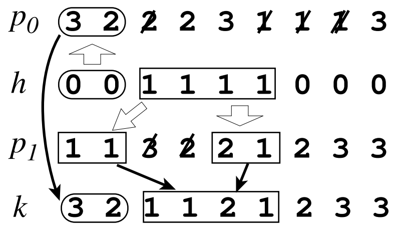

Figure 8: Precedence Preservative Crossover (PPX)

4 Heuristic crossover using an active schedule builder

The GT crossover proposed by Yamada and Nakano [24] is a problem dependent crossover operator that directly utilizes the GT algorithm. In the crossover, parents cooperatively give a series of decisions to the algorithm to build new offspring, namely active schedules. An individual represents an active schedule, so there is no repairing scheme required.

Let H be a binary matrix of size $n \times m$ [24, 8]. Here $H_{ir} = 0$ means that the i-th operation on machine r should be determined by using the first parent and $H_{ir} = 1$ by the second parent. The role of H_{ir} is similar to that of h described in Section 3.2. Let the parent schedules be p_0 and p_1 as always. The GT crossover can be defined by modifying Step 3 of Algorithm 1 as shown in Algorithm 2. It tries to reflect the processing order of the parent schedules to their offspring. It should be noted that if the parents are identical to each other, the resulting new schedule is also identical to the parents'. In general the new schedule inherits partial job sequences of both parents in different ratios depending on the number of 0's and 1's contained in H. Mutation can be put in Algorithm 2 by occasionally selecting the n-th $(n > 1)$ earliest operation in $C[M_{r^*}, i]$ with a low probability inversely proportional to n in Step 3 of Algorithm 2.

The GT crossover generates only one schedule at once. Another schedule is generated by using the same H but changing the roles of p_0 and p_1. Thus two new schedules are generated that complement each other. The outline of the GT crossover is described in Figure 9.

algorithm 2 GT crossover

1. Same as Step 1. of Algorithm 1.
2. Same as Step 2. of Algorithm 1.
3. Select one of the parent schedules $\{p_0, p_1\}$ according to the value of H_{ir} as $p = p_{H_{ir}}$. Select $O \in C[M_r, i]$ that has been the earliest scheduled operation in $C[M_r, i]$ in p.
4. Same as Step 4. of Algorithm 1.

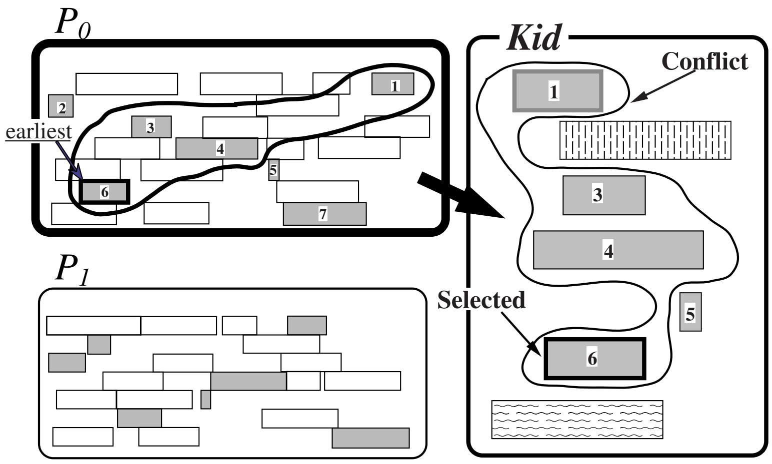

Figure 9: GT crossover

5 Genetic enumeration

Genetic enumeration methods which utilize simple representations and operators, and at the same time incorporate problem specific heuristics were proposed by Dorndorf and Pesch [19, 11] . They interpret an individual solution as a sequence of decision rules for domain specific heuristics such as the GT algorithm and the shifting bottleneck procedure.

5.1 Priority rule based GA

Priority rules [18] are the most popular and simplest heuristics for solving the JSSP. They are rules used in Step 3 of Algorithm 1 to resolve a conflict by selecting an operation O from the conflict set $C[M_r, i]$. For example, a priority rule called “SOT-rule” (shortest operation time rule) selects the operation with the shortest processing time from the conflict set.

Each individual of the *priority rule based GA* (P-GA) [11, 19] is a string of length $mn - 1$, where the entry in the i-th position represents one of the twelve priority rules to be used in the i-th iteration of the GT algorithm. The twelve rules are selected such that they are partially complementary in order to select each member in the conflict set. A simple crossover that exchanges the substrings of two cut strings are applied.

5.2 Shifting bottleneck based GA

The Shifting bottleneck (SB) proposed by Adams et al. [2] is a powerful heuristic for solving the JSSP. In the method, a one-machine scheduling problem (a relaxation of the original JSSP) is solved for each machine not yet sequenced, and the outcome is used to find a bottleneck machine; a machine having the longest makespan. Every time a new machine has been sequenced, the sequence of each previously sequenced machine is subject to reoptimization. The SB consists of two subroutines: the first one (SB I) repeatedly solves one-machine scheduling problems; the second one (SB II) builds a partial enumeration tree where each path from the root to a leaf is similar to an application of SB I. Please refer to [2, 3, 27] as well as [11, 19] for more details.

The *shifting bottleneck based genetic algorithm* (SB-GA) [11, 19] controls the selection of nodes in the enumeration tree of the shifting bottleneck heuristic. Here an individual is represented by a permutation of machine numbers $1 \dots m$, where the entry in the i-th position represents the machine selected in SB I. A cycle crossover operator is used as the crossover for this permutation representation.

6 Genetic local search and multi-step crossover fusion

It is well known that GAs can be enhanced by incorporating local search methods, such as neighborhood search into themselves. The result of such an incorporation is often referred as *Genetic Local Search (GLS)* [22]. In this framework, an offspring obtained by a recombination operator, such as crossover, is not included in the next generation directly but is used as a "seed" for the subsequent local search. The local search moves the offspring from its initial point to the nearest locally optimal point, which is included in the next generation. Mattfeld proposed an efficient GLS method called Difusion GA for JSSP with good success[9].

6.1 Neighborhood search crossover

Reeves has been exploring the possibility of integrating local optimization directly into a Simple GA with bit string representations and has proposed the Neighborhood Search Crossover (NSX) [20]. Let any two individuals be x and z. An individual y is called *intermediate* between x and z, written as $x \diamond y \diamond z$, if and only if $d(x, z) = d(x, y) + d(y, z)$ holds, where x, y and z are represented in binary strings and $d(x, y)$ is the Hamming distance between x and y. Then the *k^{th}-order 2 neighborhood* of x and z is defined as the set of all intermediate individuals at a Hamming distance of k from either x or z. Formally,

$$N_k(x, z) = \{y \mid x \diamond y \diamond z \text{ and } (d(x, y) = k \text{ or } d(y, z) = k)\}.$$

Given two parent bit strings p_0 and p_1, the neighborhood search crossover of order k (NSX$_k$) will examine all individuals in $N_k(p_0, p_1)$, and pick the best as the new offspring.

6.2 Multi-step crossover fusion

Yamada and Nakano extended the idea of the NSX to make it applicable to more complicated problems such as job-shop scheduling and proposed the Multi-Step Crossover Fusion

algorithm 3 Multi-Step Crossover Fusion (MSXF)

- Let p_0, p_1 be parent solutions.
- Set $x = p_0 = q$.

do
- For each member $y_i \in N(x)$, calculate $d(y_i, p_1)$.
- Sort $y_i \in N(x)$ in ascending order of $d(y_i, p_1)$.

do
1. Select y_i from $N(x)$ randomly, but with a bias in favor of y_i with a small index i.
2. Calculate $V(y_i)$ if y_i has not yet been visited.
3. Accept y_i with probability one if $V(y_i) \le V(x)$, and with $P_c(y_i)$ otherwise.
4. Change the index of y_i from i to n, and the indexes of y_k $(k \in \{i+1, i+2, \ldots, n\})$ from k to $k-1$.

until y_i is accepted.
- Set $x = y_i$.
- If $V(x) < V(q)$ then set $q = x$.

until some termination condition is satisfied.

- q is used for the next generation.

(MSXF): a new crossover operator with a built-in local search functionality [25, 28, 26]. The MSXF has the following characteristics compared to the NSX.

- It can handle more generalized representations and neighborhood structures.
- It is based on a stochastic local search algorithm.
- Instead of restricting the neighborhood by a condition of intermediateness, a biased stochastic replacement is used.

A stochastic local search algorithm is used for the base algorithm of the MSXF. Although the SA is a well-known stochastic method and has been successfully applied to many problems as well as to the JSSP, it would be unrealistic to apply the full SA to suit our purpose because it would consume too much time by being run many times in a GA run. A restricted method with a fixed temperature parameter is used as a good alternative in MSXF.

Let the parent schedules be p_0 and p_1, the neighborhood of an individual x be $N(x)$ and the distance between any two individuals x and y in any representation be $d(x, y)$. If x and y are schedules, then $d(x, y)$ is the DG distance. Crossover functionality can be incorporated into a local search algorithm by setting initial point: $x_0 = p_0$ and adding a greater acceptance bias in favor of $y \in N(x)$ having a small $d(y, p_1)$. The acceptance bias in the MSXF is controlled by sorting $N(x)$ members in ascending order of $d(y_i, p_1)$ so that y_i with a smaller index i has a smaller distance $d(y_i, p_1)$. Here $d(y_i, p_1)$ can be estimated easily if $d(x, p_1)$ and the direction of the transition from x to y_i are known; it is not necessary to generate and evaluate y_i. Then y_i is selected from $N(x)$ randomly, but with a bias in favor of y_i with a small index i. The outline of the MSXF is described in Algorithm 3.

In place of $d(y_i, p_1)$, one can also use $sign(d(y_i, p_1) - d(x, p_1)) + r_\epsilon$ to sort $N(x)$ members in Algorithm 3. Here $sign(x)$ denotes the sign of x: $sign(x) = 1$ if $x > 0$, $sign(x) = 0$ if $x = 0$, $sign(x) = -1$ otherwise. A small random fraction r_ϵ is added to randomize the order of members with the same sign. The termination condition can be given, for example, as the fixed number of iterations in the outer loop.

The MSXF is not applicable if the distance between p_0 and p_1 is too small compared to the number of iterations. In such a case, a mutation operator called the *Multi-Step Mutation Fusion* (MSMF) is applied instead. The MSMF can be defined in the same manner as the MSXF is except for one point: the bias is reversed, i.e. sort the $N(x)$ members in descending order of $d(y_i, p_1)$ in Algorithm 3.

6.3 MSXF-GA for Job-shop Scheduling

The MSXF is applied to the JSSP by using the active CB neighborhood [27] and the DG distance previously defined. Algorithm 4 describes the outline of the MSXF-GA routine for the JSSP using the steady state model proposed in [23, 21]. To avoid premature convergence even under a small-population condition, an individual whose fitness value is equal to someone's in the population is not inserted into the population in Step 4.

The idea of schedule reversal and left/right active schedules are introduced in [28]. A schedule is called *left* active if it is an active schedule for the original problem and *right* active if it is such for the reversed problem. A mechanism to search in the space of both the left and right active schedules is introduced into the MSXF-GA as follows. First, there are equal numbers of left and right active schedules in the initial population. The schedule q generated from p_0 and p_1 by the MSXF ought to be left (or right) active if p_0 is left (or right) active, and with some probability (0.1 for example) the direction is reversed.

Figure 10 shows all of the solutions generated by an application of (a) the MSXF and (b) a stochastic local search computationally equivalent to (a) for comparison. Both (a) and (b) started from the same solution (the same parent p_0), but in (a) transitions were biased toward the other solution p_1. The x axis represents the number of disjunctive arcs whose directions are different from those of p_1 on machines with odd numbers, i.e. the DG distance was restricted to odd machines. Similarly, the y axis representing the DG distance was restricted to even machines.

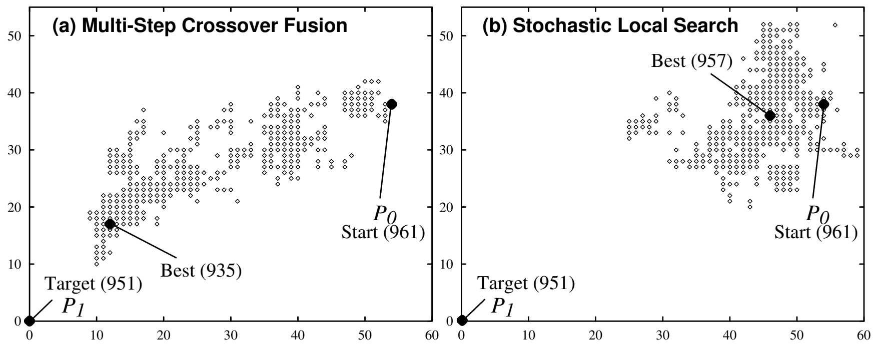

Figure 10: Distribution of solutions generated by an application of (a) MSXF and (b) a short-term stochastic local search

algorithm 4 MSXF-GA for the JSSP

- Initialize population: randomly generate a set of *left* and *right* active schedules in equal number and apply the local search to each of them.

do

1. Randomly select two schedules p_0, p_1 from the population with some bias depending on their makespan values.
2. Change the direction (*left* or *right*) of p_1 by reversing the job sequences with probability P_r.
3. Do step (3a) with probability P_c, or otherwise do Step (3b).
   (a) **If** the DG distance between p_1, p_2 is shorter than some predefined small value, apply MSMF to p_1 and generate q.
   Otherwise, apply MSXF to p_1, p_2 using the active CB neighborhood $N(p_1)$ and the DG distance and generate a new schedule q.
   (b) Apply a short term stochastic local search using the active CB neighborhood.
4. If q's makespan is shorter than the worst in the population, and no one in the population has the same makespan as q, replace the worst individual with q.

until some termination condition is satisfied.

- Output the best schedule in the population.

7 Experimental results using benchmark problems

The two well-known benchmark problems with sizes of 10×10 and 20×5 (known as mt10 and mt20) formulated by Muth and Thompson [15] are commonly used as test beds to measure the effectiveness of a certain method. The mt10 problem used to be called a "notorious" problem, because it remained unsolved for over 20 years; however it is no longer a computational challenge.

Applegate and Cook proposed a set of benchmark problems called the "ten tough problems" as a more difficult computational challenge than the mt10 problem, by collecting difficult problems from literature, some of which still remain unsolved [4].

7.1 Muth and Thompson benchmark

Table 2 summarizes the makespan performance of the methods described in this paper. This table is partially cited from [6]. The Conventional GA has only limited success and is outdated. It would be improved by being combined with the GT algorithm and/or the schedule reversal. The other results excluding the MSXF-GA results are somewhat similar to each other, although the SXX-GA is improved over the GT-GA in terms of speed and the number of times needed to find optimal solutions for the mt10 problem. The SB-GA produces better results using the very efficient and tailored shifting bottleneck procedure. The MSXF-GA which combines a GA and local search obtains the best results.

For the MSXF-GA, the population size = 10, constant temperature $c = 10$, number of iterations for each MSXF = 1000, $P_r = 0.1$ and $P_c = 0.5$ are used. The MSXF-GA experiments were performed on a DEC Alpha 600 5/226 and the programs were written

Table 2: Performance comparison using the MT benchmark problems

1963	Muth-Thompson	Test problems	10×10	20×5
1991	Nakano/Yamada	Conventional GA[16]	965	1215
1992	Yamada/Nakano	Giffler-Thompson GT-GA[24]	930	1184
	Dorndorf/Pesch	Priority-Rule based P-GA[19, 11]	960	1249
	Dorndorf/Pesch	Shifting-Bottleneck SB-GA[19, 11]	938	1178
1994	Mattfeld/Kopfer	Diffusion GA [9]	930	1165
1995	Kobayashi/Ono /Yamamura	Subsequence Exchange Crossover SXX-GA[14]	930	1178
1995	Bierwirth	Generalized-Permutation GP-GA[6]	936	1181
1996	Yamada/Nakano	Multi-step Crossover Fusion MSXF-GA[28, 26]	930	1165

in the C language. The MSXF-GA finds the optimal solutions for the mt10 and mt20 problems almost every time in less than five minutes on average.

7.2 The ten tough benchmark problems

Table 3 shows the makespan performance statistics of the MSXF-GA for the ten difficult benchmark problems proposed in [4]. The parameters used here were the same as those for the MT benchmark except for the population size = 20. The algorithm was terminated when an optimal solution was found or after 40 minutes of cpu time passed on the DEC Alpha 600 5/266. In the table, the column named lb shows the known lower bound or known optimal value (for la40) of the makespan, and the columns named bst, avg, var and wst show the best, average, variance and worst makespan values obtained, over 30 runs respectively. The columns named n_{opt} and t_{opt} show the number of runs in which the optimal schedules are obtained and their average cpu times in seconds. The problem data and lower bounds are taken from the OR-library [5]. Optimal solutions were found for half of the ten problems, and four of them were found very quickly. The small variances in the solution qualities indicate the stability of the MSXF-GA as an approximation method.

Table 4 shows comparison with various heuristic methods. In the table, MSXF represents MSXF-GA method proposed in[28, 26], Nowi and Dell are tabu search methods proposed in [17] and [10] respectively, CBSA and Aarts are SA methods in [27] and [1]. Matt is the diffusion GA in [9], and Appl is from [4].

8 Conclusions

The first serious application of GAs to solve the JSSP was proposed by Nakano and Yamada using a bit string representation and conventional genetic operators. Although this approach is simple and straightforward, it is not very powerful. The idea to use the GT algorithm as a basic schedule builder was first proposed by Yamada and Nakano [24] and by Dorndorf and Pesch [11, 19] independently. The approaches by both groups and other active schedule-based GAs are suitable for middle-size problems; however, it seems necessary to combine each with other heuristics such as the shifting bottleneck or local search to solve larger-size problems.

To solve larger-size problems effectively, it was crucial to incorporate local search

Table 3: Results of the 10 tough problems

prob	size	lb	bst	avg	var	wst	n_{opt}	t_{opt}
abz7	20×15	655	678	692.5	0.94	703	–	–
abz8	20×15	638	686	703.1	1.54	724	–	–
abz9	20×15	656	697	719.6	1.53	732	–	–
la21	15×10	–	*1046	1049.9	0.57	1055	9	687.7
la24	15×10	–	*935	938.8	0.34	941	4	864.1
la25	20×10	–	*977	979.6	0.40	984	9	765.6
la27	20×10	–	*1235	1253.6	1.56	1269	1	2364.75
la29	20×10	1130	1166	1181.9	1.31	1195	–	–
la38	15×15	–	*1196	1198.4	0.71	1208	21	1051.3
la40	15×15	*1222	1224	1227.9	0.43	1233	–	–

Table 4: Comparison with various heuristic methods on the 10 tough problems

prob	MSXF	Nowi	Dell	CBSA	Aarts	Matt	Appl
abz7	678	–	667	665	668	672	668
abz8	686	–	678	675	670	683	687
abz9	697	–	692	686	691	703	707
la21	*1046	1047	1048	*1046	1053	1053	1053
la24	*935	939	941	*935	*935	938	*935
la25	*977	*977	979	*977	983	*977	*977
la27	*1235	1236	1242	*1235	1249	1236	1269
la29	1166	1160	1182	1154	1185	1184	1195
la38	*1196	*1196	1203	1198	1208	1201	1209
la40	1224	1229	1233	1228	1225	1228	*1222

methods that use domain specific knowledge. The multi-step crossover fusion (MSXF) was proposed by Yamada and Nakano as a unified operator of a local search method and a recombination operator in genetic local search. The MSXF-GA outperforms other GA methods in terms of the MT benchmark and is able to find near-optimal solutions for the ten difficult benchmark problems, including optimal solutions for five of them.

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