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Optimization of job shop scheduling problems using modified clonal selection algorithm

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Abstract: Artificial immune systems (AISs) are one of the artificial intelligence techniques studied a lot in recent years. AISs are based on the principles and mechanisms of the natural immune system. In this study, the clonal selection algorithm, which is used commonly in AISs, is modified. This algorithm is applied to job shop scheduling problems, which are one of the most difficult optimization problems. For applying application results to the optimum solution, parameter values giving the optimum solution are determined by analyzing the parameters in the algorithm. The obtained results are given in detail in the tables and figures. The best makespan values are reached in 7 out of 10 test problems (FT06, LA01, LA02, LA03, LA04, LA05, and ABZ6). Reasonable makespan values are reached for the remaining 3 problems (FT10, LA16, and ABZ5). The obtained results demonstrate that the developed system can be applied successfully to job shop scheduling problems.

Key words: Artificial immune system, clonal selection algorithm, job shop scheduling, optimization

1. Introduction

The artificial immune system (AIS) is an artificial intelligence technique inspired by the natural immune system. This technique is used in many areas like complex problem solving, optimization, classification, diagnosis, and identification. In this study, a new system is developed by modifying the clonal selection algorithm (CSA) using some properties of the immune system. This system is used in the solution of job shop scheduling problems from NP-hard class problems. By examining many companies around the world, it can be seen that the common production type is job shop-type production. The usage rate of job shop-type production is approximately 75% [1]. Despite increased standard production works by advanced technology, since the customer demand does not change, job shop scheduling is one of the major optimization problems for companies where the product diversity and changes are high. Many studies have been done to solve this problem or to determine the closest approach to the solution [1]. Some studies about job shop scheduling are given below.

Moore listed the work needing to be done to reduce the number of delayed works in the single machine problem on a settlement date basis. Next, he removed the work that had the longest processing time from the delayed work list [2]. Gonzalez and Sahni reported that the solution to the problem for finding the optimum flow time in job shop scheduling with 2 or more machines is NP-hard [3]. Arkin and Silverberg worked on a job shop scheduling problem with fixed start and finish times. They proposed an algorithm that maximizes the work number completed with the same amount of machines [4]. Valls et al. applied the tabu search technique to

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machine scheduling problems. They sought to find a solution that minimizes the length of the work flow. They tested their work on more than 190 problems and achieved 95% success on the problems with a known optimal solution. They also attained good solutions for the problem with an unknown optimal solution [5]. Taşgetiren et al. investigated factors affecting the completion time of a work in job shop scheduling and examined the effects of these factors [6]. To find solutions for job shop scheduling problems, Jensen and Hansen used AISs. In their study, antibodies such that each of them is the solution of the problem were used. They described a robustness criterion [7]. Geyik and Cedimoğlu used algorithms for the solution of the job shop scheduling problems based on neighborhood search such as the genetic algorithm (GA), simulated annealing, and tabu search. They described a new neighborhood structure using the tabu search algorithm. In their work, they indicated that this structure can be used effectively in job shop scheduling [8]. Watanebe et al. used a GA in the solution of a job shop scheduling problem. They showed that the GA produces optimum solutions by a study made on a crossover operator [9]. Şevkli and Yenisey used the particle swarm optimization method in job shop scheduling problems and compared the obtained results with those from other methods [10]. Biroğul and Güvenç obtained the solution of a job shop scheduling problem with a GA. They reported that job shop scheduling problems cannot be solved by classical mathematical methods and the best solution would be obtained by heuristic methods. They investigated the effect of the number of products on the performance of the GA [11]. Gholami and Zandieh used simulation and GA approaches together for dynamic, flexible job shop scheduling problems. They added conditions like machines that are not always ready or interruptions at work. They determined that the average repair time of the machines has a significant impact on the scheduling efficiency [12]. Bondal discussed both job shop scheduling and AIS in detail in his research. In the job shop scheduling problem, Bondal tested the FT06, FT10, LA01, LA02, LA03, LA04, LA05, LA16, ABZ5, and ABZ6 problems with his work and evaluated the obtained results in detail. In that study, the clonal selection mechanism was used. At the end of the study, the stability of the AIS was noted [13]. Aladağ worked on a reembroidered, flexible job shop scheduling problem. AISs were examined in detail in that study and testing was carried out on 10 different problems. Successful results were obtained using a roulette wheel selection method [14]. Akhshabi et al. applied the CSA, which has an important place in AISs in flexible job shop scheduling problems. To minimize the makespan value, they adapted the clonal selection mechanism to this problem and compared the obtained results with those of other methods. They indicated that optimum results can be achieved by the changes made, especially on selection and mutation [15]. Mahapatra aimed to obtain the optimum solution in job shop scheduling problems using an AIS. In their study, the mutation process was applied to receptors and clone sets and the obtained results were compared with those of other methods [16].

The rest of this paper is organized as follows. Section 2 gives the background of job shop scheduling, a brief introduction to the CSA, and an explanation of our developed system. The results obtained in the application are given in Section 3. Consequently, in Section 4, we conclude the paper with a summarization of the results by emphasizing the importance of this study and mentioning some future work.

2. Materials and methods

2.1. Job shop scheduling problem

In scheduling, 3 elements, production, resources, and time, are in question. Determining which, when, and how the resources will be used to complete some certain tasks by considering these elements is called scheduling. It is possible to do specific activities using fewer resources in a shorter time by efficient scheduling [17–19].

Some scheduling problems fall into the NP-hard problem class. Job shop scheduling problems have a highly complex structure in terms of many criteria. There is no limitation in the number of processes and there are many alternative types of scheduling. In job shop scheduling, each order that is processed on different machines has its own processes and process order. It is very important to put these processes into a sequence according to a certain order. In addition, some constraints must be considered in order to obtain the appropriate tables.

2.2. CSA

The CSA models the response of an immune system to an antigenic stimulus by making use of the natural immune system. When an antigen enters the body, a subpopulation of B lymphocyte cells, derived from bone marrow, produces antibodies [20,21]. Antibody stimulation of antigens, cloning of the induced antibodies and destruction of the unstimulated ones, and selection and hypermutation processes are performed in the CSA [20,21]. The fundamental basis of the CSA is the reproduction of the antibody-recognizing antigens. A block diagram of the CSA is given in Figure 1.

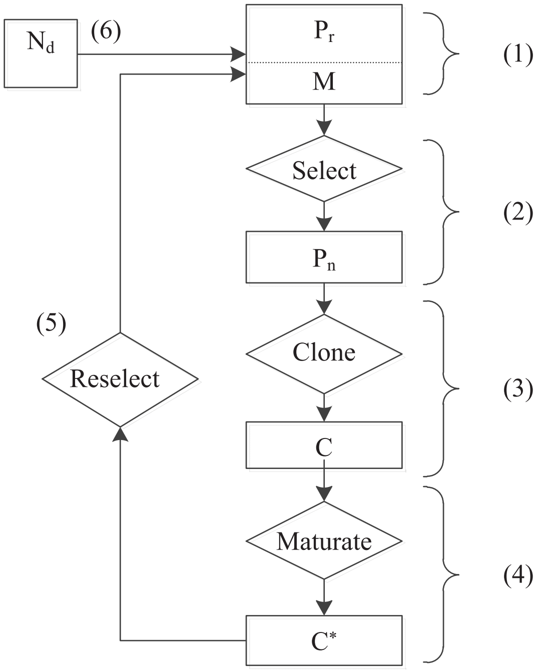


Figure 1. Block diagram of the CSA [21].

There are 6 steps in Figure 1. These steps are as follows [21]:

Step 1: Generate a set (P) of candidate solutions, composed of the subset of memory cells (M) added to the remaining (P_r) population ($P = P_r + M$).

Step 2: Determine (select) the n best individuals of the population (P_n), based on an affinity measure.

Step 3: Reproduce (clone) these n best individuals of the population, giving rise to a temporary population of clones (C). The clone size is an increasing function of the affinity with the antigen.

Step 4: Submit the population of clones to a hypermutation scheme, where the hypermutation is proportional to the affinity of the antibody with the antigen. A maturated antibody population is generated (C^*).

Step 5: Reselect the improved individuals from C^* to compose the memory set M. Some members of P can be replaced by other improved members of C^*.

Step 6: Replace d antibodies by novel ones (diversity introduction). The lower affinity cells have higher probabilities of being replaced.

2.3. Developed system

In this study, an AIS that has different mutation and selection mechanisms for the job shop production is developed. The CSA is taken as a base in the developed system. Provisions of the terms used in the developed system are given in Table 1.

Table 1. Provisions of the terms used in the developed system.

Immune system	Job shop scheduling
Antibody	Schedule
Affinity	Makespan
Population	Schedules
Memory cell	Best antibodies

Antibodies used in the developed system represent the scheduled sequence. Antibody size refers to the size of the problem. A 3 × 3 sample job shop scheduling problem is shown in Table 2. A 3 × 3 sample antibody is shown in Table 3.

Table 2. The 3 × 3 sample job shop scheduling problem.

Jobs	1	1	1	2	2	2	3	3	3
Processes	1	2	3	1	2	3	1	2	3
Machines	3	1	2	1	2	3	3	1	2
Time	4	2	1	10	3	12	2	9	7

Table 3. The 3 × 3 sample antibody representation.

1	2	3	2	1	3	3	2	1

The solution diagram for the antibody shown in Table 3 is given in Figure 2, where the m-axis refers to the machines and the t-axis represents time. The affinity (makespan) value for this antibody is 29.

The population is composed of antibodies. Initially, it is generated randomly. In the selection of the antibodies to be cloned in the population, normalized affinity values and a cloning multiplier are taken as the basis. The normalization process is given in Eq. (1). The cloned antibody set is obtained in the amount of multiplication of the normalized affinity value of each antibody in the population with a cloning multiplier. The mutation process is applied to the cloned antibodies. In the mutation process, unrepeated gene state pairs are obtained in the amount of half of the size of the antibodies. Values of the genes in the specified location change their location. To make this change possible, a randomly generated number needs to be smaller than the mutation rate determined by the user.

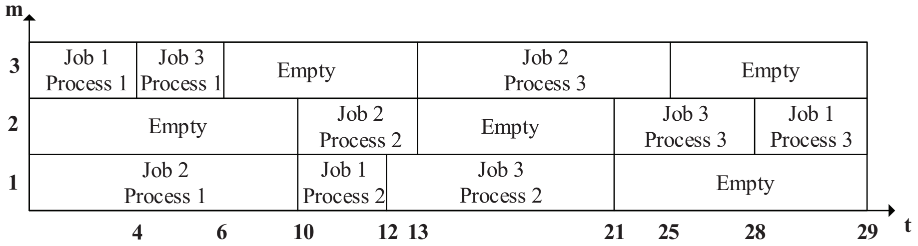


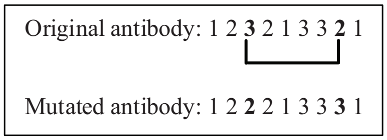
Figure 2. Solution diagram of a 3 × 3 problem.

$$\text{Normalized affinity value} = \frac{\text{Biggest makespan -Current makespan}}{\text{Biggest makespan-Smallest makespan}} \tag{1}$$

Antibodies in the amount calculated in Eq. (2) having the best affinity value from the set consisting of the cloned and mutated antibodies are used as the memory cell. Unselected antibodies constitute the receptor set. Antibodies in the receptor set are subjected to 5 different mutations. The affinity values of the antibodies created after the mutation process are compared with each other. The antibody having the best affinity value is replaced by the antibody in the receptor set. All of the mutation operations are given below. Moreover, they are also shown in Figures 3–7. All of the mutation operations are implemented in parallel order.

$$\text{Clone number} = \text{Population size} \times \text{Cloning rate} \tag{2}$$

Mutation 1: Two values chosen randomly from the antibody's change location.

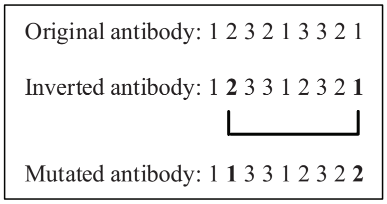


Original antibody: 1 2 **3** 2 1 3 3 **2** 1

Mutated antibody: 1 2 **2** 2 1 3 3 **3** 1

Figure 3. Mutation 1 representation.

Mutation 2: All of the values of the antibody are inverted and 2 values chosen randomly change location.



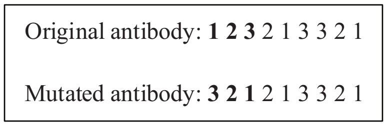
Original antibody: 1 2 3 2 1 3 3 2 1

Inverted antibody: 1 **2** 3 3 1 2 3 2 **1**

Mutated antibody: 1 **1** 3 3 1 2 3 2 **2**

Figure 4. Mutation 2 representation.

Mutation 3: Starting from the mth value of the antibody, n values are reversed.



Original antibody: **1 2 3** 2 1 3 3 2 1

Mutated antibody: **3 2 1** 2 1 3 3 2 1

Figure 5. Mutation 3 representation.

Mutation 4: All value pairs of the antibody randomly change location.

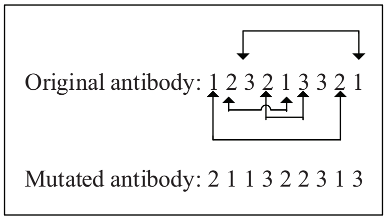


Figure 6. Mutation 4 representation.

Mutation 5: All of the values of the antibody are inverted and then all value pairs of the antibody randomly change location.

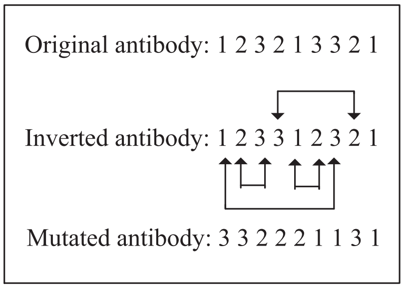


Figure 7. Mutation 5 representation.

Antibodies having the best affinity values in the amount calculated in Eq. (3) among the antibodies in the mutated receptor set and memory cells are added to a new population in order to be used in the next iteration. In addition, random antibodies in the amount of the number calculated in Eq. (4) are produced and added to the new population. These steps are repeated until the number of iterations is reached. A flow chart of the developed system is given in Figure 8.

$$\text{Best selected number} = \text{Best selection rate} \times \text{Population size} \tag{3}$$

$$\text{Random selected number} = \text{Population size Best selected number} \tag{4}$$

3. Experimental results

The developed system was applied to 10 test problems: FT06, FT10, LA01, LA02, LA03, LA04, LA05, LA16, ABZ5, and ABZ6 (http://people.brunel.ac.uk/∼mastjjb/jeb/orlib/files/jobshop1.txt). For the FT06 problem, there are 6 jobs and 6 machines, and the optimal makespan value is 55. For the FT10 problem, there are 10 jobs and 10 machines, and the optimal makespan value is 930. For the LA01 problem, there are 10 jobs and 5 machines, and the optimal makespan value is 666. For the LA02 problem, there are 10 jobs and 5 machines, and the optimal makespan value is 665. For the LA03 problem, there are 10 jobs and 5 machines, and the optimal makespan value is 597. For the LA04 problem, there are 10 jobs and 5 machines, and the optimal makespan value is 590. For the LA05 problem, there are 10 jobs and 5 machines, and the optimal makespan value is 593. For the LA16 problem, there are 10 jobs and 10 machines, and the optimal makespan value is 945. For the ABZ5 problem, there are 10 jobs and 10 machines, and the optimal makespan value is 1234. For the ABZ6 problem, there are 10 jobs and 10 machines, and the optimal makespan value is 943.

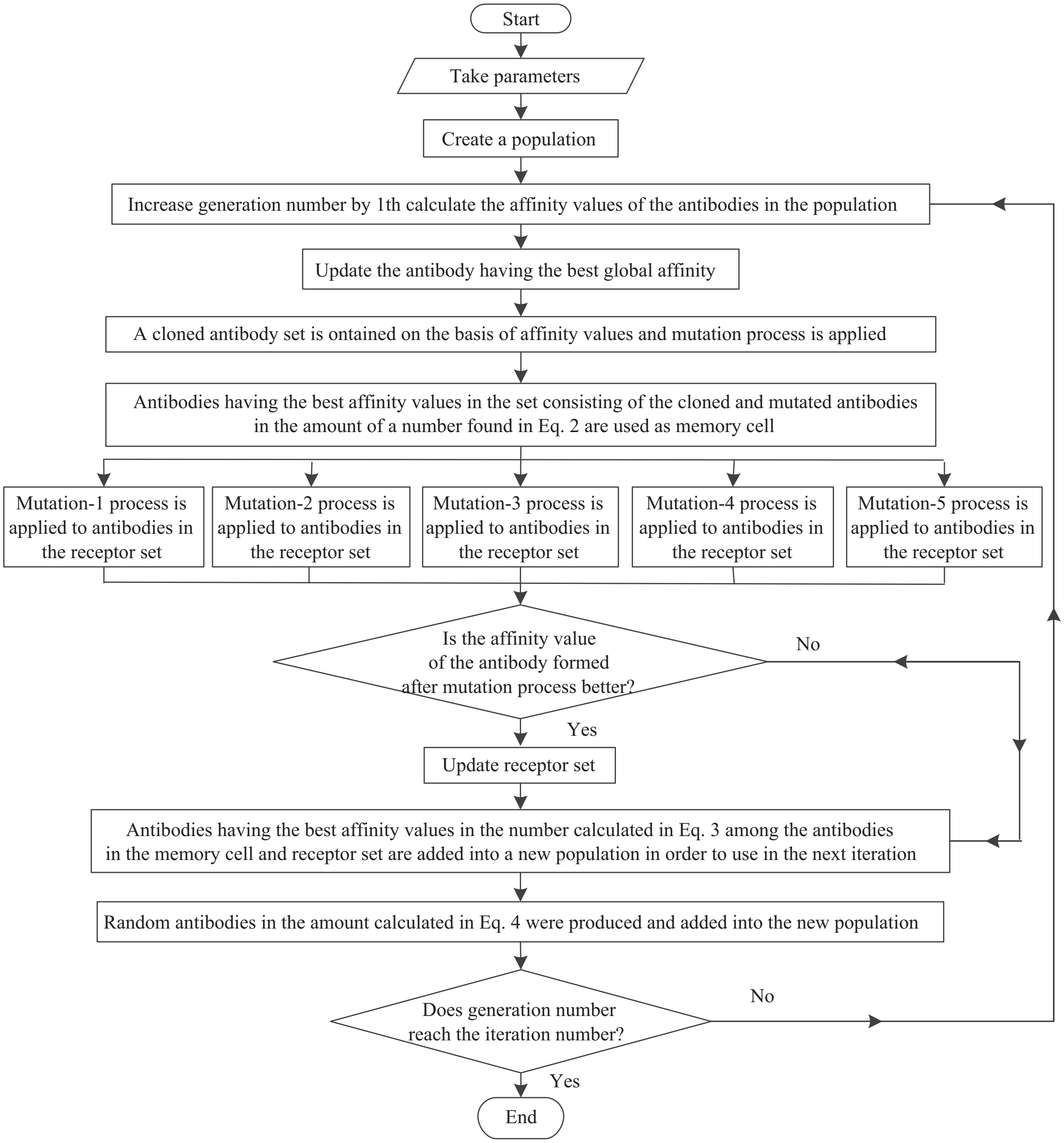


Figure 8. Flow chart of the developed system.

Four different parameter values, the mutation rate, cloning multiplier, clonal rate, and best selection rate, are used in the developed system. The mutation rate parameter determines if the antibodies are mutated or not. The cloning multiplier parameter is used to determine the number of antibodies to be cloned. The clonal rate parameter is used to determine the number of antibodies to be taken into the memory cell. The best selection rate parameter is used to determine the number of antibodies to be added to the new population among the antibodies in the mutated receptor set and memory cells. In this study, the analysis of the cloning multiplier parameters is carried out. The effect of the cloning multiplier parameter is evaluated in the test problems with 10 different values, from 10 to 55. Other parameter values are assumed as constant. The values of the parameters used in the developed system are given in Table 4. The results obtained for the various values of the cloning multiplier are given in detail in Table 5. The values shown in Table 5 represent the best makespan values. The best makespan values obtained for each problem are stated in bold in Table 5.

Table 4. Parameter values used in the developed system.

Population size	Iteration number	Mutation rate	Cloning multiplier	Clonal rate	Best selection rate
100	10,000	0.8	10	0.6	0.7

Table 5. Results obtained depending on the cloning multiplier parameter in the developed system.

Cloning multiplier	FT06	FT10	LA01	LA02	LA03	LA04	LA05	LA16	ABZ5	ABZ6
10	**55**	1070	673	701	619	620	**593**	1056	1345	1020
15	**55**	1082	**666**	669	618	612	**593**	1040	1321	967
20	**55**	1051	675	669	611	611	**593**	**1024**	1324	955
25	**55**	1046	**666**	686	605	601	**593**	1043	1330	956
30	**55**	**1034**	**666**	658	612	606	**593**	1042	1321	1000
35	**55**	1048	**666**	659	608	613	**593**	1066	1297	940
40	**55**	1051	**666**	**655**	601	601	**593**	1058	1311	945
45	**55**	1068	**666**	702	610	**590**	**593**	1053	1309	945
50	**55**	1065	**666**	656	603	603	**593**	1041	1302	945
55	**55**	1050	**666**	**655**	**597**	606	**593**	1041	**1270**	**943**

The application is run 5 times for each parameter of the cloning multiplier. The average makespan values corresponding to each value of the parameters for the 10 test problems are given in Figures 9–18 in detail.

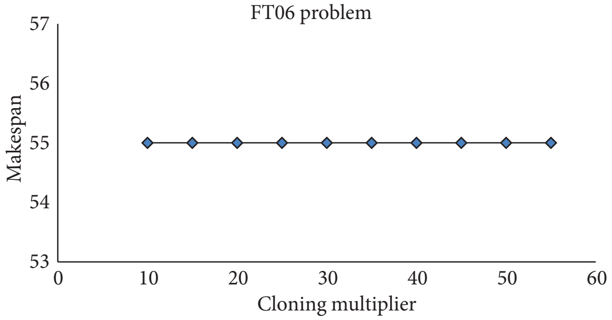


Figure 9. Average of the makespan values for the FT06 test problem.

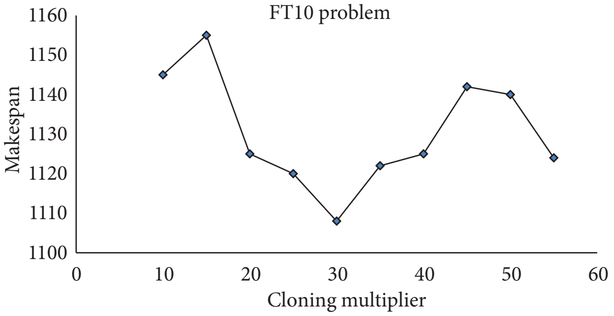


Figure 10. Average of the makespan values for the FT10 test problem.

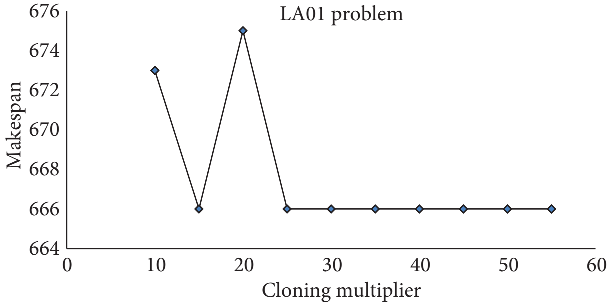


Figure 11. Average of the makespan values for the LA01 test problem.

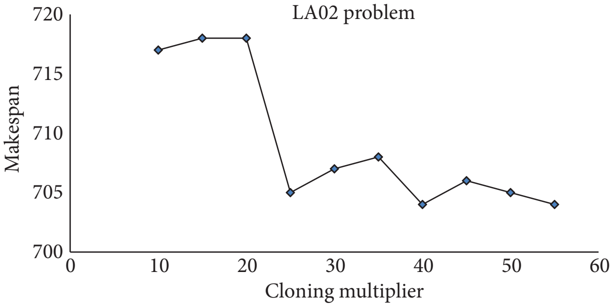


Figure 12. Average of the makespan values for the LA02 test problem.

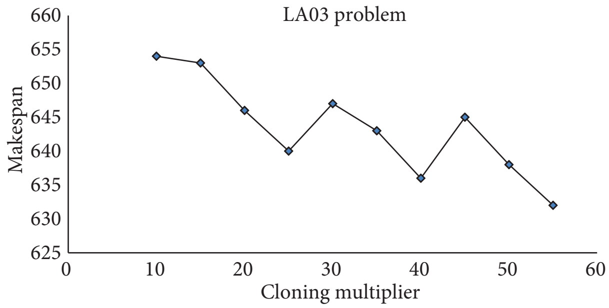


Figure 13. Average of the makespan values for the LA03 test problem.

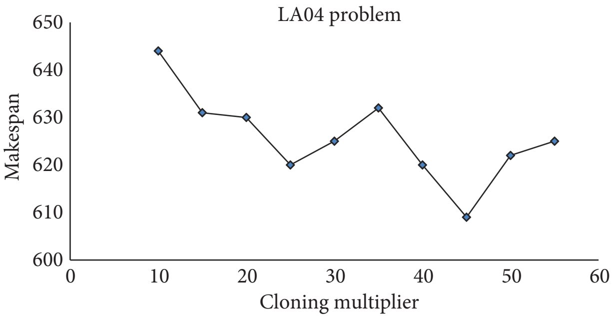


Figure 14. Average of the makespan values for the LA04 test problem.

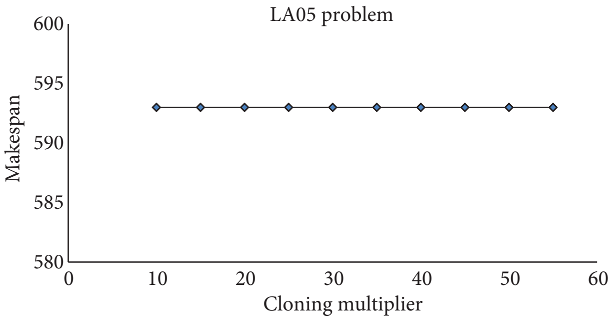


Figure 15. Average of the makespan values for the LA05 test problem.

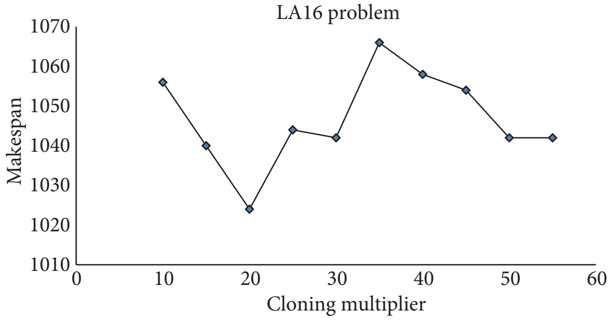


Figure 16. Average of the makespan values for the LA16 test problem.

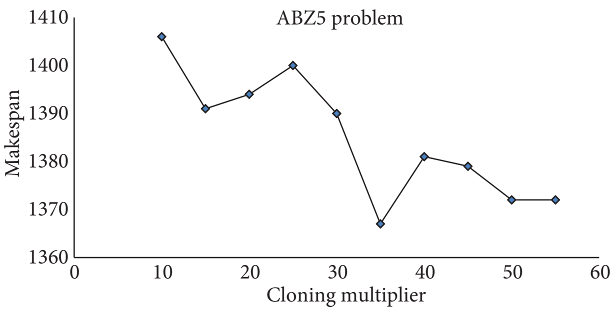


Figure 17. Average of the makespan values for the ABZ5 test problem.

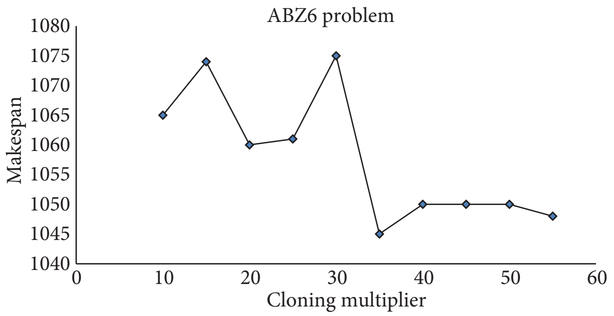


Figure 18. Average of the makespan values for the ABZ6 test problem.

When the makespan values obtained as a result of the application of the developed system are divided into 10 test problems, the developed system is seen to be applied in this field successfully. The best makespan values are reached in 7 out of 10 test problems (FT06, LA01, LA02, LA03, LA04, LA05, and ABZ6). In the remaining 3 problems (FT10, LA16, and ABZ5), the best makespan values are approached. It is also seen that optimum results can be achieved in the remaining 3 problems (FT10, LA16, and ABZ5) by increasing the iteration number or the value of the cloning multiplier parameter. The cloning multiplier parameter is an important parameter in order to obtain the best makespan value.

The developed system gives reasonable results when we compare it with the studies made on this problem in the literature. The comparison results are given in Table 6, where the values shown in bold represent the best makespan values. The results of the developed system are determined to be better than the results mentioned in [13] and [22]. The same makespan values specified in [23] are reached. While better results are obtained for the ABZ6 and LA04 problems with the developed system than those in [8], worse results are found for the FT10, ABZ5, and LA16 problems. While better results are obtained for LA03 and LA02 than those in [24], worse results are obtained for the LA16 and FT10 problems. When the results of the developed system are compared with the results in [16] and [25], worse results are obtained only for the FT10 problem. The same makespan values are obtained for the other problems.

Table 6. Comparative results of studies in the literature.

Studies	FT06	FT10	LA01	LA02	LA03	LA04	LA05	LA16	ABZ5	ABZ6
Best known solution	55	930	666	655	597	590	593	945	1234	943
Present study	**55**	1034	**666**	**655**	**597**	**590**	**593**	1024	1270	**943**
Geyik and Cedimoğlu [8]	**55**	971	**666**	**655**	**597**	593	**593**	**962**	**1238**	947
Bondal (AISs) [13]	**55**	1208	702	708	672	644	**593**	1124	1434	1084
Bondal (GA) [13]	**55**	1099	**666**	716	638	619	**593**	1033	1339	1043
Mahapatra [16]	**55**	**930**	**666**	**655**	**597**	**590**	**593**	-	-	-
Chaudhuri and De [23]	-	1136	-	-	-	-	-	-	-	-
Luh and Chueh [24]	**55**	-	**666**	**655**	**597**	**590**	**593**	-	-	-
Udomsakdigool and Kachitvichyanukul [25]	**55**	944	**666**	658	603	**590**	**593**	977	-	-
Käschel et al. [26]	**55**	951	-	-	-	-	-	-	-	-

4. Conclusions

Job shop scheduling is one of the major optimization problems in companies where product diversity and changes are high. Many studies have been conducted to solve this problem. Obtaining the optimum solution for these problems is still not possible with the current studies. Therefore, studies on this subject are still in progress. In this study, a system was developed, inspired by the CSA, to solve the job shop scheduling problem. An application that can be used by companies having job shop production was developed in this study by making changes in the selection of the clone-receptor of the CSA and mutation mechanism. It was aimed in the developed system to optimize the timetable in systems with job shop production and to contribute to the company with production of this type.

The developed system was applied to the FT06, FT10, LA01, LA02, LA03, LA04, LA05, ABZ5, and ABZ6 test problems and the results were evaluated. The parameter values in the developed system were tried in the test problems. The parameter of the cloning multiplier is an important parameter in terms of the best makespan value. As a result of the application, the best makespan values were obtained, and how many times the best makespan values obtained during iteration were reached was shown in the tables and figures.

The application results were compared with the studies in the literature. The best makespan values were reached in 7 out of 10 problems (FT06, LA01, LA02, LA03, LA04, LA05, and ABZ6). Reasonable makespan values were reached for the remaining 3 problems (FT10, LA16, and ABZ5). In the future, new systems can be developed on the basis of features like constraints in job shop scheduling and priority rules. In addition, hybrid systems can be developed using AISs and other artificial intelligence techniques.

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