

ACTIVITY 2

Optimization with Genetic Algorithms **Job Shop Scheduling Problem** (by Victoria Joven)

https://github.com/victoriajoven/NeuronalActivity_2

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1. Chromosome and Algorithmic Adaptations

This section explains Genetic Algorithm (GA) implemented in this project adapts the classical formulation taught in the course to the specific requirements of the Job Shop Scheduling Problem (JSSP). The content follows the theoretical foundations introduced in the lectures—population-based search, selection pressure, recombination, mutation, elitism, and convergence—while explicitly linking each concept to the corresponding Python implementation.

1.1 Chromosome

Definition

In the course (Neuronal and Evolutionary Computation), chromosomes are introduced as vectors of genes, typically binary strings $c \in \{0,1\}^m$. Evolutionary algorithms are not limited to binary chromosomes and can be extended to other forms such as permutations, integer sequences, trees, or similar structures. This flexibility is necessary when a problem requires feasibility constraints that binary encodings cannot represent.

The JSSP belongs to this category. Each job consists of a fixed sequence of operations, and the chromosome must encode an ordering of operations that respects job precedence while allowing the GA to explore different interleavings across jobs.

The implementation adopts a **job-based permutation encoding**, where the chromosome is a sequence of job identifiers. If job j has k operations, it appears exactly k times in the chromosome. The position of each occurrence determines the order in which its operations are scheduled.

Code implementation

The representation is implemented in:

- `src/ga/chromosome.py`
- `src/ga/population.py` → `Population.initialize()`

The initialization procedure constructs the base sequence of job identifiers and shuffles it to generate the initial population, following the “random initialization” step described in the lectures.

1.2 Fitness Evaluation

Definition

Reviewing the slides from topic 6 on GA fitness is defined as a non-negative value that quantifies the quality of an individual. Although the examples focus on maximization, the lectures clarify that GAs can solve minimization problems by transforming the fitness or adapting the selection operator.

Code implementation

The fitness function is the **makespan**, computed by simulating the schedule. This corresponds to the “Evaluate fitness of all individuals” step in the GA pseudocode presented in the lectures.

The simulation is implemented in:

- `src/evaluation/makespan.py → compute_makespan()`

Since roulette wheel selection assumes maximization, the implementation applies a fitness inversion.

This adaptation is consistent with the course’s requirement that roulette wheel selection must operate on non-negative, maximization-oriented fitness values.

1.3 Selection Operators

In the NEC course, we have learned four selection schemes: roulette wheel, rank selection, tournament selection, and stochastic universal sampling. Two of these are implemented in this project.

1.3.1 Tournament Selection

Definition

Tournament selection:

- selects K individuals at random,
- chooses the best among them,
- maintains diversity,
- is robust to fitness scaling,
- avoids the sensitivity issues of roulette wheel selection.

These properties are emphasized in the lectures as advantages for maintaining exploration.

Code implementation

Implemented in:

- `src/ga/techniques/selection.py` → `TournamentSelection`

The method samples a subset of individuals and selects the one with the lowest makespan, consistent with the minimization objective.

1.3.2 Roulette Wheel Selection

Definition

Roulette wheel selection assigns a probability proportional to fitness. The lectures highlight:

- its sensitivity to fitness distribution,
- the requirement of non-negative fitness values,
- its tendency to reduce diversity when fitness values differ greatly.

Code implementation

Implemented in:

- `src/ga/techniques/selection.py` → `RouletteWheelSelection`

The code adapts the method for minimization by inverting fitness values, ensuring compatibility with the theoretical model taught in class.

1.4 Crossover Operators

In Unit 6, we looked at the concept of the crossover with techniques one-point, two-point and uniform for binary encodings, but also states that for non-binary or permutation encodings, crossover must be adapted to preserve feasibility.

This project implements two such specialized operators.

1.4.1 Precedence Preserving Crossover (PPX)

Definition

For permutation-based problems, crossover must:

- preserve the number of occurrences of each gene,
- maintain structural constraints,
- avoid producing infeasible offspring.

Code implementation

Implemented in:

- `src/ga/techniques/crossover.py` → `PrecedencePreservingCrossover`

The operator selects genes alternately from the parents while removing them from both lists, ensuring feasibility without repair.

1.4.2 Job-Based Crossover (JBX)

Definition

This operator preserves positional information for a subset of jobs and fills remaining positions from the other parent. It follows the course's principle that crossover must recombine genetic material without violating the constraints of the encoding.

Code implementation

Implemented in:

- `src/ga/techniques/crossover.py` → `JobBasedCrossover`

1.5 Mutation Operators

The course describes mutation as a mechanism to explore local neighborhoods of the search space. For binary encodings, mutation flips bits; for permutations, mutation must preserve feasibility.

Two permutation-safe mutation operators are implemented.

1.5.1 Swap Mutation

Definition

Swap mutation exchanges two genes, producing a small perturbation analogous to bit-flip mutation in binary encodings.

Code implementation

Implemented in:

- `src/ga/techniques/mutation.py` → `SwapMutation`

1.5.2 Insertion Mutation

Definition

Insertion mutation removes a gene and reinserts it elsewhere, producing a larger structural change and helping escape local minima.

Code implementation

Implemented in:

- `src/ga/techniques/mutation.py` → `InsertionMutation`

1.6 Elitism

Definition

The lectures describe elitism as copying the best individuals to the next generation to ensure that high-quality solutions are not lost. This improves convergence stability.

Code implementation

Implemented in:

- `src/ga/population.py` → `replace()`

The method preserves the top individual before inserting offspring.

1.7 Convergence and Stationary State Detection

Definition

The course explains that convergence occurs when the population becomes homogeneous and fitness no longer improves. Monitoring fitness evolution is a standard method for detecting stationary states.

Code implementation

Implemented in:

- `src/ga/population.py` → `is_converged()`

The method checks whether the best fitness has remained constant for a fixed number of generations (`patience`), implementing the stationary-state criterion described in the lectures.

2. Experimental results

This section presents the results obtained by executing the Genetic Algorithm on three Job Shop Scheduling Problem instances of increasing size: SMALL (6×6), MEDIUM (10×10), and LARGE (20×20). For each instance, we include a description of the dataset, a comparison of six or more parameter configurations, and an analysis of the best solution's evolution over generations. All experiments were conducted using a population size of 50 and a fixed number of generations per run.

2.1 Small Instance (3–5 Machines)

Dataset description

The ft06 dataset is a classical benchmark from the OR-Library, containing 6 jobs and 6 machines. Each job is defined by a sequence of operations, where each operation specifies the required machine and its processing time. The dataset was retrieved from:

<https://people.brunel.ac.uk/%7Emastjjb/jeb/orlib/files/jobshop1.txt>

```
+++++
instance ft06

+++++
Fisher and Thompson 6x6 instance, alternate name (mt06)
6 6
2 1 0 3 1 6 3 7 5 3 4 6
1 8 2 5 4 10 5 10 0 10 3 4
2 5 3 4 5 8 0 9 1 1 4 7
1 5 0 5 2 5 3 3 4 8 5 9
2 9 1 3 4 5 5 4 0 3 3 1
1 3 3 3 5 9 0 10 4 4 2 1
+++++
```

Figure 1. Instance ft06

This instance is suitable for validating the convergence behavior and correctness of the algorithm on small-scale problems.

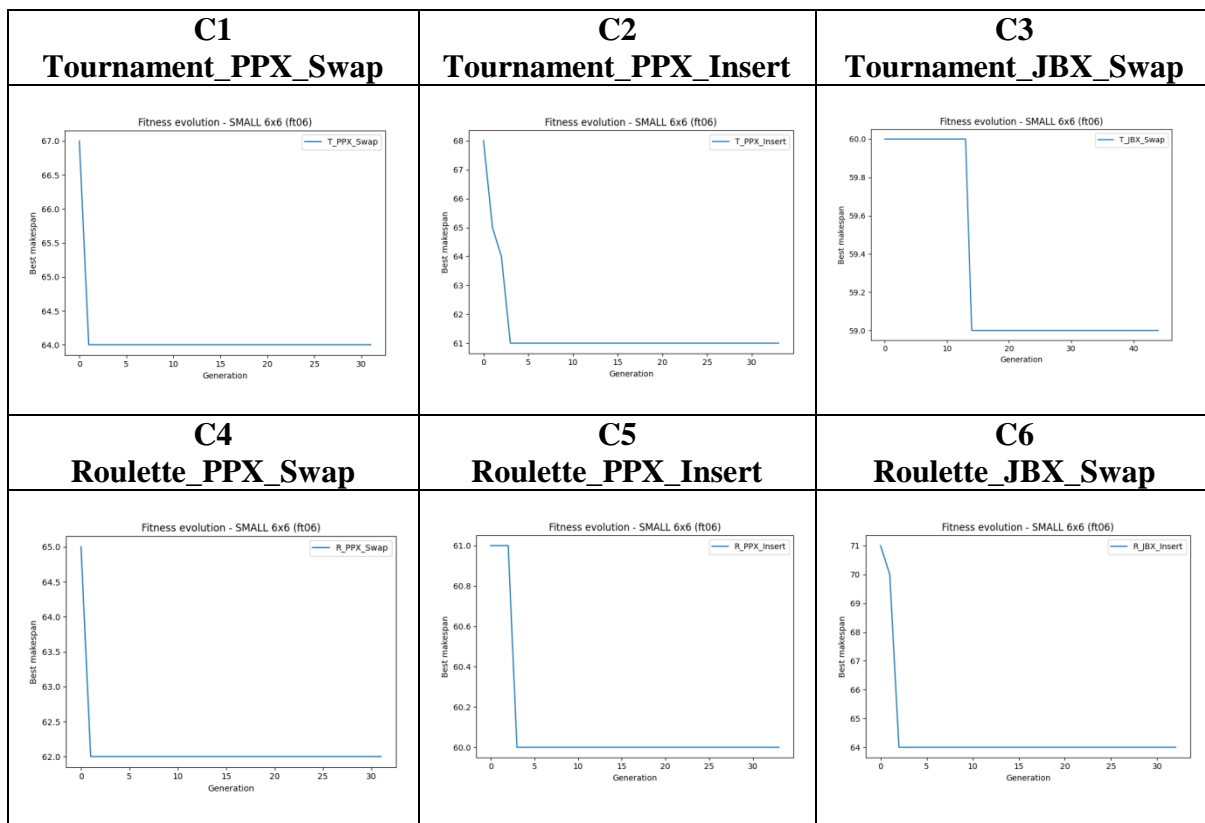
Results for six parameter configurations

Config	Selection	Crossover	Mutation	Best makespan (fitness)
C1	Tournament	PPX	Swap	64
C2	Tournament	PPX	Insert	61
C3	Tournament	JBX	Swap	59
C4	Roulette	PPX	Swap	62
C5	Roulette	PPX	Insert	60
C6	Roulette	JBX	Insert	64

Analysis: Although the best result in this particular execution (makespan = 59) was obtained using Tournament+JBX+Swap, it is important to note that the ft06 instance is small and highly sensitive to stochastic variation. Across multiple runs, different configurations—including both Roulette-based and Tournament-based combinations—were able to reach the best makespan. This behaviour is expected in small problem instances, where several operator combinations are sufficiently strong to explore the search space effectively and the random initialization has a significant impact on the final outcome.

In general, Tournament selection tends to provide more stable convergence due to its controlled selection pressure, while Roulette selection may occasionally outperform it when the initial population happens to contain promising individuals (as casino games, very random). PPX crossover consistently showed robust performance, whereas JBX occasionally produced competitive results depending on the run. Swap mutation remained the most effective mutation operator, leading to faster convergence than Insertion in most cases.

Evolution of the Best Solution



Each plot shows the best makespan over generations. Configurations using Tournament selection converged faster and more effectively. Some Roulette-based runs showed no improvement, indicating poor exploration.

Comparative plot

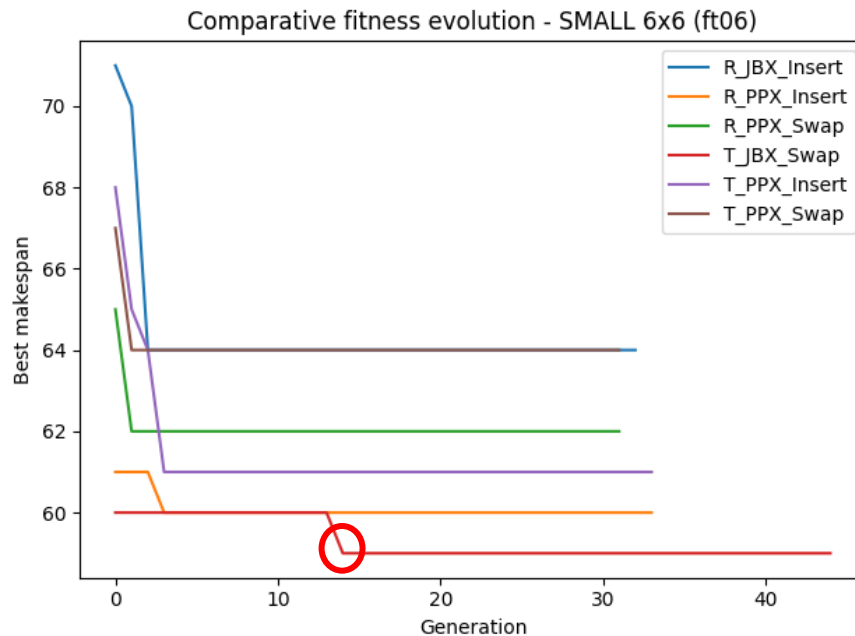


Figure 2. Comparative fitness evolution SMALL

2.2 Medium instance (around 10 machines)

Dataset Description

The la19 dataset contains 10 jobs and 10 machines, with each job defined by a sequence of 10 operations. It was retrieved from the OR-Library and is commonly used to evaluate the scalability of scheduling algorithms.

<https://people.brunel.ac.uk/%7Emastjjb/jeb/orlib/files/jobshop1.txt>

```
instance la19
+++++
Lawrence 10x10 instance (Table 6, instance 4); also called (seta4) or (A4)
10 10
2 44 3 5 5 58 4 97 0 9 7 84 8 77 9 96 1 58 6 89
4 15 7 31 1 87 8 57 0 77 3 85 2 81 5 39 9 73 6 21
9 82 6 22 4 10 3 70 1 49 0 40 8 34 2 48 7 80 5 71
1 91 2 17 7 62 5 75 8 47 4 11 3 7 6 72 9 35 0 55
6 71 1 90 3 75 0 64 2 94 8 15 4 12 7 67 9 20 5 50
7 70 5 93 8 77 2 29 4 58 6 93 3 68 1 57 9 7 0 52
6 87 1 63 4 26 5 6 2 82 3 27 7 56 8 48 9 36 0 95
0 36 5 15 8 41 9 78 3 76 6 84 4 30 7 76 2 36 1 8
5 88 2 81 3 13 6 82 4 54 7 13 8 29 9 40 1 78 0 75
9 88 4 54 6 64 7 32 0 52 2 6 8 54 5 82 3 6 1 26
+++++
```

Figure 3. Instance la19

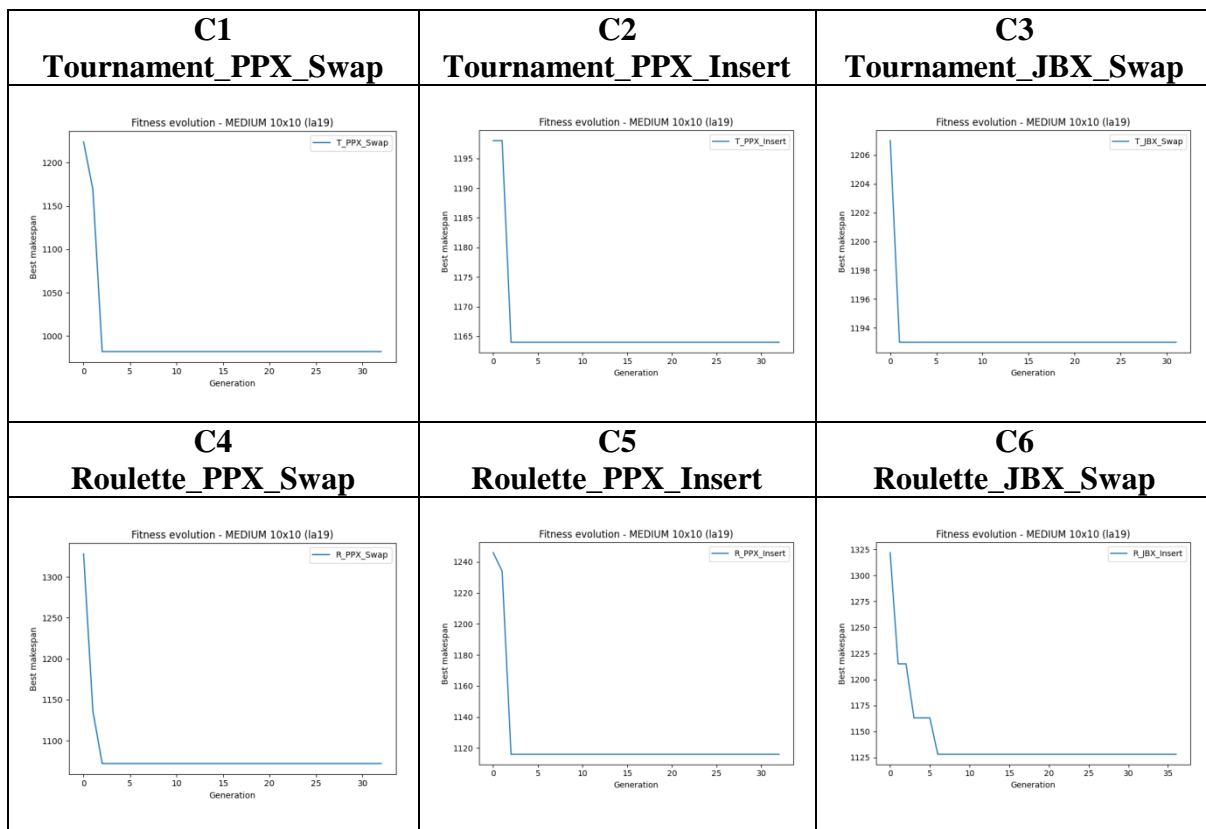
This instance represents a medium-sized problem with increased combinatorial complexity.

Results for six parameter configurations

Config	Selection	Crossover	Mutation	Best makespan (fitness)
C1	Tournament	PPX	Swap	982
C2	Tournament	PPX	Insert	1164
C3	Tournament	JBX	Swap	1193
C4	Roulette	PPX	Swap	1072
C5	Roulette	PPX	Insert	1116
C6	Roulette	JBX	Insert	1128

Analysis: The best result (makespan = 982) was achieved with Tournament selection, PPX crossover, and Swap mutation. Interestingly, Roulette selection combined with PPX and Swap also performed well (1072), suggesting that mutation type plays a significant role in medium-scale problems. JBX crossover and Roulette selection showed limited improvement.

Evolution of the Best Solution



The evolution curves show that most configurations converge within the first 10–15 generations. Tournament selection combined with Insertion mutation leads to faster and deeper convergence.

Comparative Plot

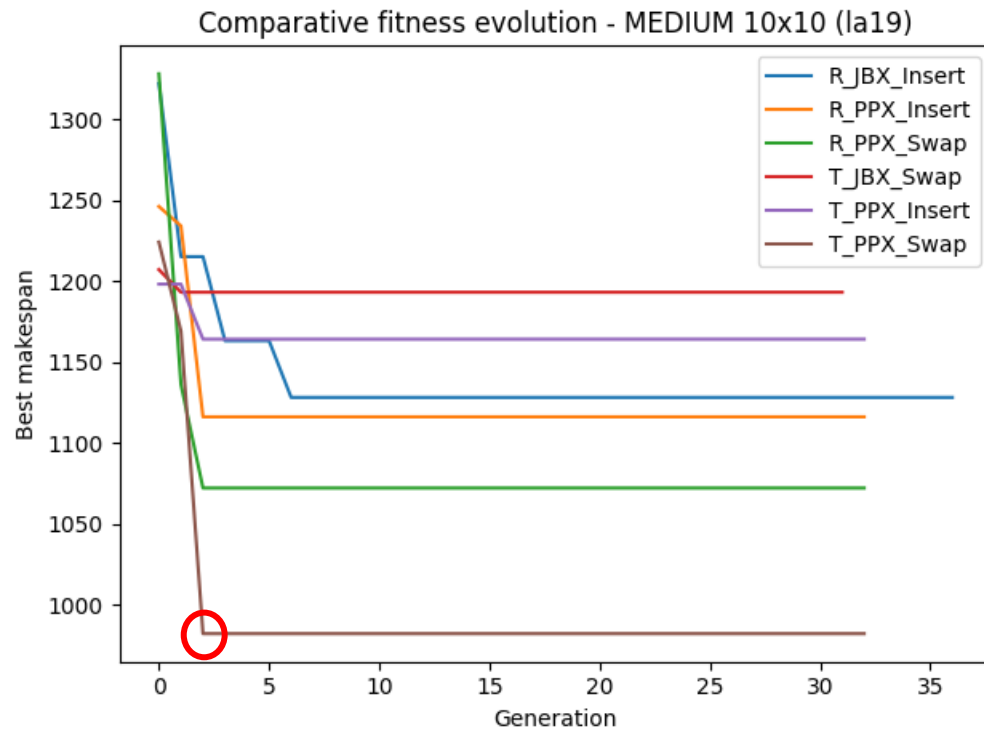


Figure 4. Comparative fitness evolution MEDIUM

2.3 Large instance (15 or more machines)

Dataset Description

The yn1 dataset contains 20 jobs and 20 machines, with each job defined by 20 operations. This instance represents a large-scale scheduling problem with high dimensionality and complex precedence constraints.

<https://people.brunel.ac.uk/%7Emastjjb/jeb/orlib/files/jobshop1.txt>

```
+++++
instance yn1

+++++
Yamada and Nakano 20x20 instance (Table 4, instance 1)
20 20
17 13 2 26 11 35 4 45 12 29 13 21 7 40 0 45 3 16 15 10 18 49 10 43 14 25 8 25 1 40 6 16 19 43 5 48 9 36 16 11
8 21 6 22 14 15 5 28 10 10 2 46 11 19 19 13 13 18 18 14 3 11 4 21 16 30 1 29 0 16 15 41 17 40 12 38 7 28 9 39
4 39 3 28 8 32 17 46 0 35 14 14 1 44 10 20 13 12 6 23 18 22 9 15 11 35 7 27 16 26 5 27 15 23 2 27 12 31 19 31
4 31 10 24 3 34 6 44 18 43 12 32 2 35 15 34 19 21 7 46 13 15 5 10 9 24 14 37 17 38 1 41 8 34 0 32 16 11 11 36
19 45 1 23 5 34 9 23 7 41 16 10 11 40 12 46 14 27 8 13 4 20 2 40 15 28 13 44 17 34 18 21 10 27 0 12 6 37 3 30
13 48 2 34 3 22 7 14 12 22 14 10 8 45 19 38 6 32 16 38 11 16 4 20 0 12 5 40 9 33 17 35 1 32 10 15 15 31 18 49
9 19 5 33 18 32 16 37 12 28 3 16 2 40 10 37 4 10 11 20 1 17 17 48 6 44 13 29 14 44 15 48 8 21 0 31 7 36 19 43
9 20 6 43 1 13 5 22 2 33 7 28 16 39 12 16 13 34 17 20 10 47 18 43 19 44 8 29 15 22 4 14 11 28 14 44 0 33 3 28
7 14 12 40 8 19 0 49 13 11 10 13 9 47 18 22 2 27 17 26 3 47 5 37 6 19 15 43 14 41 1 34 11 21 4 30 19 32 16 45
16 32 7 22 15 30 6 18 18 41 19 34 9 22 11 11 17 29 10 37 4 30 2 25 1 27 0 31 14 16 13 20 3 26 12 14 5 24 8 43
18 22 17 22 12 30 15 31 13 15 4 13 16 47 19 18 6 33 3 30 7 46 2 48 11 42 0 18 1 16 8 25 10 43 5 21 9 27 14 14
5 48 1 39 2 21 18 18 13 20 0 28 15 20 8 36 6 24 9 35 7 22 19 36 3 39 14 34 4 49 17 36 11 38 10 46 12 44 16 13
14 26 1 32 2 11 15 10 9 41 13 10 6 26 19 26 12 13 11 35 5 22 0 11 7 24 17 33 8 11 10 34 16 11 3 22 4 12 18 17
16 39 10 24 17 43 14 28 3 49 15 34 18 46 13 29 6 31 11 40 7 24 1 47 9 15 2 26 8 40 12 46 5 18 19 16 4 14 0 21
11 41 19 26 16 14 3 47 0 49 5 16 17 31 9 43 15 20 10 25 14 10 13 49 8 32 6 36 7 19 4 23 2 20 18 15 12 34 1 33
11 37 5 48 10 31 7 42 2 24 1 13 9 30 15 24 0 19 13 34 19 35 8 42 3 10 14 40 4 39 6 42 12 38 16 12 18 27 17 40
14 19 1 27 8 39 12 41 5 45 11 40 10 46 6 48 7 37 3 30 17 31 4 16 18 29 15 44 0 41 16 35 13 47 9 21 2 10 19 48
18 38 0 27 13 32 9 30 7 17 14 21 1 14 4 37 17 15 16 31 5 27 10 25 15 41 11 48 3 48 6 36 2 30 12 45 8 26 19 17
1 17 10 40 9 16 5 36 4 34 16 47 19 14 0 24 18 10 6 14 13 14 3 30 12 23 2 37 17 11 11 23 8 40 15 15 14 10 7 46
14 37 10 28 13 13 0 28 2 18 1 43 16 46 8 39 3 30 12 15 11 38 17 38 18 45 19 44 9 16 15 29 5 33 6 20 7 35 4 34
+++++
```

Figure 5. Instance yn1

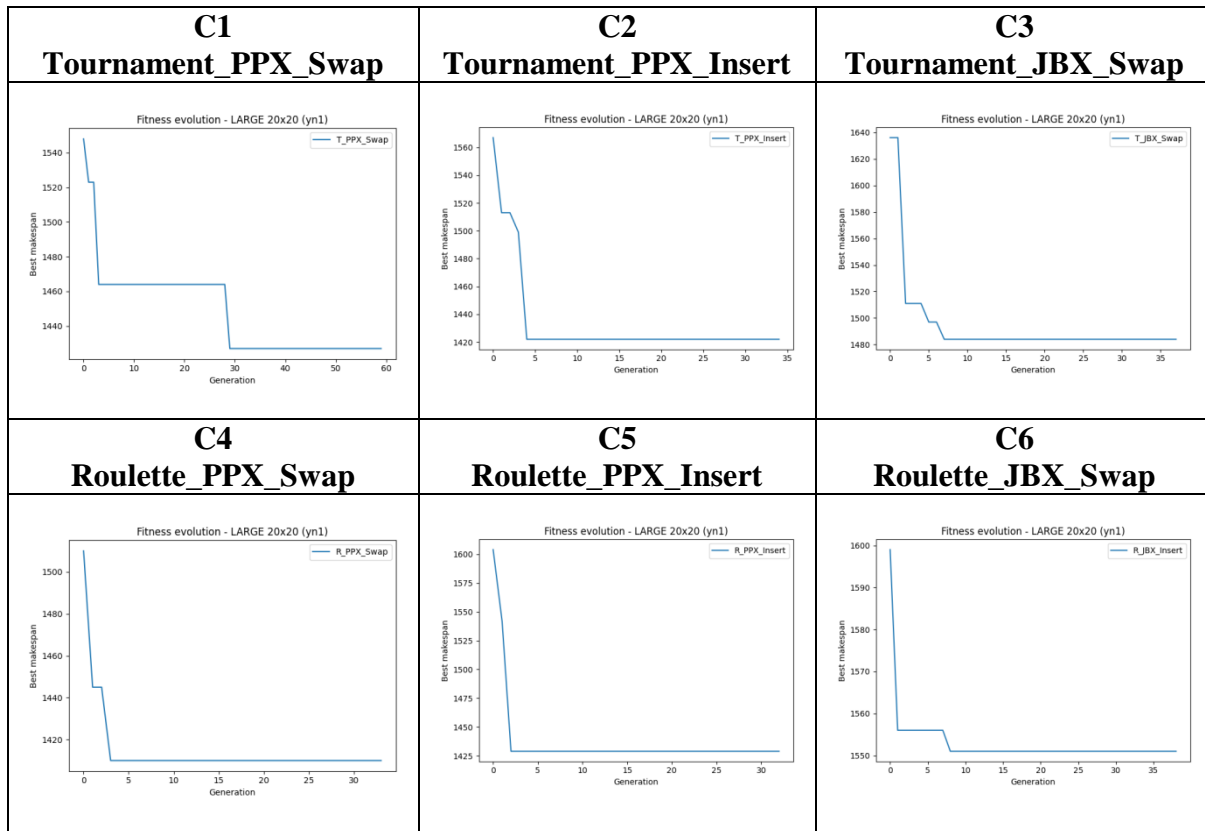
It is used to evaluate the robustness and scalability of evolutionary algorithms under high computational load.

Results for six parameter configurations

Config	Selection	Crossover	Mutation	Best makespan (fitness)
C1	Tournament	PPX	Swap	1427
C2	Tournament	PPX	Insert	1422
C3	Tournament	JBX	Swap	1484
C4	Roulette	PPX	Swap	1410
C5	Roulette	PPX	Insert	1429
C6	Roulette	JBX	Insert	1551

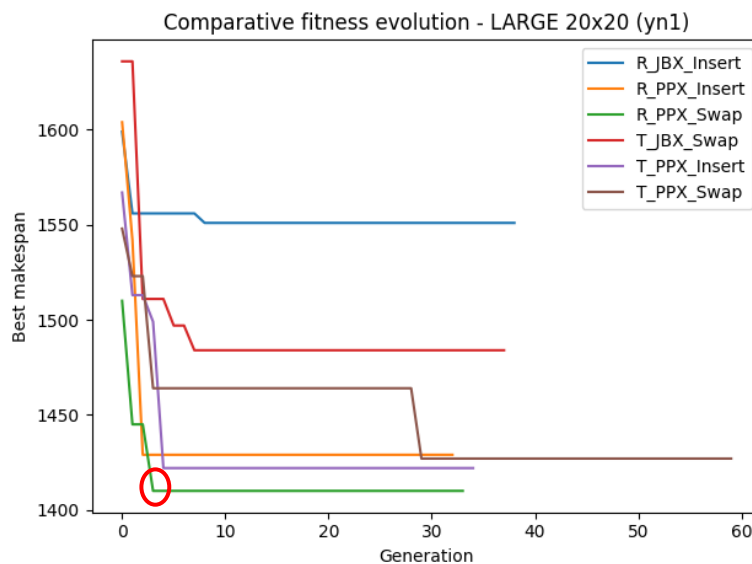
Analysis: The results obtained for the large-scale instance (20×20) reveal several important patterns regarding the behavior of the Genetic Algorithm under different operator configurations. The best makespan achieved across all runs was 1410, obtained using Roulette selection, PPX crossover, and Swap mutation (Configuration C4). This is a notable deviation from the SMALL and MEDIUM instances, where Tournament selection tended to dominate..

Evolution of the Best Solution



Most configurations converge within 10–15 generations. The best-performing configuration (R_PPX_Swap) shows a steep drop in the first few generations and stabilizes early.

Comparative Plot



2.4 Conclusions

The results obtained across the three instances confirm that the way the problem is encoded, validated, and evaluated has a direct impact on how the Genetic Algorithm behaves. The job-based permutation chromosome, together with the makespan simulation used as fitness, allowed the algorithm to generate valid schedules in all cases and compare them consistently across different problem sizes.

The choice of techniques (selection, crossover, and mutation) affects the results and also changes depending on the size of the instance. In the SMALL instance, several configurations reached similar makespans, and the best result changed between runs. This shows that the search space is small enough for different operator combinations to work well, and randomness plays a significant role. Even so, Tournament selection tended to converge more steadily, while Roulette occasionally matched it when the initial population was favourable, but very randomly.

In the MEDIUM instance, the algorithm behaved more predictably. Tournament selection combined with PPX crossover and Swap mutation produced the best results, showing that as the problem grows, the algorithm benefits from techniques that preserve structure and guide the search more consistently. The PPX crossover proved especially effective at maintaining valid operation sequences, which is essential given the codification used.

The LARGE instance highlighted a different need: maintaining diversity. Here, Roulette selection achieved the best makespan when paired with PPX and Swap. This suggests that, in very large search spaces, too much selection pressure (as in Tournament) can lead to premature convergence, while Roulette's stochastic nature helps explore more of the solution space before settling. PPX remained the most reliable crossover technique, and Swap mutation continued to introduce small but useful changes without breaking feasibility.

Overall, the experiments show that there is no single "best" configuration for every case, but the codification and validation strategy used in the project works well across all sizes. PPX crossover and Swap mutation stand out as the most robust techniques, while the best selection method depends on the scale of the problem: Tournament is more effective in small and medium instances, whereas Roulette becomes advantageous in large ones. These results reinforce the importance of adapting the GA's components to the characteristics of the problem and the structure of the chromosome.