Supplementary Material for "A Bi-Level Intelligent Control Framework Integrating Deep Reinforcement Learning and Bayesian Optimization for Multi-Objective Adaptive Scheduling in Opto-Mechanical Automated Manufacturing"

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This document accompanies the main manuscript and provides detailed specifications of the benchmark instances used in the scalability analysis (Section 6.3).

S1. Detailed Specifications of Benchmark Instances for Scalability Analysis

This section provides the detailed machine categorization, corresponding quantities, and task sequencing information for each problem scale tested in the scalability analysis (5×5, 10×10, 15×15, 25×25, 50×50, and 100×100).

S1.1 Machine Categorization and Quantities

For each problem scale, the machines are categorized into the same five functional categories as in the main manuscript (Cleaning, Precision Coating, High-precision Assembly, Calibration Testing, and Special Handling). The distribution of machines across categories scales proportionally with the overall problem size.

Table S1: Machine categorization and quantities for each problem scale

Scale	Cleaning	Precision Coating	High-precision Assembly	Calibration Testing	Special Handling	Total Machines
5×5	1	1	1	1	1	5
10×10	2	2	2	2	2	10
15×15	3	3	3	3	3	15
20×20*	3	2	5	6	4	20
25×25	4	3	6	8	4	25
50×50	8	6	12	16	8	50
100×100	16	12	24	32	16	100

Note: The 20×20 scale corresponds to the main benchmark instance detailed in the manuscript (Table 2). The distribution for other scales follows the same proportional logic while maintaining the functional requirements of opto-mechanical manufacturing.

Table S2: Detailed machine ID mapping for each category and scale

Problem Scale	Category	Machine IDs	Quantity
5×5	Cleaning	M3	1

Problem Scale	Category	Machine IDs	Quantity
	Precision Coating	M1	1
	High-precision Assembly	M4	1
	Calibration Testing	M5	1
	Special Handling	M2	1
10×10	Cleaning	M3, M9	2
	Precision Coating	M1, M6	2
	High-precision Assembly	M4, M10	2
	Calibration Testing	M5, M7	2
	Special Handling	M2, M8	2
15×15	Cleaning	M3, M9, M14	3
	Precision Coating	M1, M6, M12	3
	High-precision Assembly	M4, M10, M15	3
	Calibration Testing	M5, M7, M13	3
	Special Handling	M2, M8, M11	3
20×20	Cleaning	M6, M10, M12	3
	Precision Coating	M4, M11	2

Problem Scale	Category	Machine IDs	Quantity
	High-precision Assembly	M3, M8, M9, M13, M18	5
	Calibration Testing	M1, M2, M5, M15, M16, M20	6
	Special Handling	M7, M14, M17, M19	4
25×25	Cleaning	M6, M10, M12, M23	4
	Precision Coating	M4, M11, M22	3
	High-precision Assembly	M3, M8, M9, M13, M18, M25	6
	Calibration Testing	M1, M2, M5, M15, M16, M20, M21, M24	8
	Special Handling	M7, M14, M17, M19	4
50×50	Cleaning	M6, M10, M12, M23, M30, M37, M42, M48	8
	Precision Coating	M4, M11, M22, M31, M39, M47	6
	High-precision Assembly	M3, M8, M9, M13, M18, M25, M28, M33, M36, M41, M44, M50	12
	Calibration Testing	M1, M2, M5, M15, M16, M20, M21, M24, M26, M29, M32, M35, M38, M40, M45, M49	16
	Special Handling	M7, M14, M17, M19, M27, M34, M43, M46	8
100×100	Cleaning	M6, M10, M12, M30, M42, M48, M55, M63, M72, M81, M89, M97, M58, M66, M74, M85	16
	Precision Coating	M4, M11, M39, M47, M53, M62, M70, M79, M88, M96, M100, M67	12

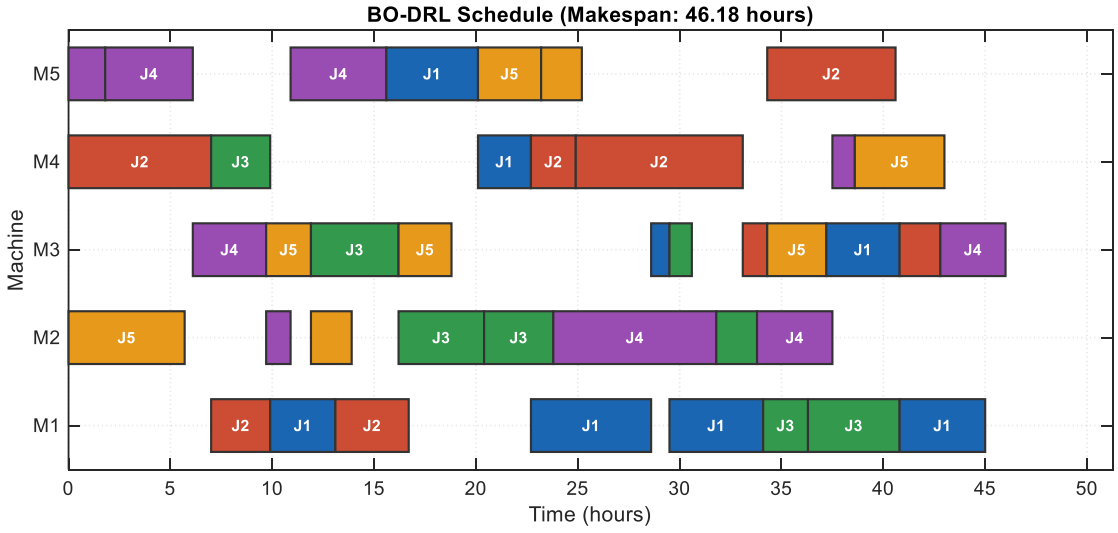
Problem Scale	Category	Machine IDs	Quantity
	High-precision Assembly	M3, M8, M9, M13, M18, M25, M33, M41, M44, M50, M52, M60, M69, M77, M86, M94, M99, M23, M28, M36, M45, M54, M64, M73	24
	Calibration Testing	M1, M2, M5, M15, M16, M20, M21, M24, M26, M29, M32, M35, M38, M40, M45, M49, M51, M57, M61, M65, M71, M75, M80, M84, M90, M93, M98, M31, M34, M43, M46, M56	32
	Special Handling	M7, M14, M17, M19, M27, M34, M43, M46, M59, M68, M78, M87, M92, M95, M22, M37	16

S1.2 Task Sequencing Information (Gantt Charts)

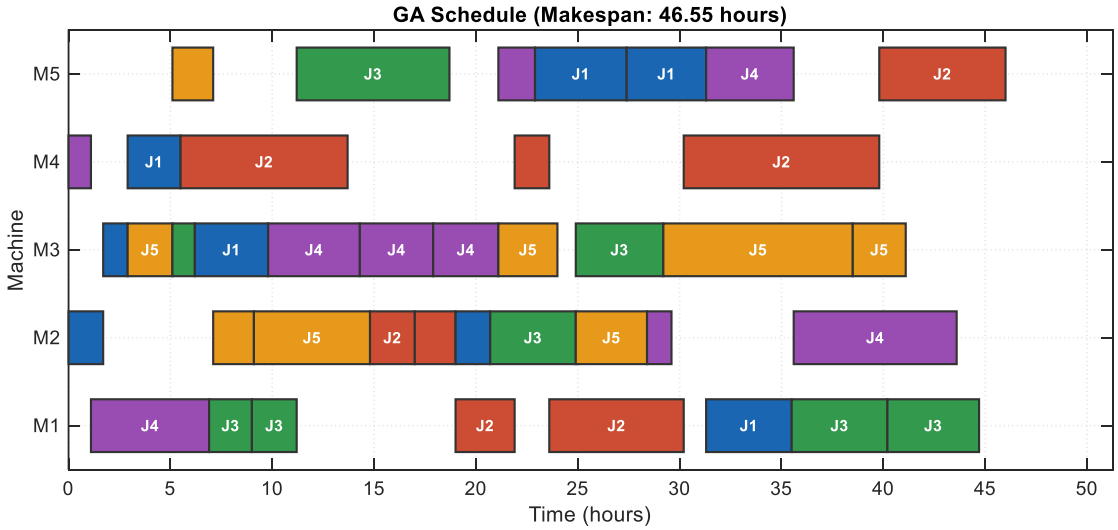
This section presents the Gantt charts showing the scheduling results for each problem scale (5×5, 10×10, 15×15, 25×25, 50×50, and 100×100) under the three compared algorithms: BO-DRL, GA, and PSO. Each Gantt chart visually represents the task sequencing, machine assignments, and schedule compactness achieved by each algorithm.

Important Note on Gantt Chart Interpretation:

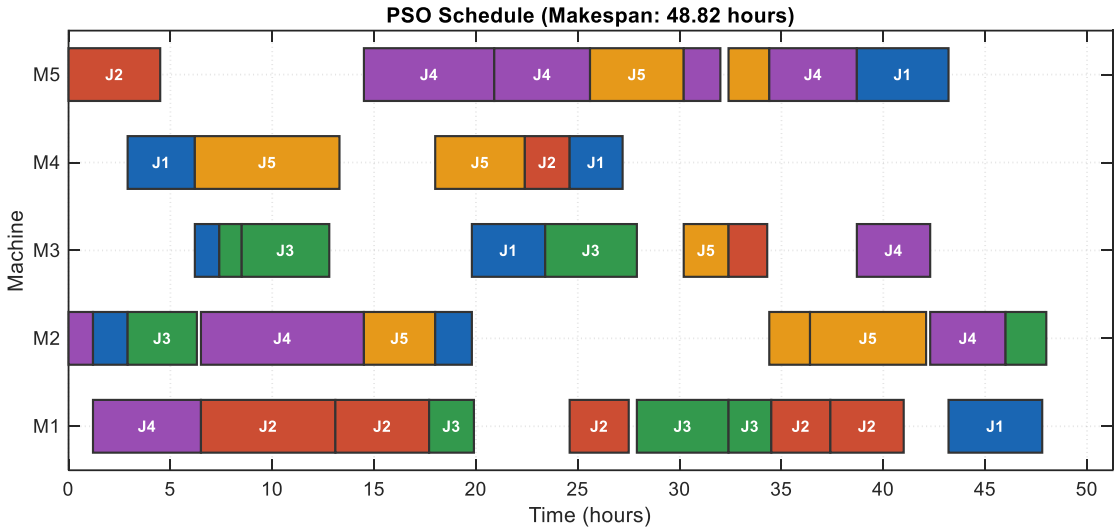
1. Each horizontal bar represents the processing of an operation on a specific machine
2. The x-axis represents time (hours)
3. The y-axis lists the machines (by ID)
4. Different colors/shades represent different jobs
5. Gaps between bars on the same machine indicate idle time
6. The overall length of the schedule (rightmost bar) represents the makespan



(a)BO-DRL scheduling Gantt chart for 5×5 scale

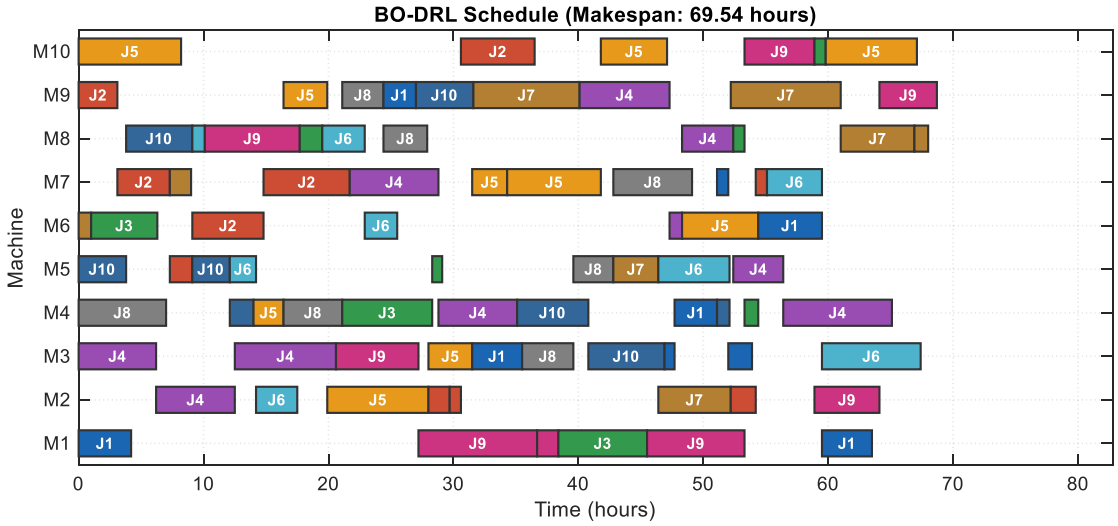


(b) GA scheduling Gantt chart for 5×5 scale

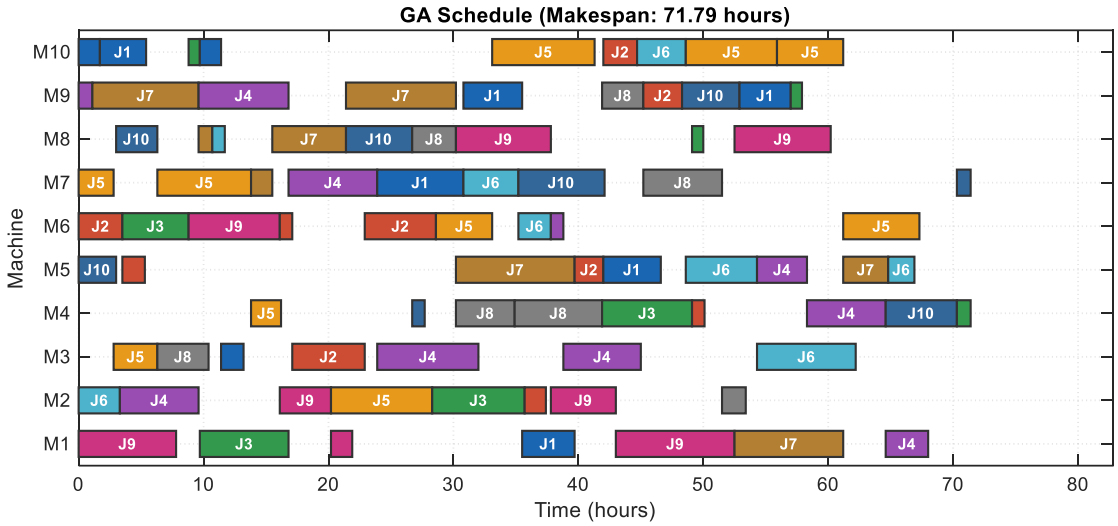


(c) PSO scheduling Gantt chart for 5×5 scale

Figure S1. 5×5 Problem Scale

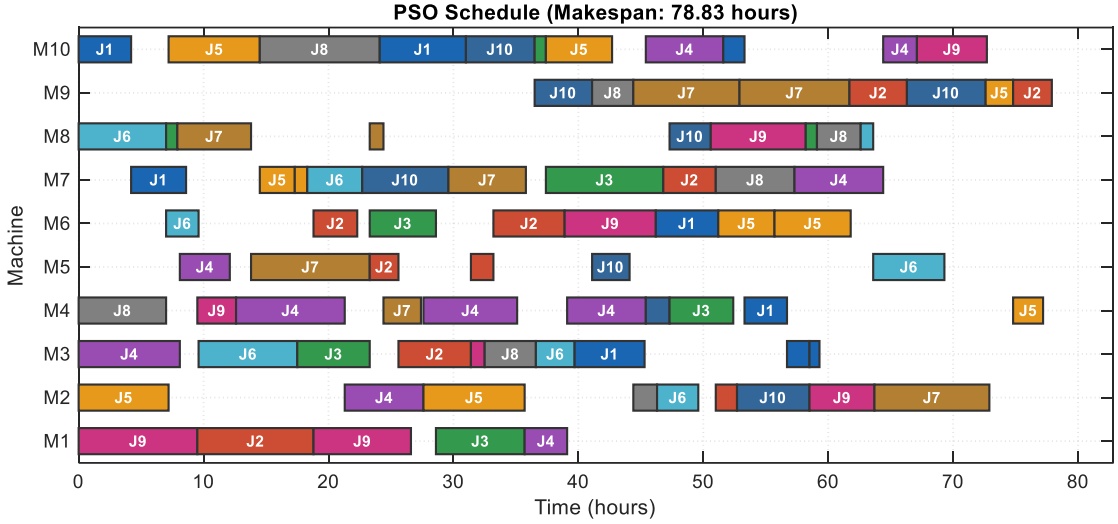


(a) BO-DRL scheduling Gantt chart for 10×10 scale



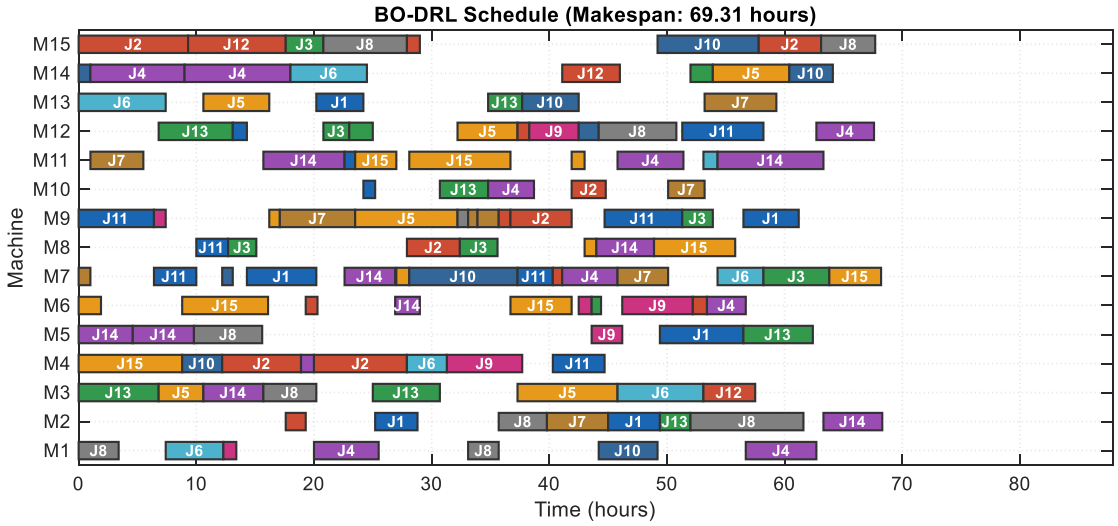
(b) GA scheduling Gantt chart for 10×10 scale

Figure S2.3:

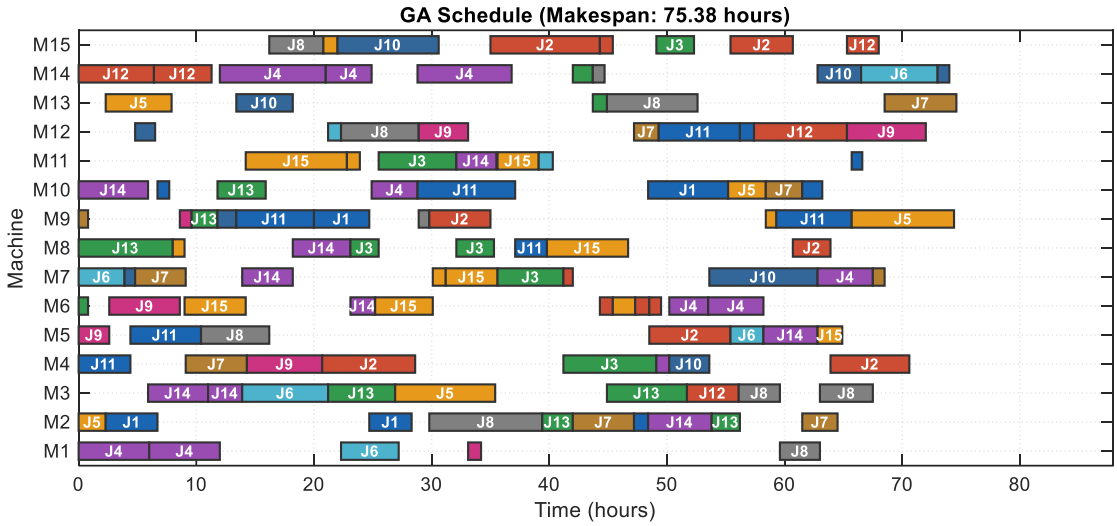


(c) PSO scheduling Gantt chart for 10×10 scale

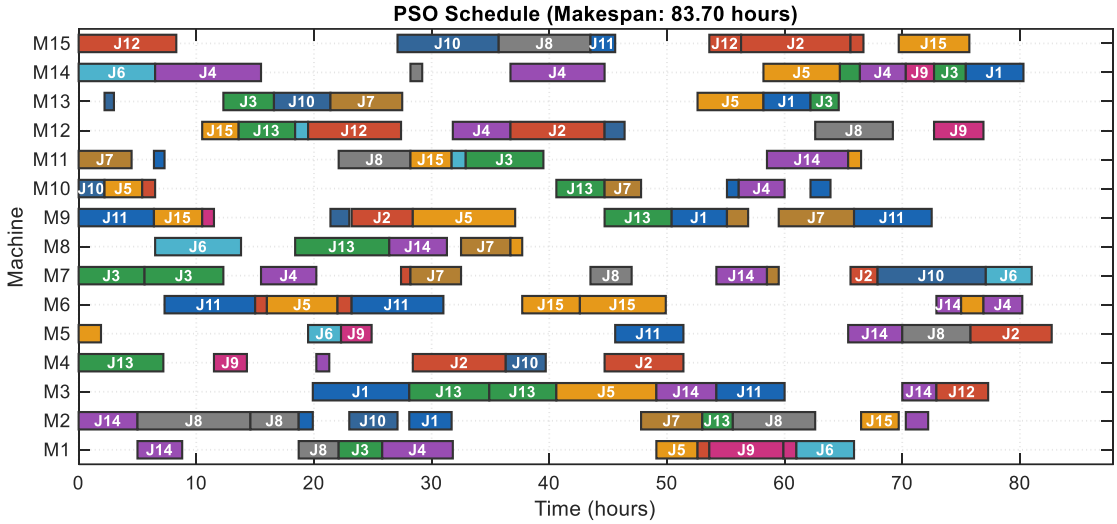
Figure S2. 10×10 Problem Scale



(a) BO-DRL scheduling Gantt chart for 15×15 scale

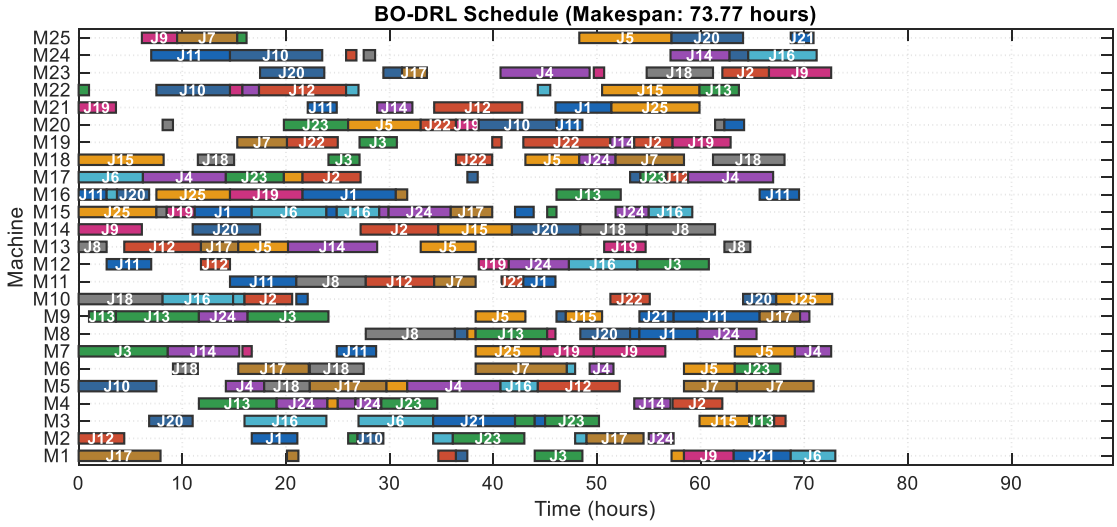


(b) GA scheduling Gantt chart for 15×15 scale

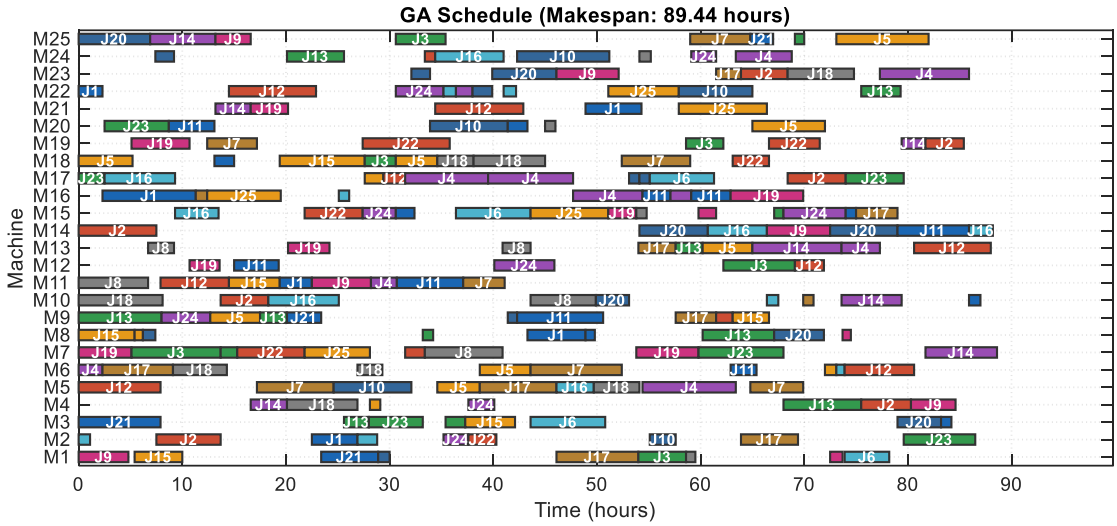


(c) PSO scheduling Gantt chart for 15×15 scale

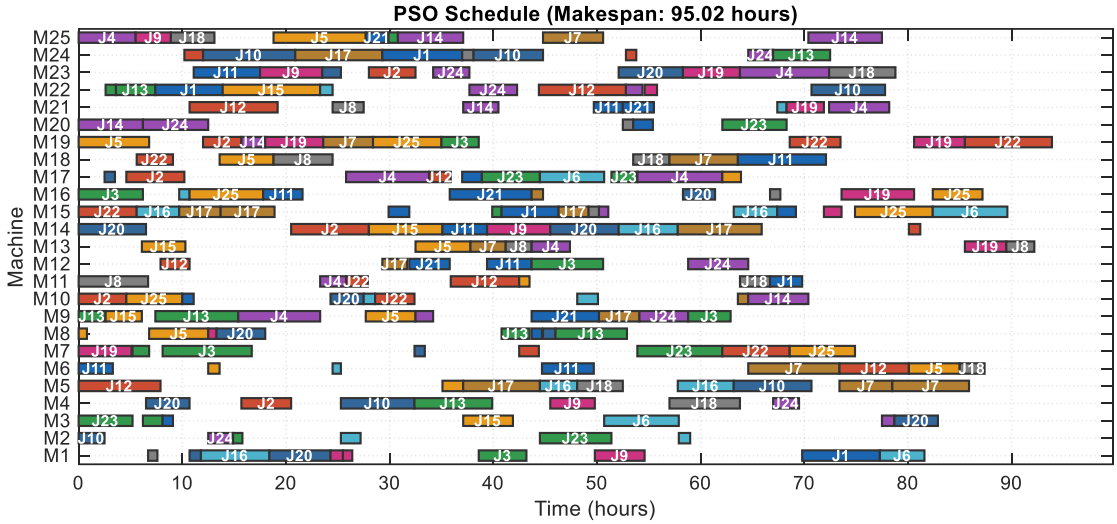
Figure S3. 15×15 Problem Scale



(a) BO-DRL scheduling Gantt chart for 25×25 scale

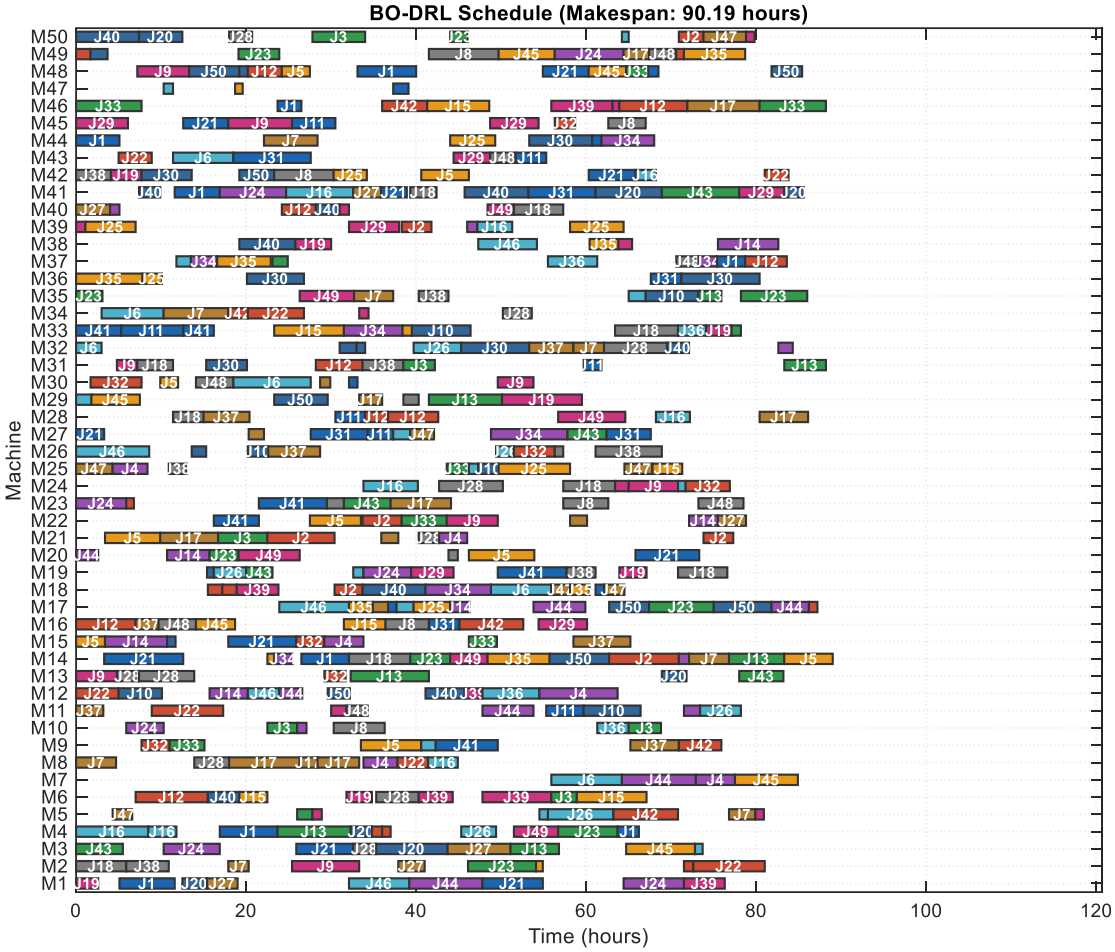


(b) GA scheduling Gantt chart for 25×25 scale

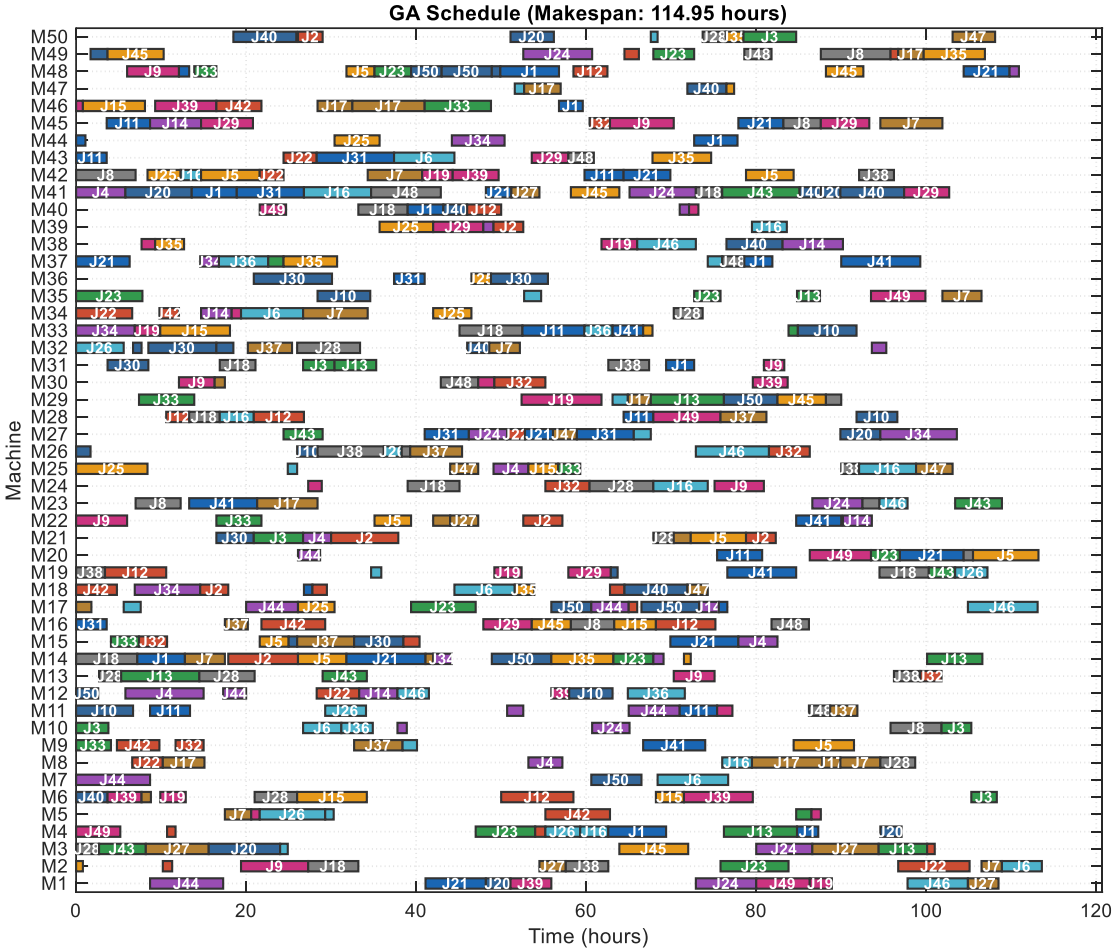


(c) PSO scheduling Gantt chart for 25×25 scale

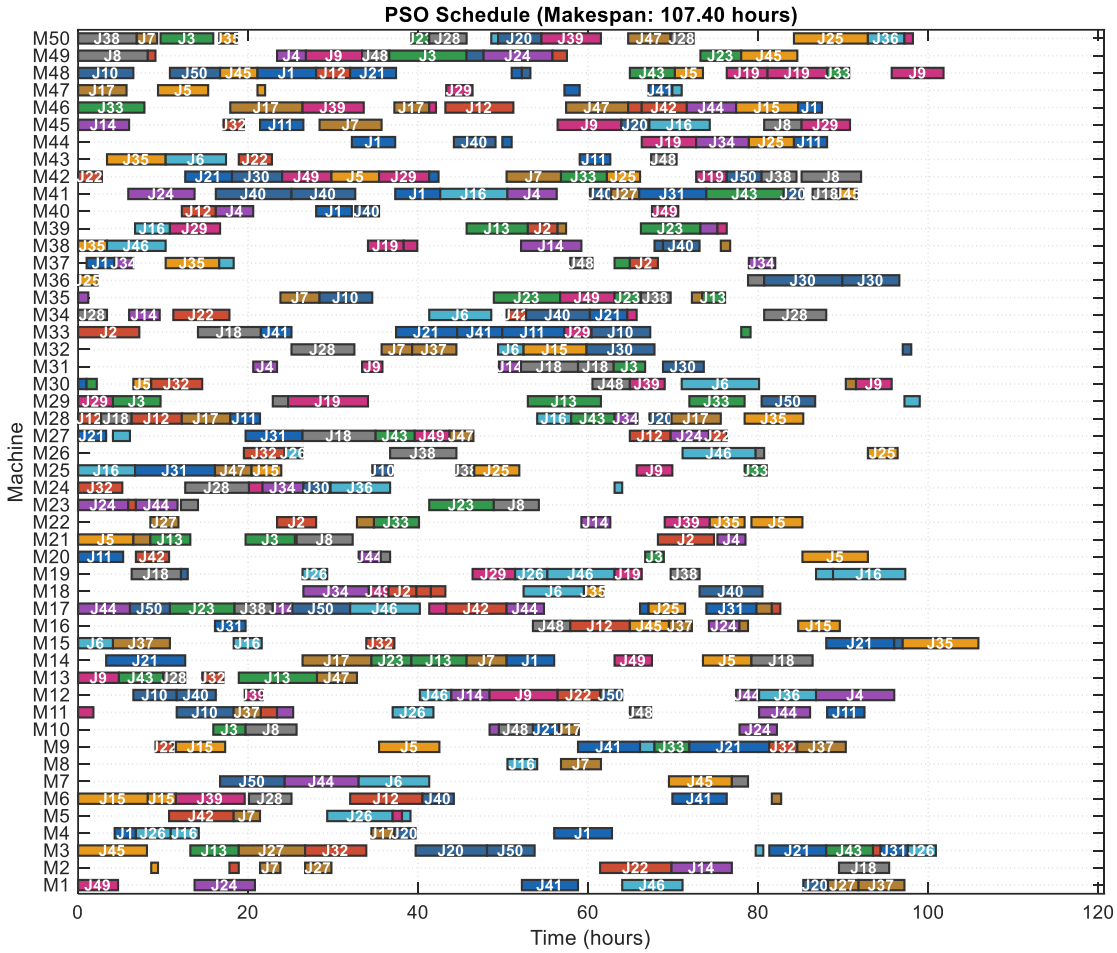
Figure S4. 25×25 Problem Scale



(a) BO-DRL scheduling Gantt chart for 50×50 scale

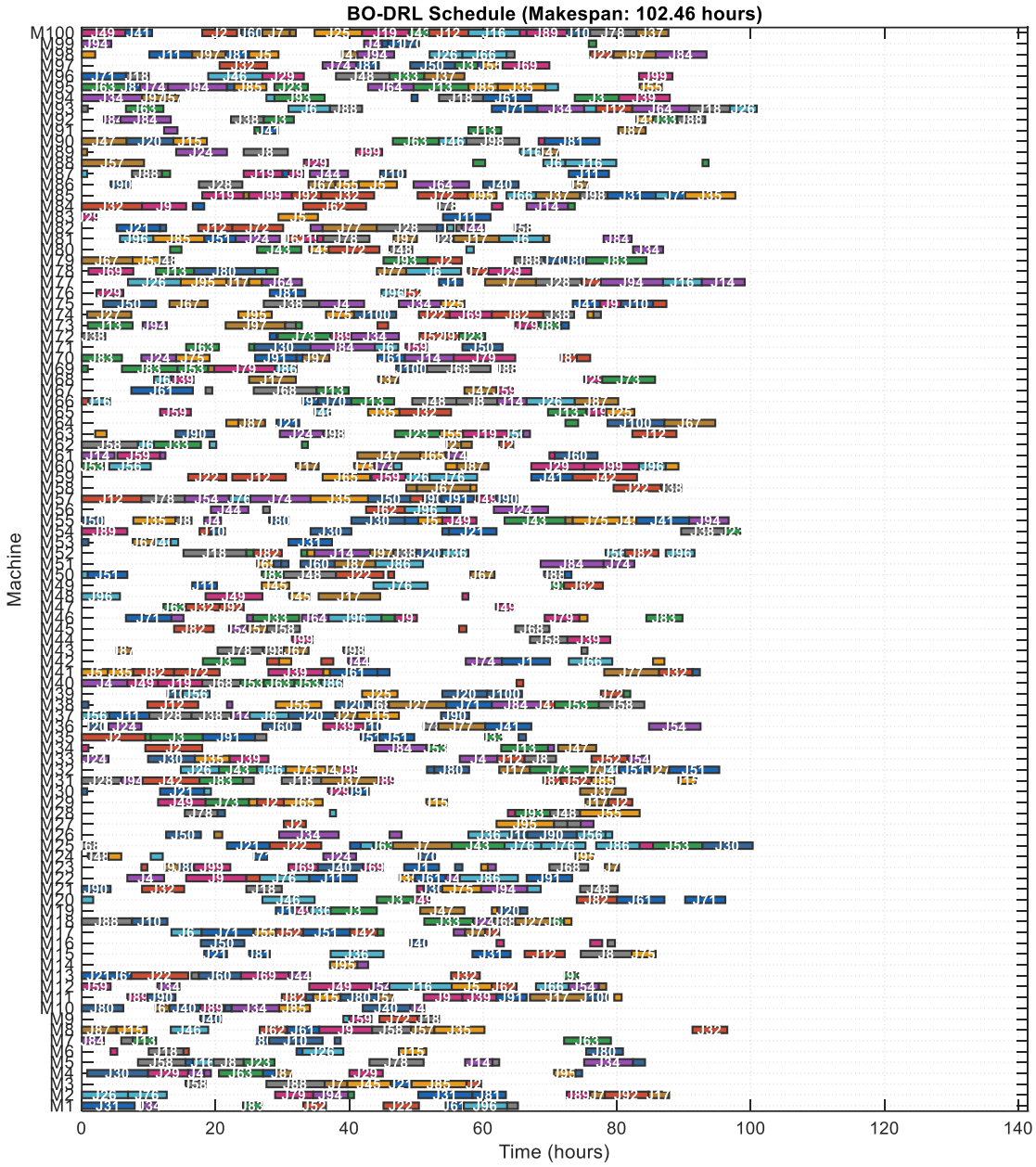


(b) GA scheduling Gantt chart for 50×50 scale

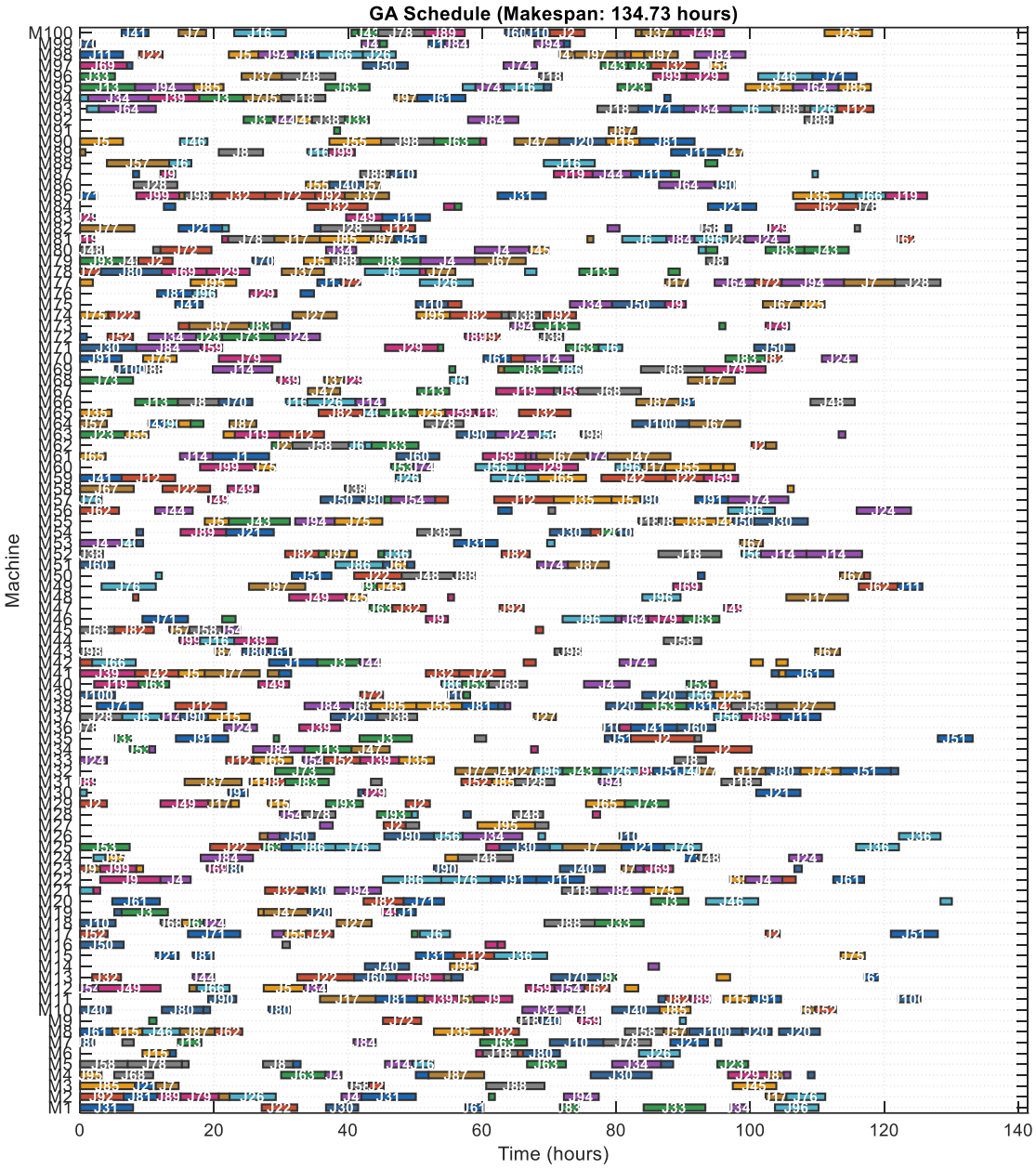


(c) PSO scheduling Gantt chart for 50×50 scale

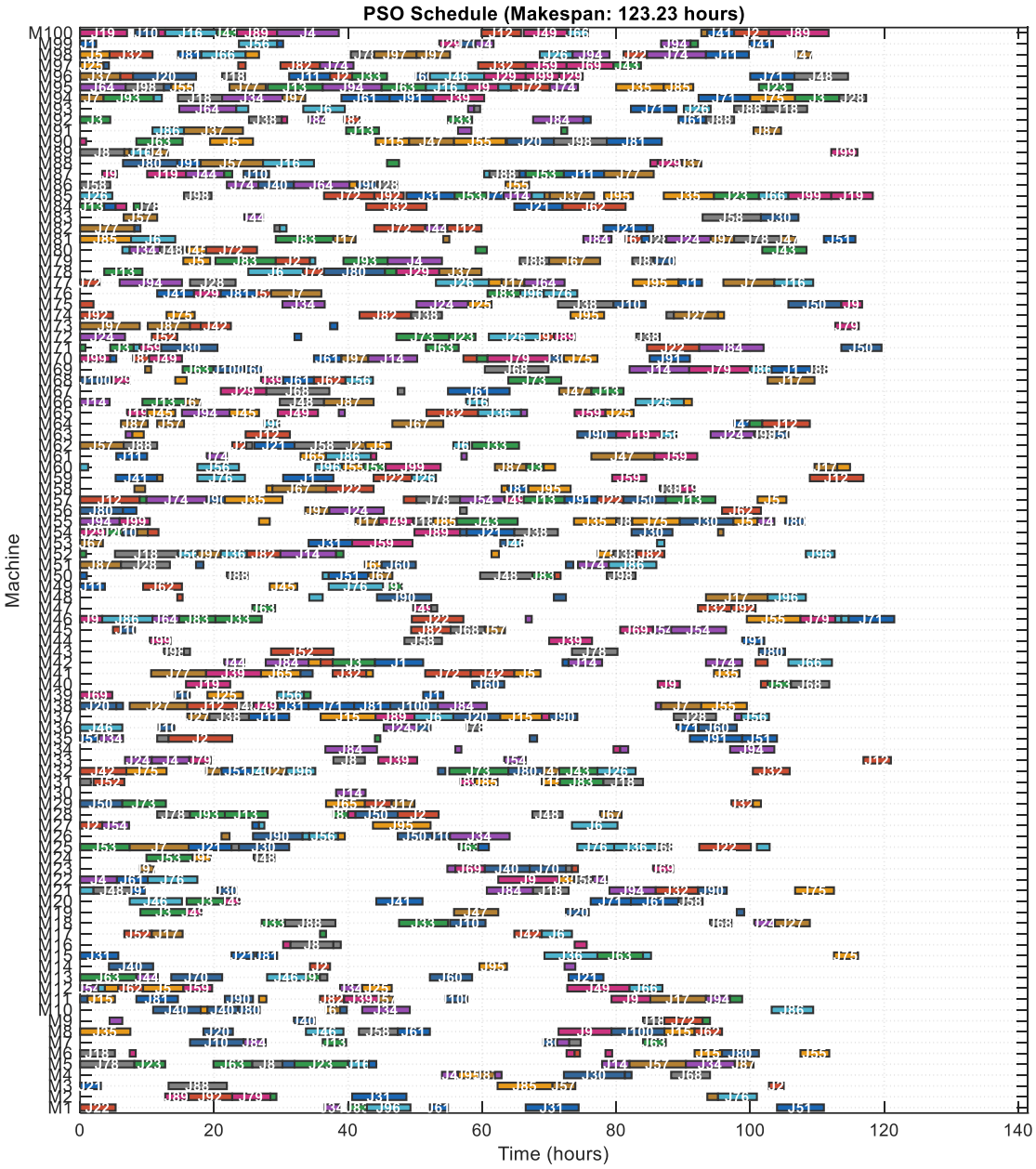
Figure S5. 50×50 Problem Scale



(a) BO-DRL scheduling Gantt chart for 100×100 scale



(b) GA scheduling Gantt chart for 100×100 scale



(c) PSO scheduling Gantt chart for 100×100 scale

Figure S6. 100×100 Problem Scale

S2. Data Structure Specification and Accessibility

To ensure the reproducibility of our study and to provide the detailed data as requested, all benchmark instances (from 5×5 to 100×100) have been structured and made publicly available.

S2.1 Data Structure Definition

The data for each problem scale (n×m) is stored in an individual data file named jobs+scale.mat (e.g., jobs20.mat). This file contains a structure array named jobs, whose length equals the number of jobs n. Each element of the jobs array represents one job and contains the following fields:

1. name: Job name/identifier.

2. num_operations: Total number of operations for this job.
3. due_date: Job due date (for tardiness calculation).
4. priority: Job priority weight.
5. operations: A num_operations × 1 structure array defining the detailed process plan. Each operation structure contains:
    a) machine_options: An integer vector listing the machine IDs capable of performing this operation.
    b) processing_times: A double-precision vector listing the processing times required on the corresponding machines in machine_options. The elements in machine_options and processing_times are positionally matched.

S2.2 Data Access

The complete set of .mat data files for all problem scales used in this study (jobs5.mat, jobs10.mat, ..., jobs100.mat) is hosted in a public GitHub repository: https://github.com/mengyanglii/Opto-Mechanical-Job-Shop-Scheduling-Benchmark-Datasets/tree/main

S3. Key Observations from Gantt Chart Analysis

1. **BO-DRL Consistency:** Across all scales, BO-DRL produces the most compact schedules with continuous machine utilization and minimal idle time. The schedules exhibit coherent patterns that scale effectively with problem size.
2. **GA Limitations:** Genetic Algorithm schedules show increasing fragmentation as problem scale grows, with noticeable idle gaps and less efficient load balancing, particularly evident at 50×50 and 100×100 scales.
3. **PSO Scalability Issues:** Particle Swarm Optimization demonstrates significant scalability limitations, producing disconnected schedules with poor coordination between machines, especially at larger problem sizes.
4. **Pattern Preservation:** The scheduling patterns observed in the main manuscript's 20×20 benchmark (Figure 4) are consistent across all scales, with BO-DRL maintaining its relative advantage in schedule compactness and load balancing regardless of problem size.

S4. Data Availability

The complete datasets for all benchmark instances, including:

1. Detailed machine specifications for each scale
2. Complete job operation sequences and processing times
3. Raw scheduling results for all algorithms
4. Scripts for generating and visualizing the Gantt charts

are available from the corresponding author upon reasonable request.