MULTI-OBJECTIVE WORKFORCE ALLOCATION FOR OFF-SITE CONSTURCTION ASSEMBLY USING PARALLEL SIMULATED ANNEALING

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18 – 20 August 2026 | Northumbria University, UK

Agenda

1. **Background**
   Why may data driven production scheduling improve off-site construction?

2. **Problem Description**
   How to address workforce dimensioning in construction assembly?

3. **Optimizer**
   How parallel Simulated Annealing and custom neighbour move works?

4. **Results**
   What are the operational benefits for decision-makers?

5. **Final Remarks**
   Conclusions and further research opportunities

Background

Why is Off-site Construction (OSC) operationally challenging?

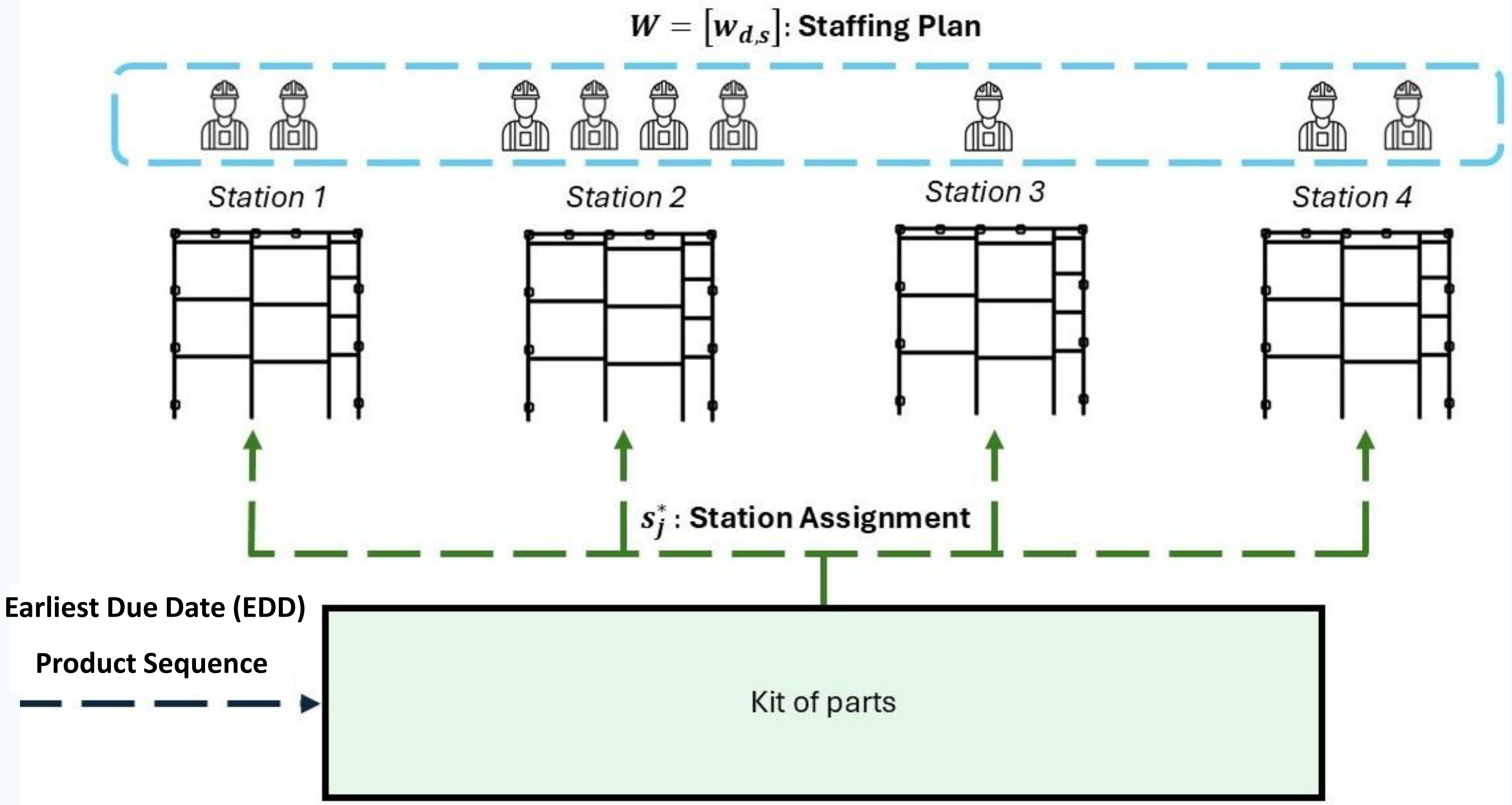
- Highly project-based and variable
- Dependent on manual, labour-intensive assembly
- Constrained by delivery deadlines linked to site installation
- Limited visibility of workforce utilisation and process deviations
- Poor staffing decisions increase tardiness, cost, and disruption

The Role of Optimisation Models in OSC Production Control

- Job sequencing
- Daily workforce allocation
- Workstation assignment
- Capacity balancing across stations
- Trade-offs between labour cost, tardiness, and delay severity

Problem Description

The off-site job shop assembles final products from kit of parts across multiple stations



Minimise

Σ **Tardiness** → Sum of production delay

£ **Cost** → Total labour Cost

μ **Delay severity** → Average delay

Problem Description

The OSC job shop is modelled by different information

Decision Variable

- Products sorting by **EDD**
- Daily **staffing matrix** to assign workers to assembly stations
- Fixed **workstation assignment**

Parameters

- **Assembly jobs, available workstations and working days** within the planning horizon
- **Job-specific workload** based on the required number of screws
- **Delivery deadline** associated with each assembly job
- **Average screw installation** time under standard working conditions
- **Maximum daily working** time per operator and staffing limit per workstation
- **Workforce efficiency** factor accounting for coordination and workspace limitations
- **Hourly labour cost** associated with workforce utilisation

Operational Constraints

- **Integer** and **bounded worker allocation** at each station and working day
- **Productivity increases** with collaborative staffing but with diminishing returns
- Full **completion** of each product workload **within the planning horizon**
- Daily station **workload** cannot exceed the **available processing capacity**
- Each product is **assigned** to one station based on **earliest feasible completion**
- Products follow the fixed EDD sequence **without overlapping** at the same station

Optimizer

The framework workflow is structured into 5 main steps before convergence

Initialisation

- Sort products by EDD
- Assign 2 workers to 2 stations
- Calculate objectives

Build Context

Evaluate

- **Pressure:** Delayed product
- **Slack**: Positive margin before deadline
- Utilisation

Parallel Search

For each temperature iter M

- Evaluate candidates via neighbour move
- Batch Evaluation

Pareto Acceptance

- **Dominating:** Accept deterministically
- **Non-dominated:** Probabilistic acceptance

Pareto Archive

- Stores non-dominated solutions
- Early termination for objective plateau

Optimizer: Neighbor Moves

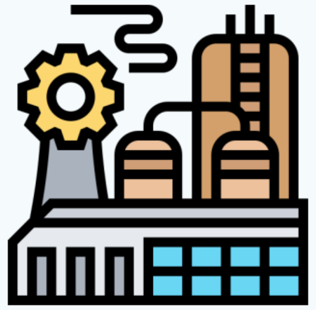
The neighbourhood operator perturbs the staffing matrix by probabilistically selecting one of three move families

Family	Operator	Operator Probability	Staffing Change	Station assignment
Redistribution	Rebalance Day	38%	Transfers one worker between two active stations on the same day	Reused
	Shift Same Station	30%	Moves one worker for the same station from a slack day to a higher-pressure day.	Reused
	Single Station	22%	Increases or decreases one active station-day by one worker.	Reused
	Station Block	10%	Increases or decreases one active station over a consecutive 2–3-day block.	Reused
Opening	Station Day	35%	Activates an unused station on one high-pressure day.	Recomputed
	Station Block	65%	Activates an unused station over a consecutive 2–3-day block.	Recomputed
Closing	Station Day	85%	Deactivates a low-risk station- day while keeping another station active.	Recomputed
	Station Block	15%	Deactivates a station over a low-pressure 2–3-day block.	Recomputed

Case Study

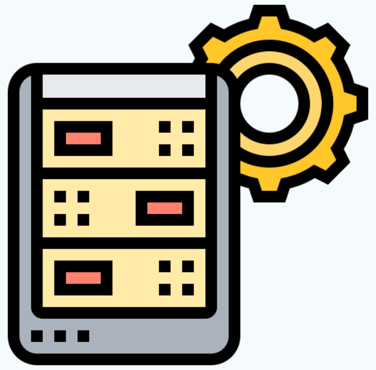
The optimization framework has been tested and validated in an OSC job shop in the North Est of England

OCS



Simulated Annealing

Workstation



- Products: 1769
- Screws ∈ $[2, 204]$
- Workday: 8 h
- Deadlines: 5 date
- Unitary time; 60 sec/(screw*op)
- Parallel factor: 0.9
- Labor: 20 £/h, 4 max op/station
- Stations: 4
- Production Start: 5/05/2025

- p_0: 80%
- M: 50 iterations
- N: 17690 iterations
- α_{cool}: 80%

- AMD Ryzen 5
- 6 cores with 2 threads per core
- 16 GB RAM

Results

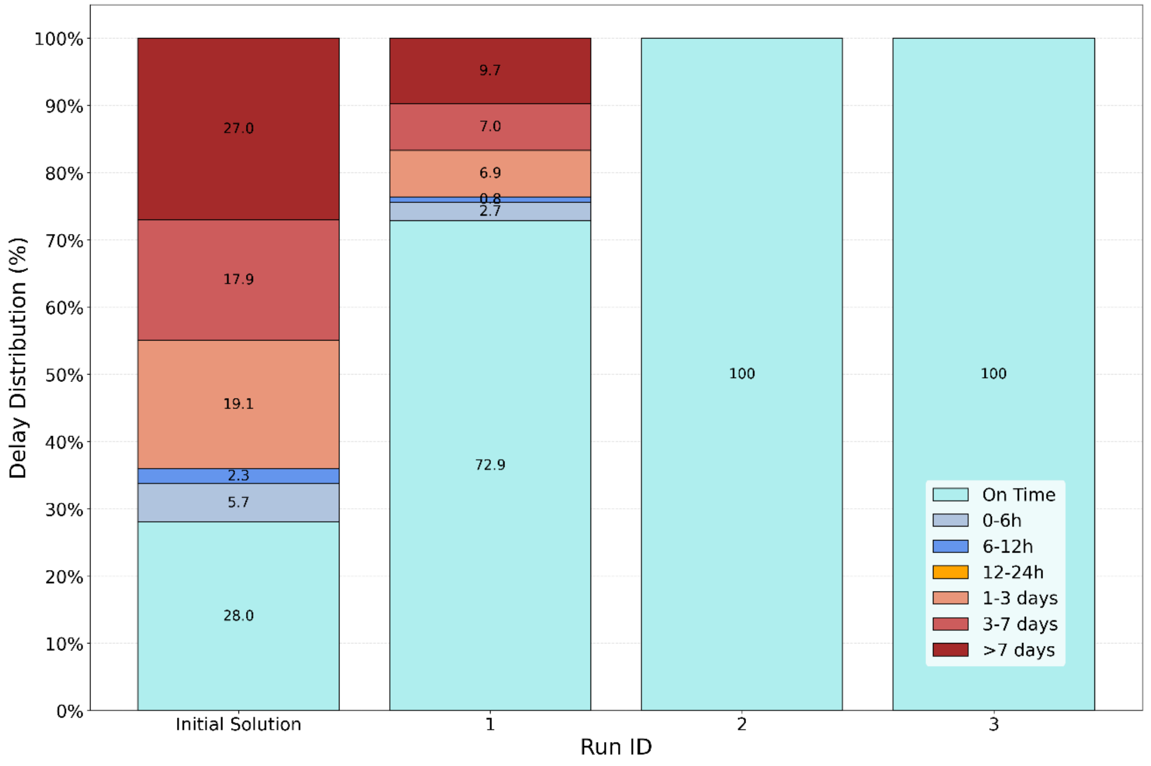
Three different parallel SA configurations are benchmarked again the initial greedy solution that sorts the products by EDD and assign 2 workers to 2 stations.

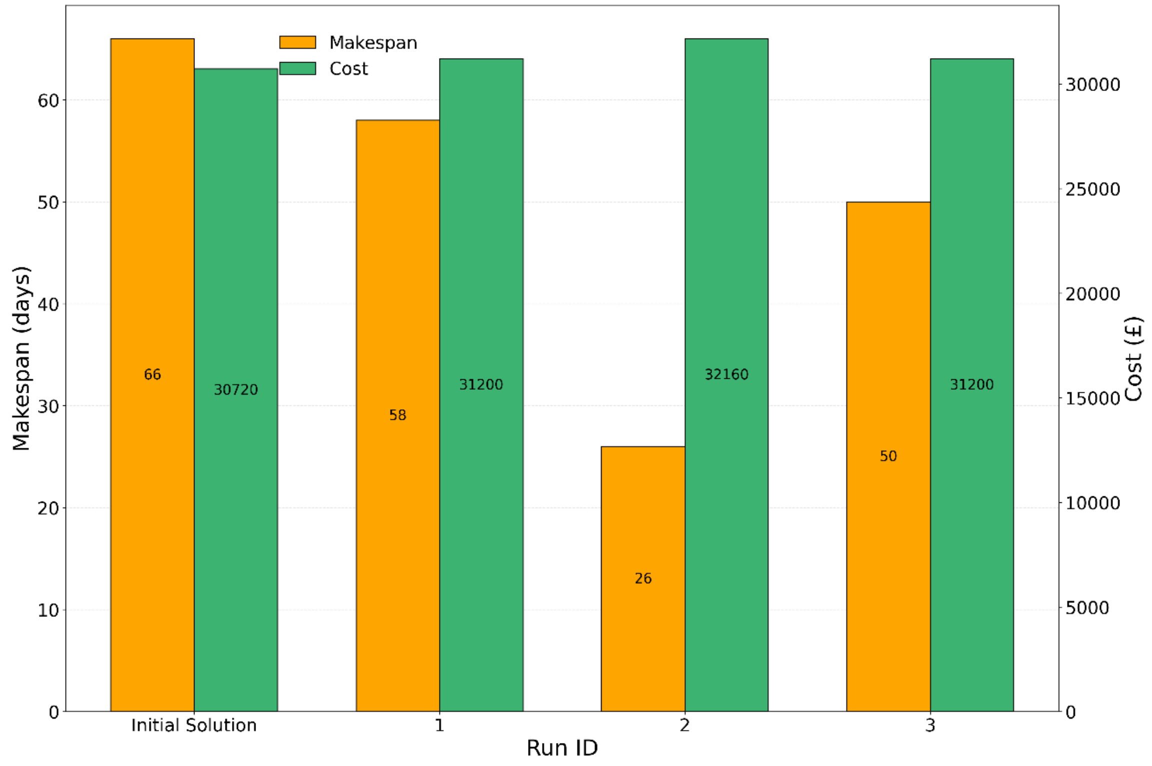
Run ID	Redistribute	Opening	Closing	Tardiness (h)	Cost (£)	Severity (h)	Run Time (h)
Initial	-	-	-	176955.22	30720	139	-
R1	100	0	0	50836.57	31200	106.13	2.01
R2	80	20	0	0	32160	0	1.6
R3	**70**	**15**	**15**	**0**	**31200**	**0**	**2.18**

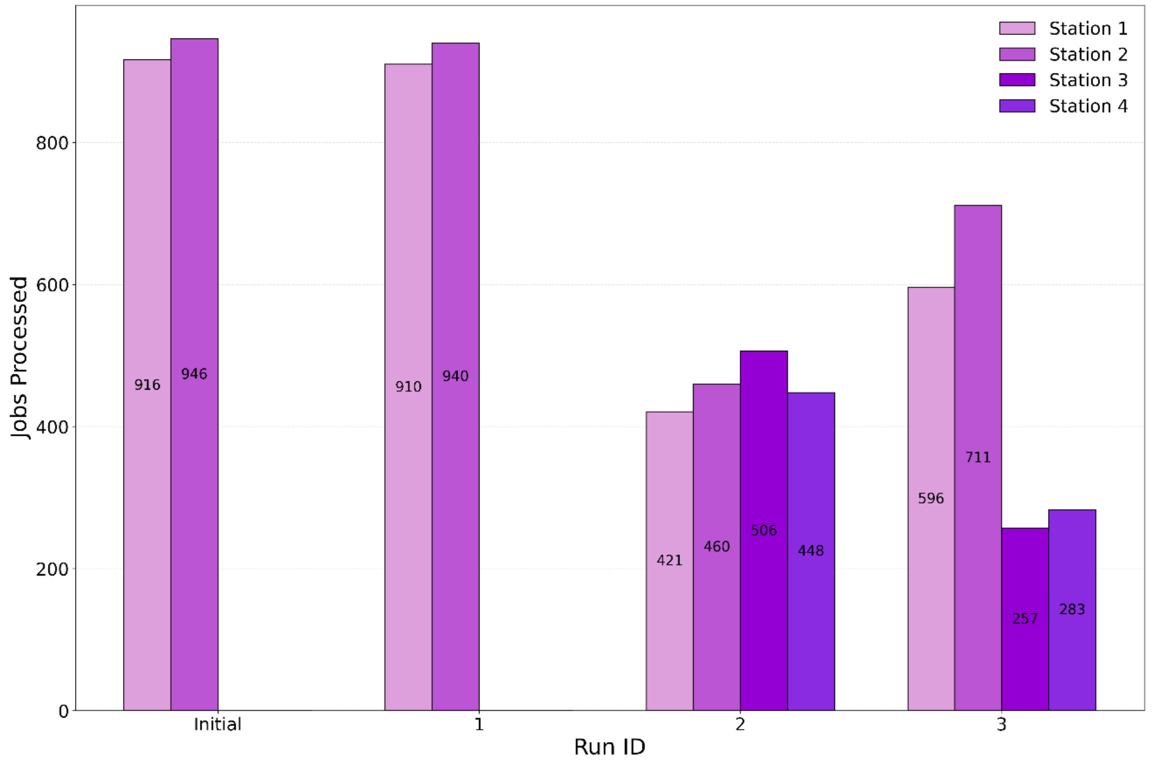
- Neighbour moves effectively **minimise** production objectives
- R3 has a **higher run time** due to a higher share of **job to station re-evaluation**
- R3 is the **most performing configuration** with no production delays and lowest labour cost

Results

How optimization factors translate to operational Key Performance Indicators?







From more than **60% products late**, R2 and R3 achieve **full-on time delivery**

R3 has a **greater makespan** compared to R2 but **lowest labour cost**

The optimiser introduces new resources but **station utilisation** is always greater than **98.7%**

Final Remarks

Conclusions

OSC job shops productivity
Tend to suffer from cost overruns and constantly delayed deadlines due to poor operations management

Validated human centric optimizer
Parallel Simulated Annealing to dimension workforce and minimize labour cost and production delays

Increased schedule reliability
Slashed production delays from more that 60% to zero with minimal cost increase

Further Research

1. **Stochasticity**
   Capture operator variability, learning effect and reworks

2. **Software Integration**
   Integrate the optimizer into the company software ecosystem

3. **Construction 5.0**
   Model workers physical resilience such as fatigue