Processing Time Optimization for Multi-Robot Systems Using Heuristic Algorithms.

Murad Muradi | 21.11.2020

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

Rolls-Royce
Motor Cars Limited

AGENDA.

1. Introduction.
2. Collision Detection
3. Motion planning
4. Optimization Algorithm
5. Results of experimental evaluation
6. Summary

INTRODUCTION.
1.1 USE-CASE : PVC-SEALING.

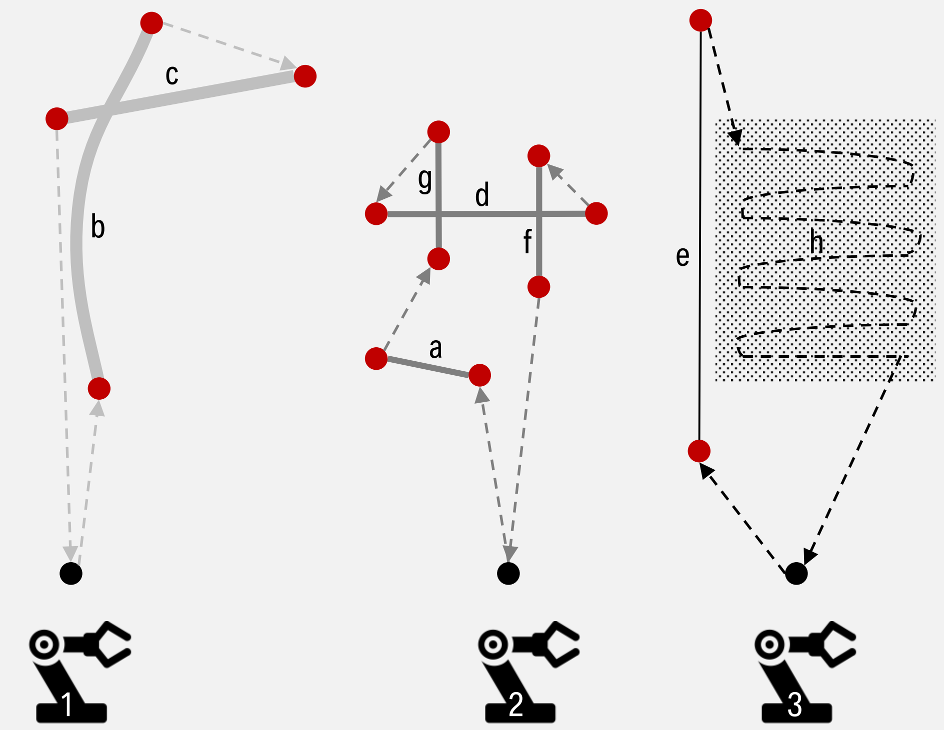
PVC sealing is an important process for:

- Corrosion protection.
- Vehicle tightness.
- Abrasion protection.
- Soundproofing.

INTRODUCTION.
1.2 DEFINITION OF TASK.

Calculate production plan in which all seams are processed within a minimal time span.

Robotic Task



Optimization Tasks

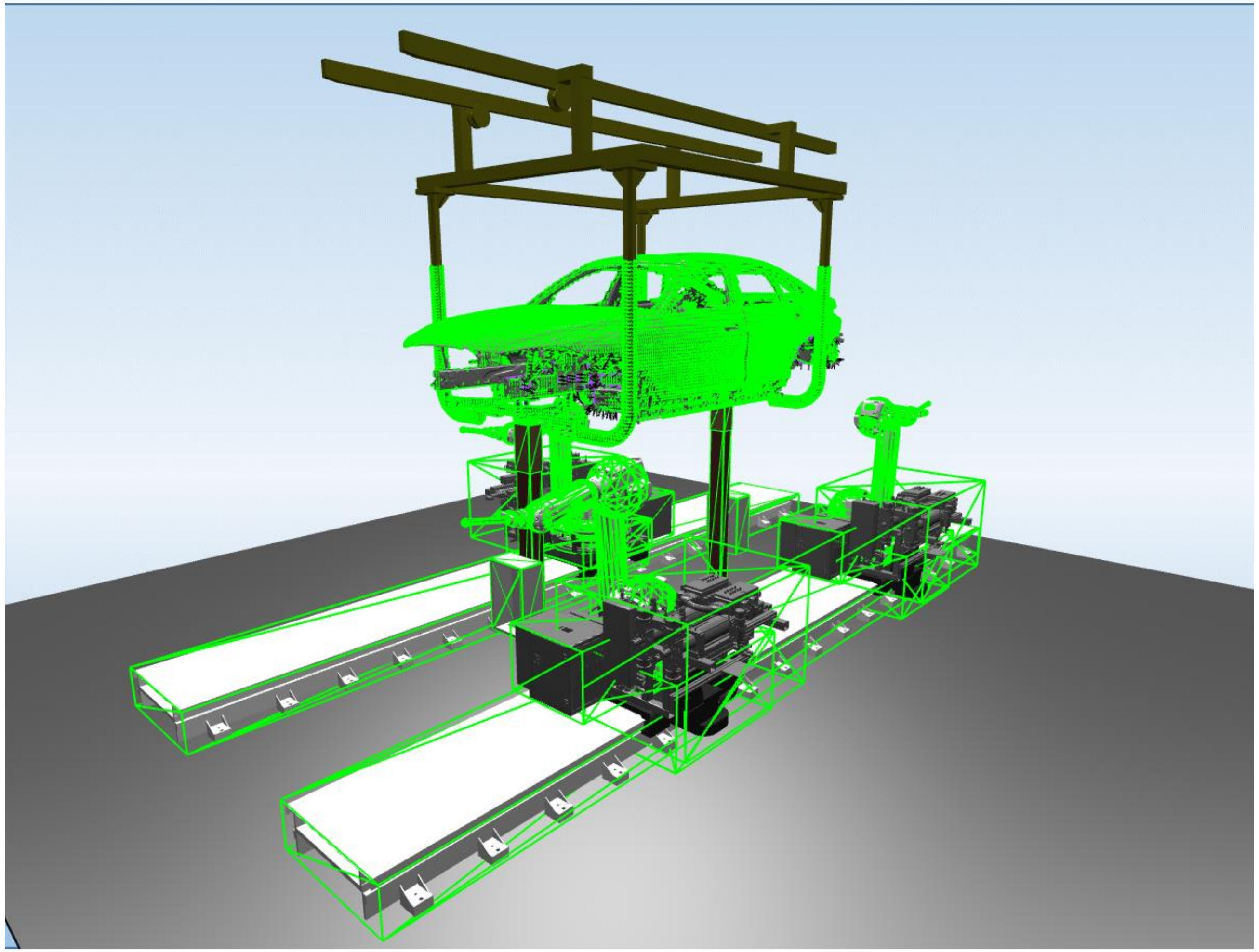
Scheduling:
Efficient allocation of tasks to available robots.

Sequencing and Motion Planning:
Minimizing the routes for all robots and creation of collision-free robot movements.

Goals

- Automatically generation of robot programs.
- Increasing efficiency of existing production facilities.
- Providing key values for manufacturability of new car models in early phases.

INTRODUCTION.
1.3 PROCESS MODELLING.



Robot cell.

- Cell Periphery and conveyor system
- Robots
- Car body

Robot task data.

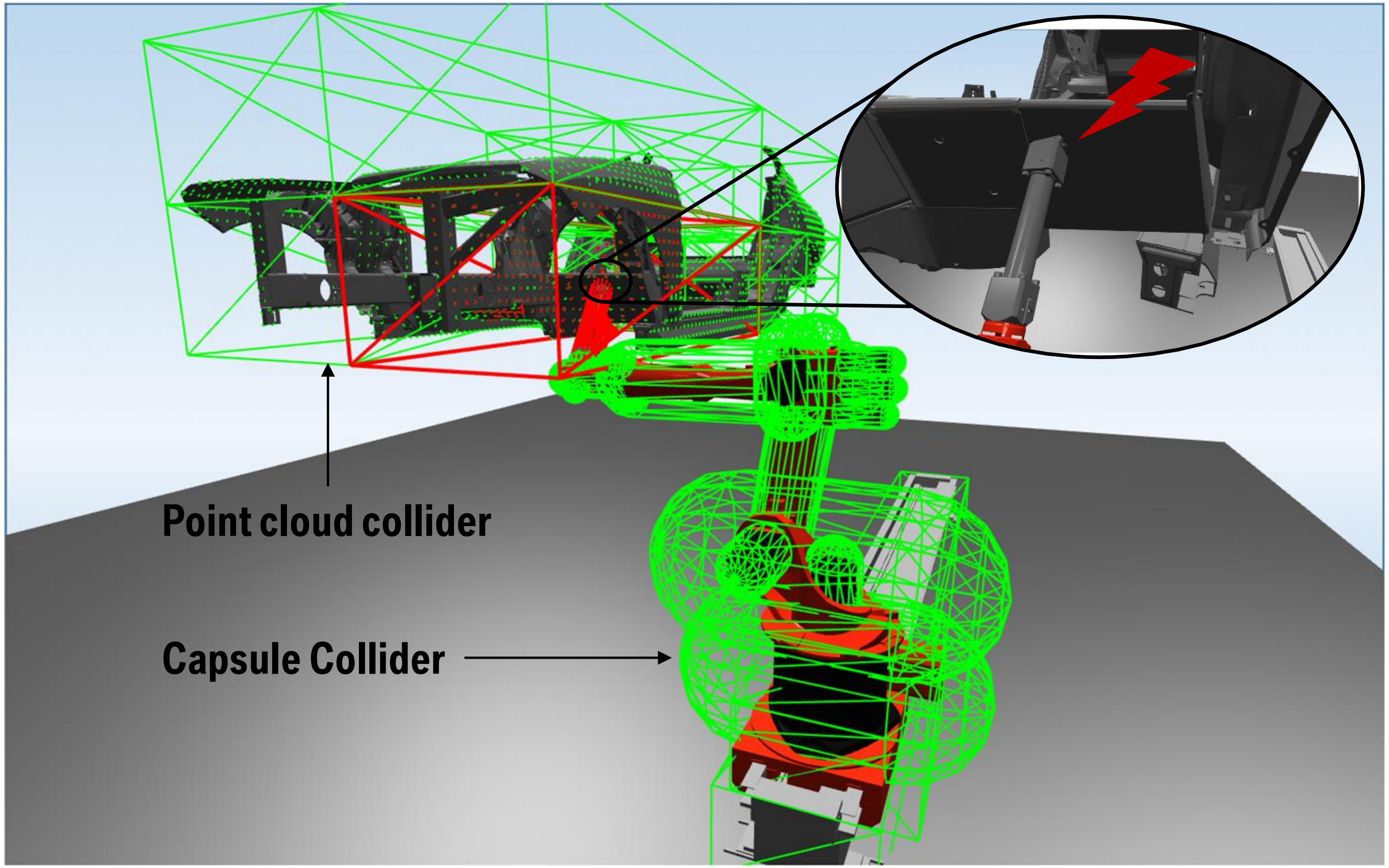
- Seam center line
- Spraying vector

Envelope body.

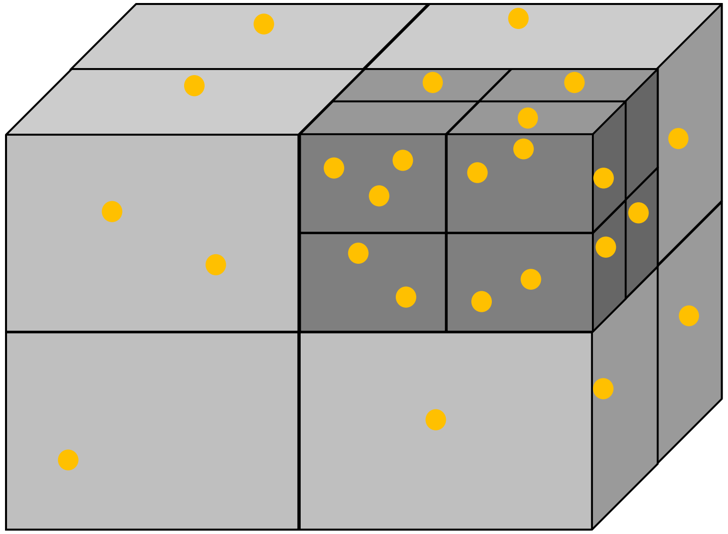
- Box collider
- Capsule collider
- Point cloud collider

02
COLLISION DETECTION.

COLLISION DETECTION.
2.1 COLLISION TEST: ROBOTS VS. CAR BODY.



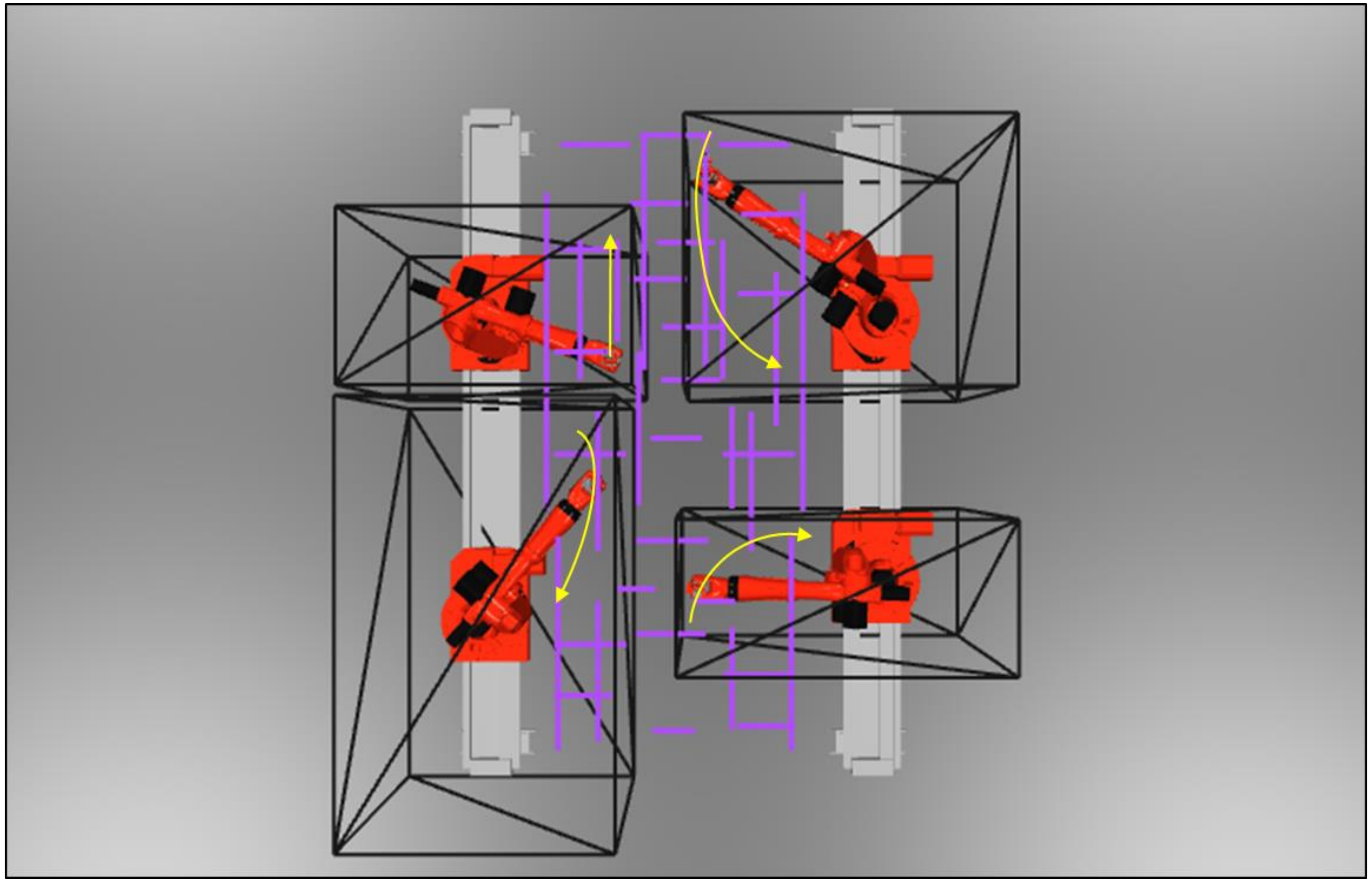
Octree data structure



Two-stage collision test

1. Collision test with all boxes.
2. Collision test with all points of colliding boxes.

COLLISION DETECTION.
2.2 COLLISION TEST: ROBOTS VS. ROBOTS



Collision test

1. Calculate minimum working space for each robot movement.
2. Checking whether the workspaces of the robots intersect at any time.

03
MOTION PLANNING.

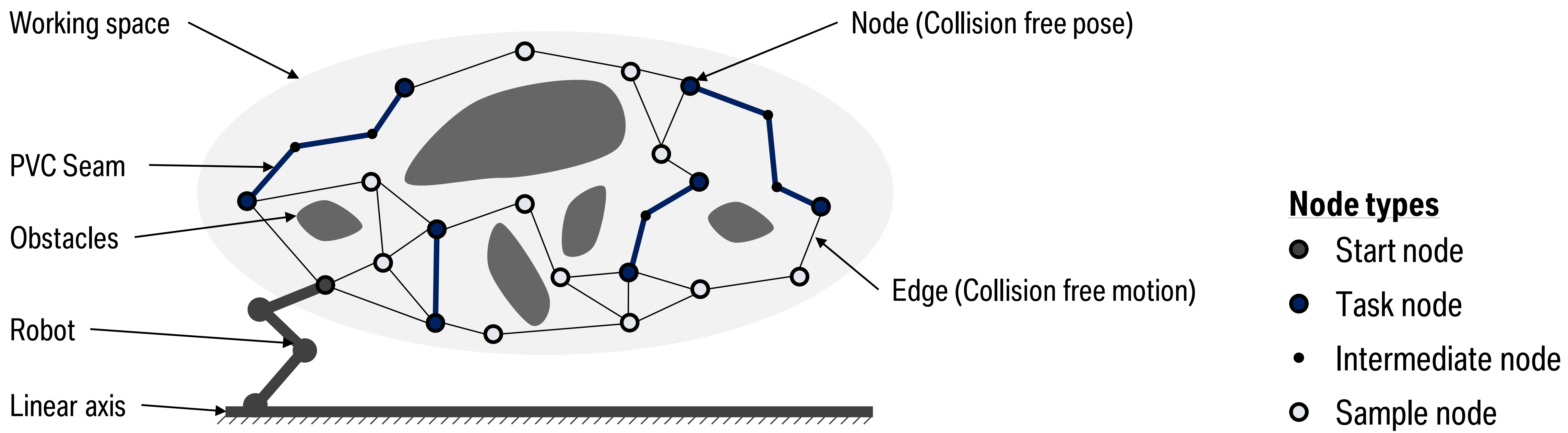
MOTION PLANNING.
3.1 SAMPLE-BASED MOTION PLANNING.

Procedure

- Sampling working space with random and collision free robot poses.
- Linking robot poses to a graph.
- Graph search for motion planning (A* algorithm).

Learn phase

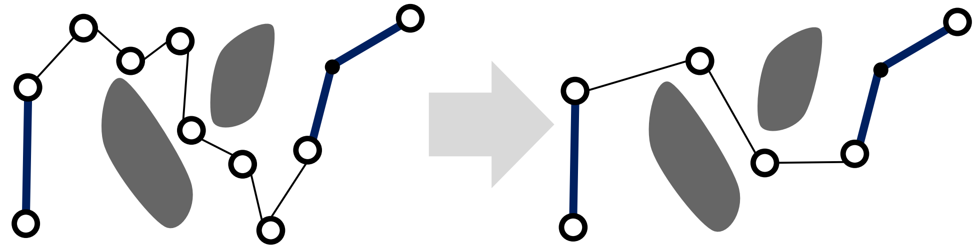
Query phase



MOTION PLANNING.
3.2 PATH OPTIMIZATION.

Procedure:

- Plan path between task nodes.
- Optimize path in post-processing
  - With simulated annealing (SA).
  - Max Span: Directly moving to the next backmost reachable node in the path.
- Store path information in table format.



Start node $[l\ s\ t\ e\ d\ c]$	Goal node $[l\ s\ t\ e\ d\ c]$	Motion duration in sec.	Collision information
…	…	…	…

- The first and second column contain the nodes to be connected.
- The third column shows the corresponding movement time.
- The last column contains further information for checking the freedom of collisions between the different robots.

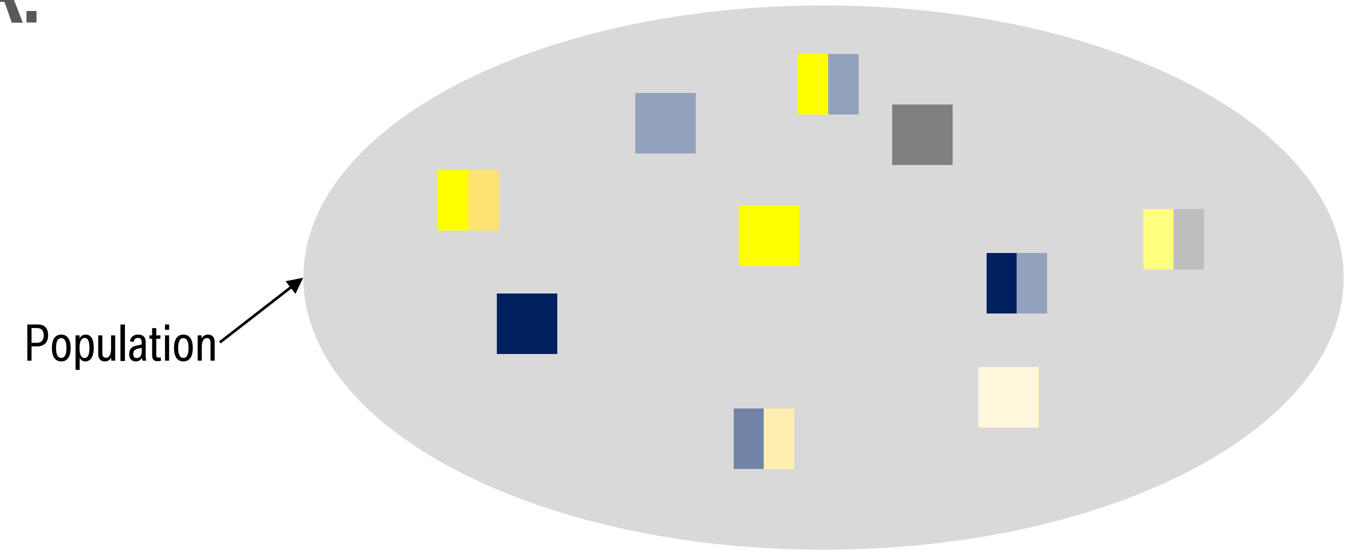
→ The problem can be described as an abstract multiple debot multiple traveling salesmen problem (MDMTSP).
→ Ensuring applicability of other solvers without much effort for adaptation.

04
OPTIMIZATION ALGORITHM.

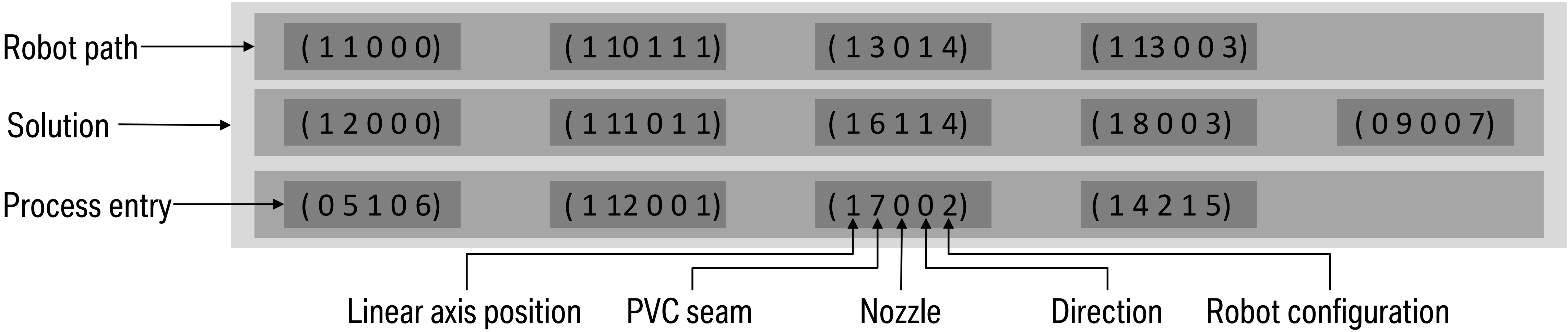
OPTIMIZATION ALGORITHM.
4.1 GENETIC ALGORITHM SOLVER.

Procedure:

- Initialization
- While termination condition not met:
  - Recombination.
  - Mutation.
  - Evaluation.



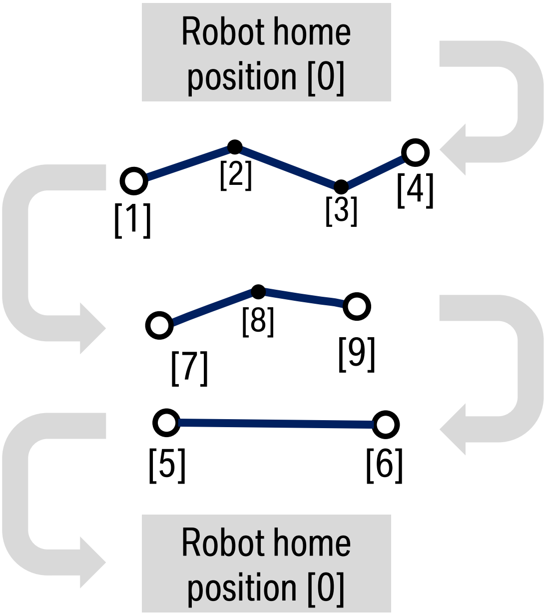
Genotype



OPTIMIZATION ALGORITHM.
4.2 INITIALIZATION OF POPULATION.

Creation of robot path by selecting random node from the incidence list associated to a yet unprocessed seam.

Robot path (example with 3 seams)

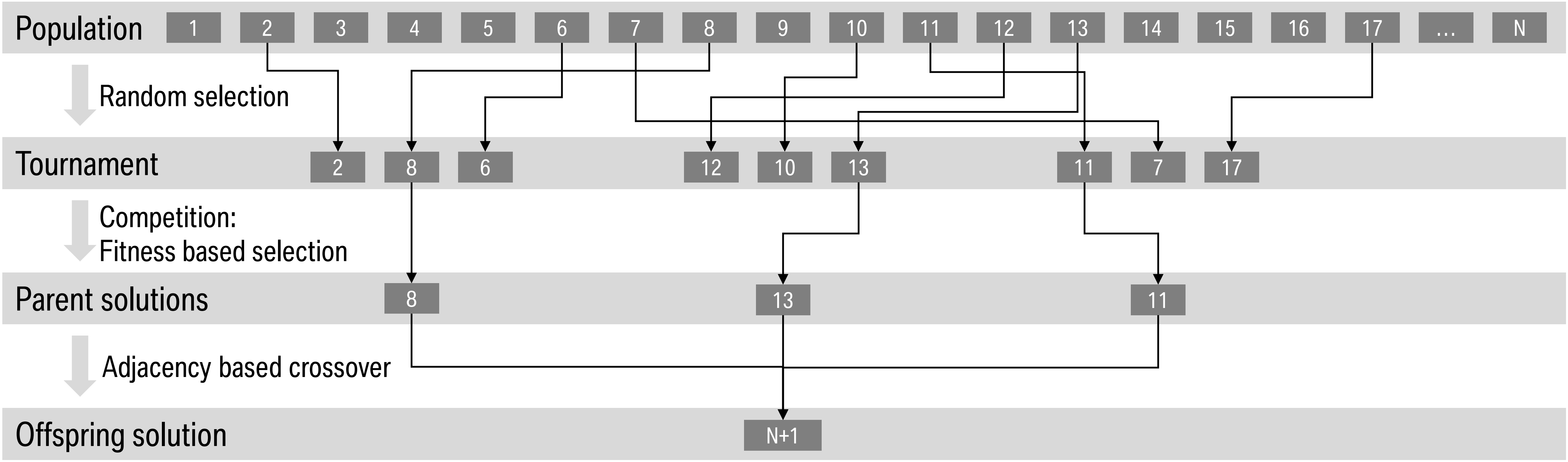


Incidence list

Node	Reachable adjacent nodes
0	1, 4, 5, 6
1	0, 4, 7, 9
4	0, 1, 7, 9
5	0, 6, 7
6	0, 5, 9
7	1, 4, 5, 9
9	1, 4, 7, 6

- Resulting path: [0]→[4]→[3]→[2]→[1]→[7] →[8] →[9] →[5] →[6] →[0]
- Join robot paths of one robot cell together to form a solution.
- Build entire population with solutions.

OPTIMIZATION ALGORITHM.
4.3 RECOMBINATION.



Adjacency based crossover (Multi-parent recombination method):

- Next entry in offspring's robot path is based on the successor entries of the current entry in the parents' robot paths.
- Repeat whole process with different parents if procedure leads to a dead end.
- Seam allocation of best parent solution is applied to offspring solution.

→ Best parts of parent solutions predominate in the offspring solutions (survival of the fittest).

OPTIMIZATION ALGORITHM.
4.4 SCHEDULING AND LOAD BALANCING.

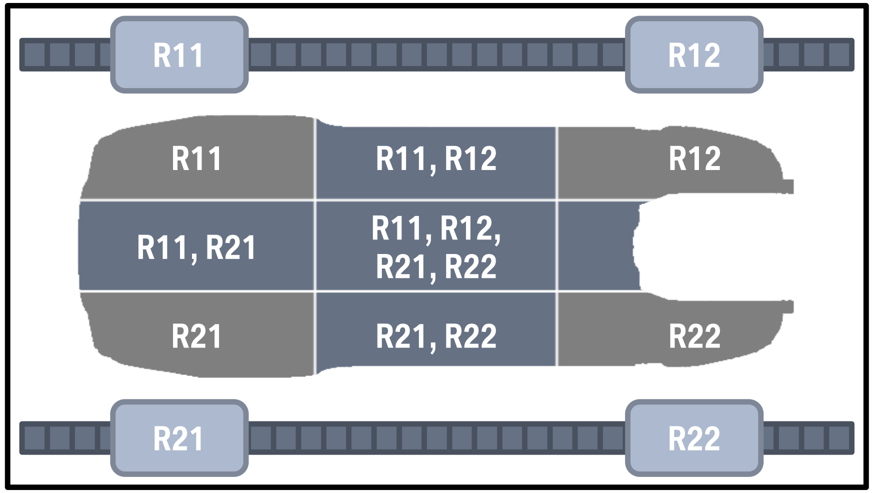
Seam allocation depends on the distance between the base position of the robots and the gravity point of the seams .

$$P_{gravity} = \frac{1}{2} \cdot (P_{Start} + P_{End})$$

Seams are classified in fixed and common seams.

- Fixed seams: Seams in far inside the works pace of one robots.
- Common seams: Seams in the border area of multiple robots.

Common seams are reallocated to the adjacent robots.



Load balancing through reallocation mutation.

– High load robots are more likely to lose a common seam.
– Lower load robots are more likely to be assigned a common seam.

→Balanced work distribution leads to optimal workload for each robot and reduces the total cycle time.

05
RESULTS OF EXPERIMENTAL EVALUATION.

RESULTS OF EXPERIMENTAL EVALUATION.
5.1 PATH QUALITY AND COMPUTING TIME.

Further optimization of initial path of PRM in post-processing :

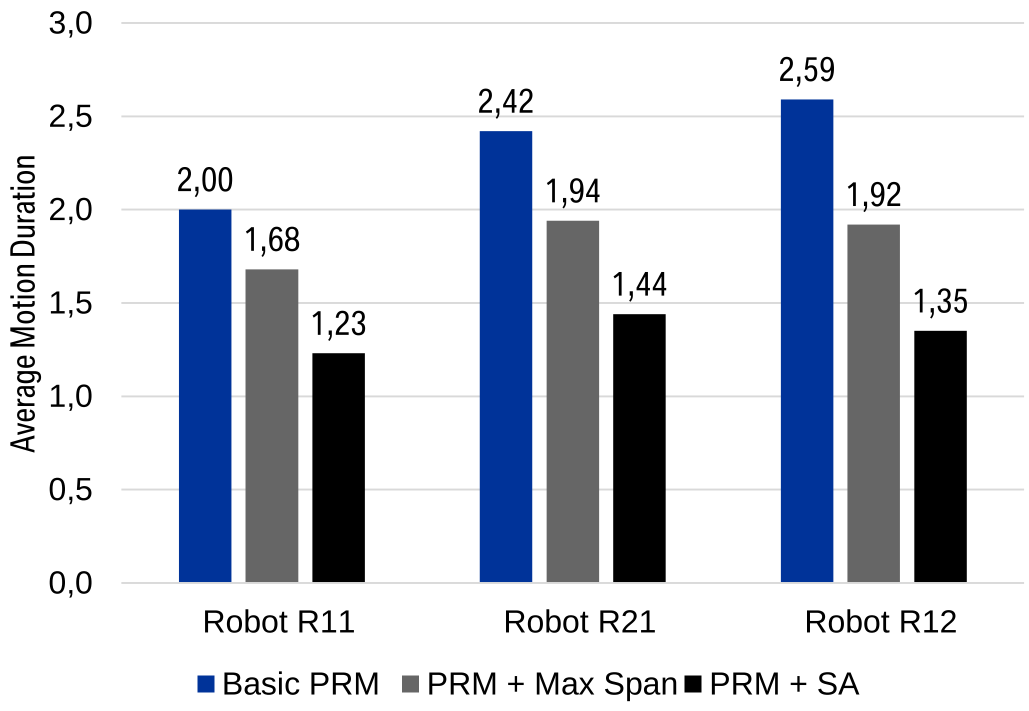
- Max Span: Directly moving to the backmost reachable node in the path and skipping unnecessary nodes in between.
  →Reducing average motion time by 16% to 34%.
- Using SA to modify path by skipping and moving nodes.
  →Reducing average motion time by 39% to 62%.

Post-processing increases computing time to generate motion table.

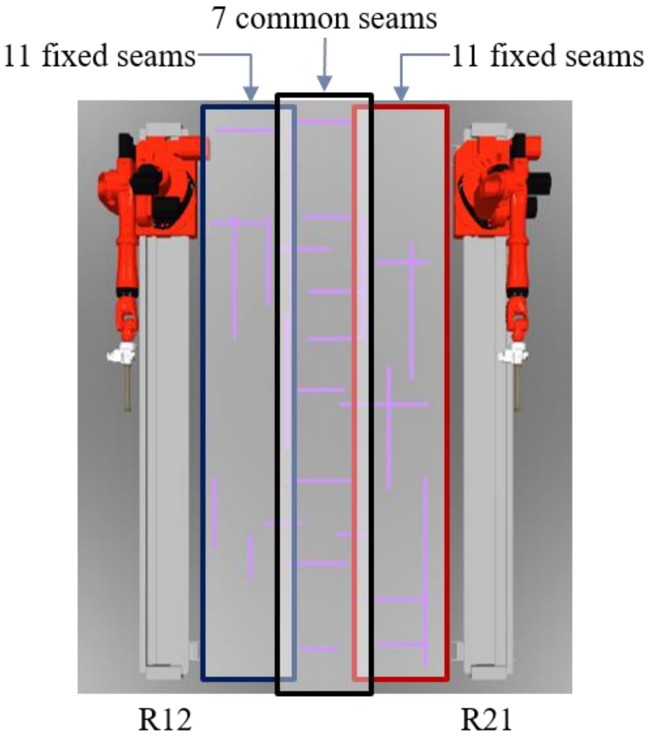
	PRM	PRM + Max Span	PRM + SA
Computing Time	2h	3h	70h

→ For offline robot programming PRM + SA is most suitable.
→ PRM + Max Span is a good compromise between path quality and computing time.

Average duration of robot movements in motion planning graph



RESULTS OF EXPERIMENTAL EVALUATION.
5.2 RESULTS TEST PROBLEM.



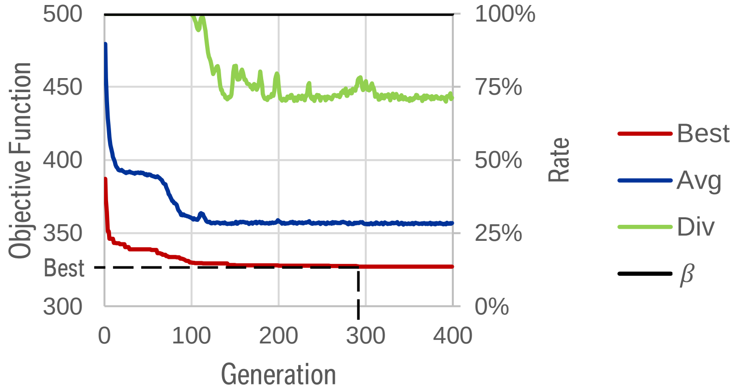
Objective Function:

$$F = w \cdot \max_{r \in R}\{T_r\} + \sum_{r \in R} T_r$$

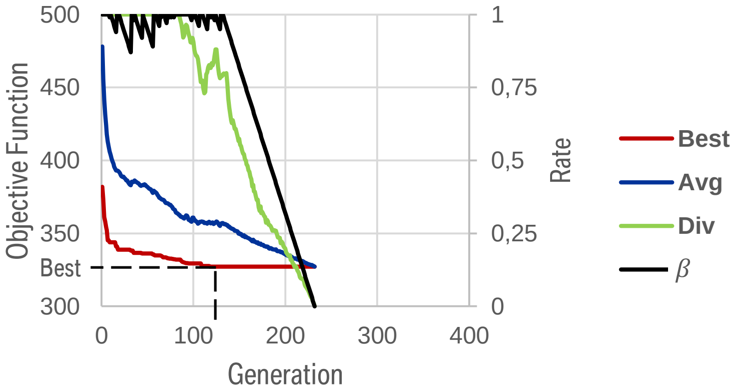
Solver	Computing time	Objective value (w =9)
Exact solver	25.85 h	327.15
Heuristic solver	11.36 h	327.15

- Exact solver is combination of Held-Karp algorithm and branch-and-bound algorithm.
- Heuristic solver is able to find optimal solution.
- Computing time of heuristic solver is 56% less compared to the exact solver.

Constant scaling factor for mutation $\beta = 1$



Adaptive scaling factor for mutation $\beta = 1 - \frac{g}{G}$

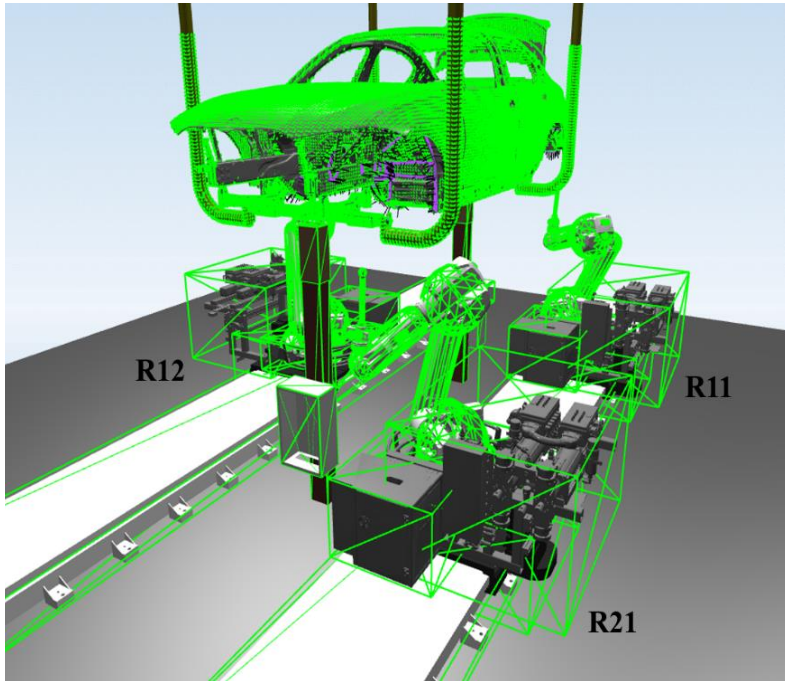


- G: Max. number of generations without improvement.
- g: Counter for generations without improvement.

→ Adaptive scaling factor for mutation β improves convergence behavior of heuristic.
→ Number of generations to find optimal solution is reduced from 299 to 132 by 56%.

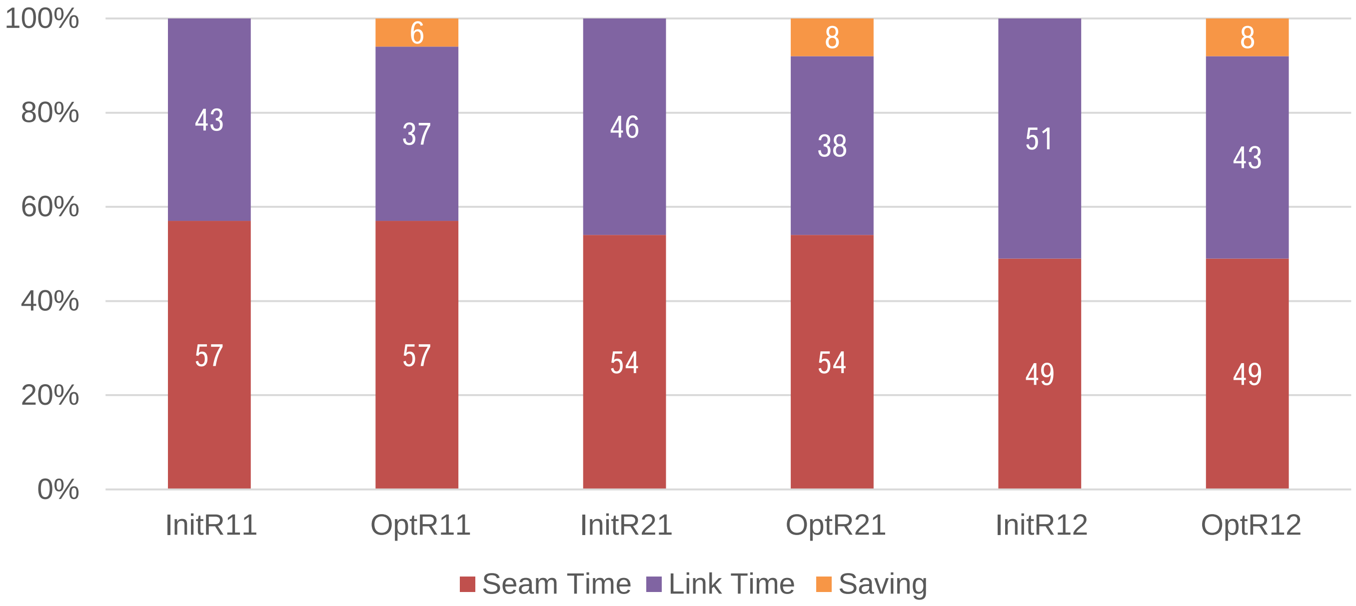
RESULTS OF EXPERIMENTAL EVALUATION.
5.3 RESULTS BUSINESS PROBLEM.

Practical application



- Cell with three robots.
- Car body with over 150 PVC-seams.
- Application tool with three nozzles.

Initial and optimized processing time (normalized)

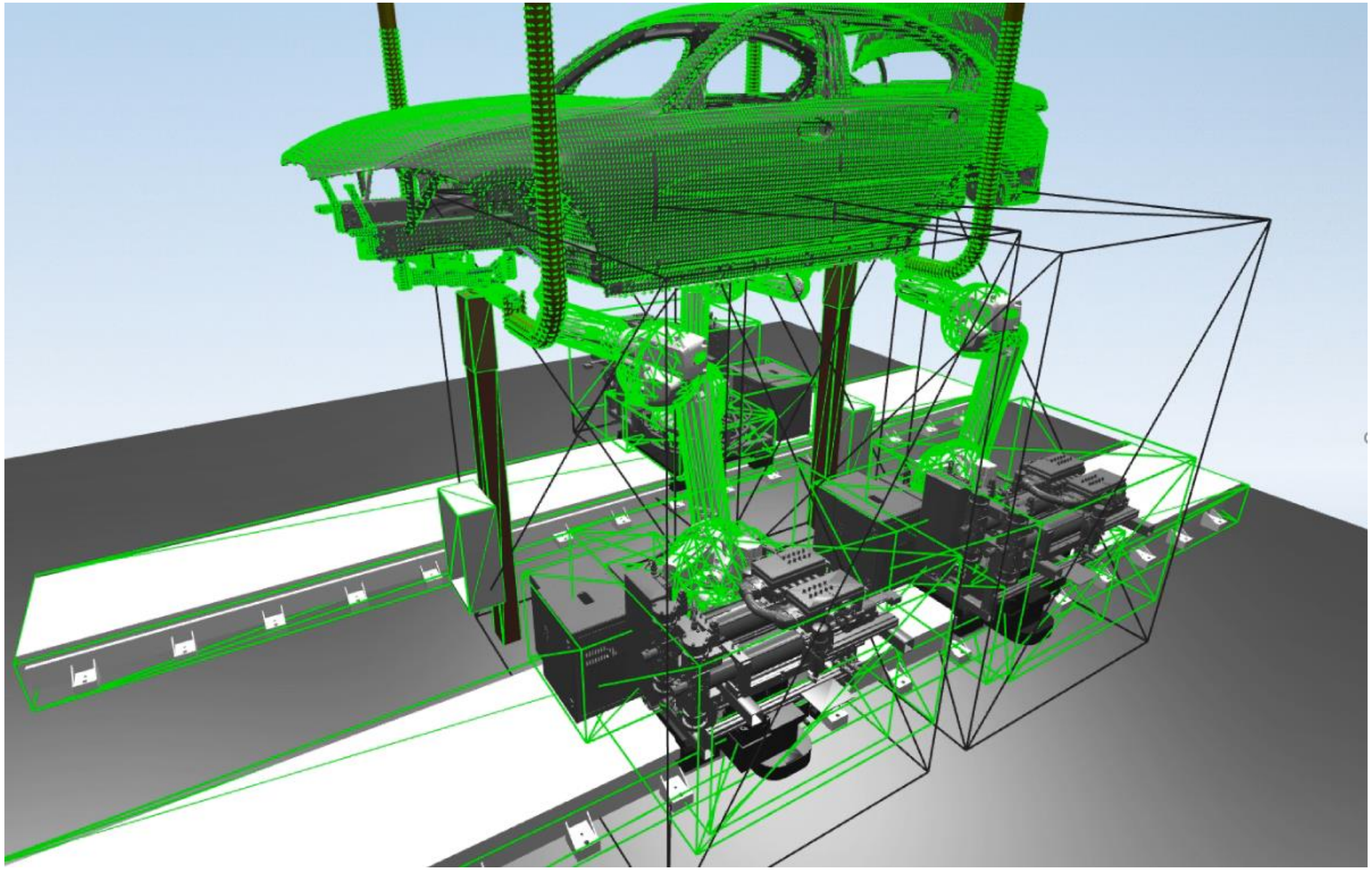


Processing time are broken down into:

- Value-adding part (Seam Time).
- Non-value-adding part (Link Time).
- Through optimization Link Time of robots could be reduced by up to 17%.

06
SUMMARY.

SUMMARY.
PREVIEW OF OPTIMIZATION FRAMEWORK.

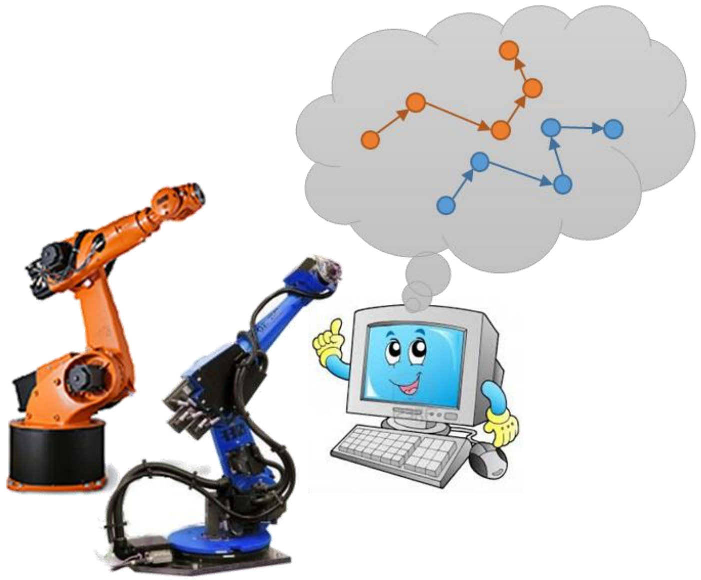


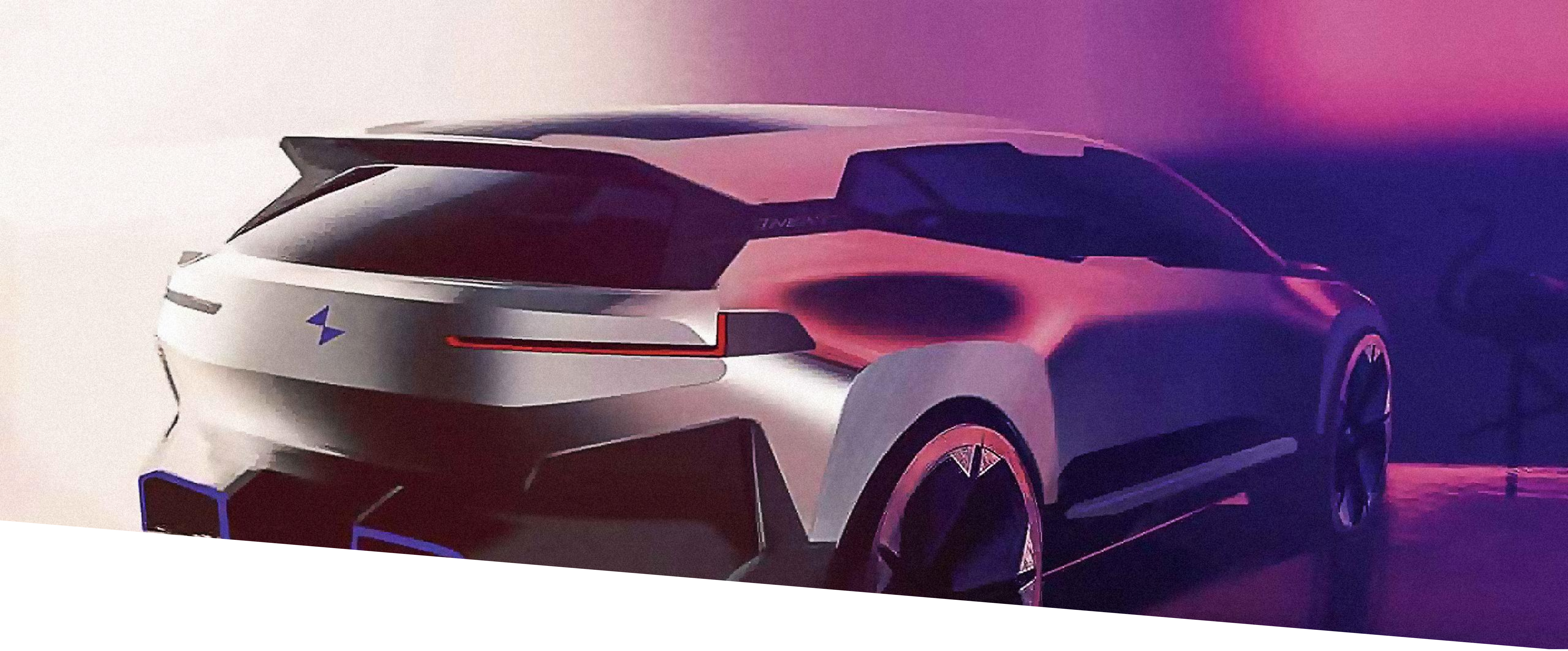
Steps for automatic robot program optimization and generation:

- Sampling robot workspace with nodes.
- Connecting adjacent nodes with edges.
- Optimization with genetic algorithm.
- Unique workspaces for collision avoidance between robots.
- Different collider types for fast and accurate collision detection between robot and car body.

SUMMARY.

- PVC-sealing is a complex process for the tightness and corrosion resistance of the car body.
- Fast and accurate collision detection with suitable collider pairs.
- Using PRM-based motion planning algorithm to generate collision free path between PVC seams.
- Further optimization of path in post-processing to generate short and smooth robot motions.
- Implementation of a genetic algorithm for process optimization and load balancing.
- Successfully application of methodology on real business problem.
  → Reduction of non-value-adding part of processing time by up to 17%.





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