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ProSeqqo: A Generic Solver for Process Planning and Sequencing in Industrial Robotics

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EPIC Robotics Training Part 1
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SZTAKI Fraunhofer

Motivation

Sequence planning as a common problem in industry

Known mathematical representations and solutions

- Individually developed solutions
- Frequently changing products, production lines
- Dynamically changing tasks
- Sequencing connected to selection of execution mode (e.g. robot configurations)
- Technology-specific aspects
- Geometric aspects

- Similar mathematical basics
- Traveller Salesman Problem (TSP)
- Vehicle routing problem (VRP)
- Extensions and versions of the above
- Effective solution procedures

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Agenda

- Examples from literature
- Mathematical models
- Illustrative example
- Problem representation
- Solution approach
- Implementation
- Case studies

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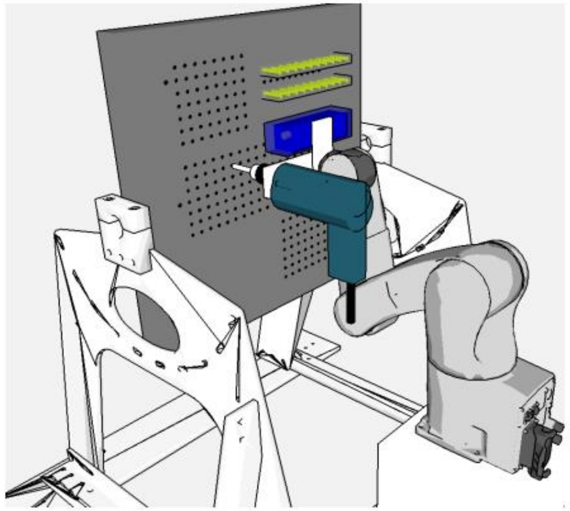
Example from literature: robotic drilling



- Application: robotic drilling
- Problem model
  - Decisions: task sequencing + selection of IK solution
  - Objective: minimal distance (Euclidean task space)

- Mathematical model: GTSP – Generalized Travelling Salesman Problem
- Algorithm
  - Sequencing in task space using different TSP solvers (exact in SCIP, 2-opt, RNN)
  - Selection of IK solutions via graph shortest path
  - (Collision-free path using RRT)

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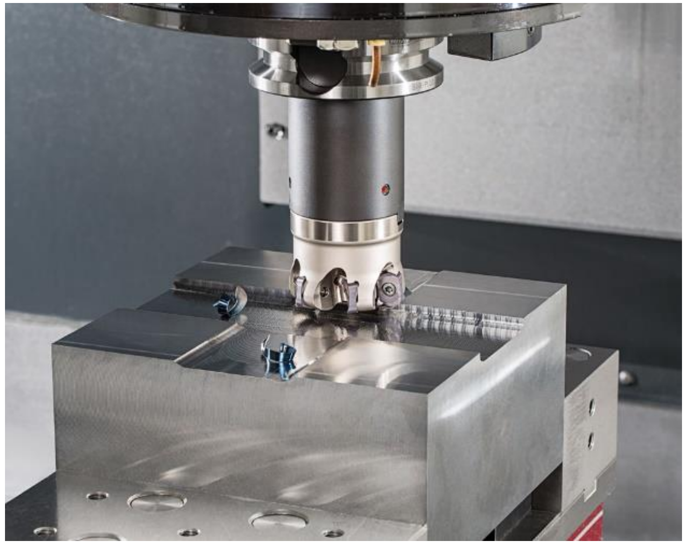
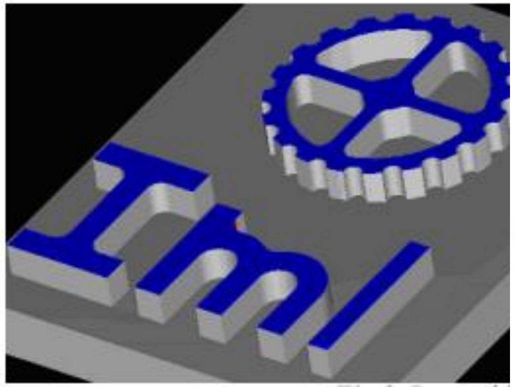
F. Suarez, T. Lembono, Q. C. Pham
RoboTSP – a fast solution to the robotic task sequencing problem,
2018 IEEE International Conference on Robotics and Automation (ICRA), 2018, pp. 1611–1616.

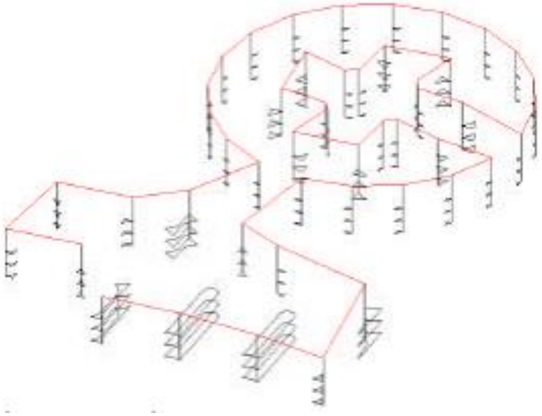
Example from literature: machining

- Application: machining
- Problem model
  - Decisions: task sequencing + selection of contour entry / exit points
  - Side constraints: precedences (embedded contours)
  - Objective: minimal cycle time



- Mathematical model: PCGTSP – Precedence-constrained GTSP
- Algorithm
  - Conversion into TSP (no precedences) or SOP (precedences)
  - TSP or SOP heuristics





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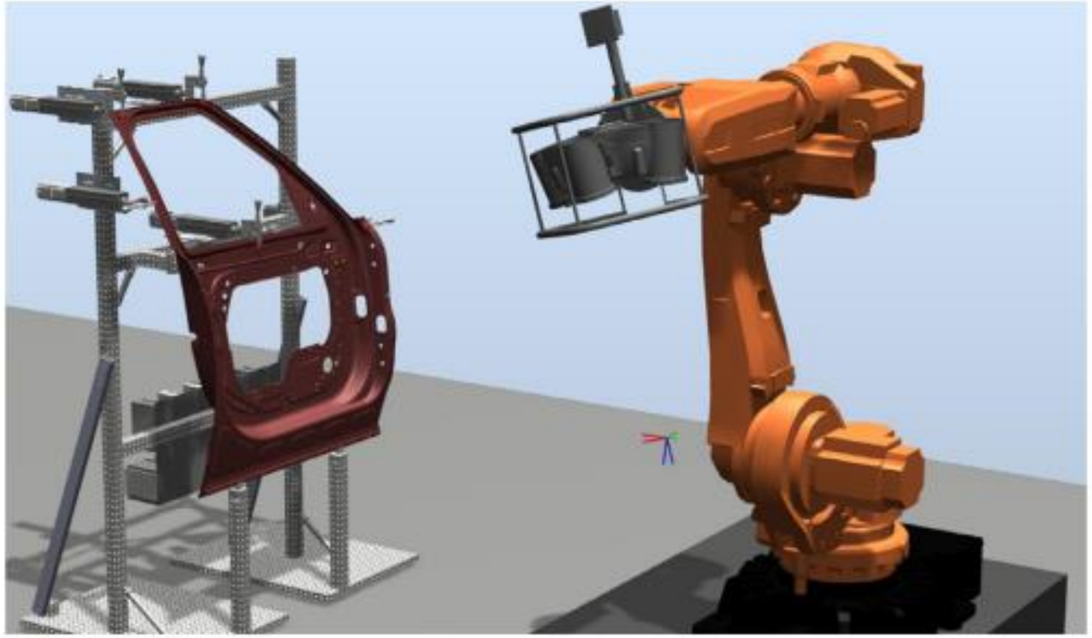
K. Castelino, R. D'Souza, P. K. Wright,
Toolpath optimization for minimizing airtime during machining,
Journal of Manufacturing Systems 22 (3) (2003) 173–180.

Example from literature: robotic inspection

- Application: robotic inspection
- Problem model
  - Decisions: task sequencing + selection of viewpoint and IK solution
  - Objective: minimal cycle time
- Mathematical model: GTSP – Generalized TSP
- Algorithm: heuristics



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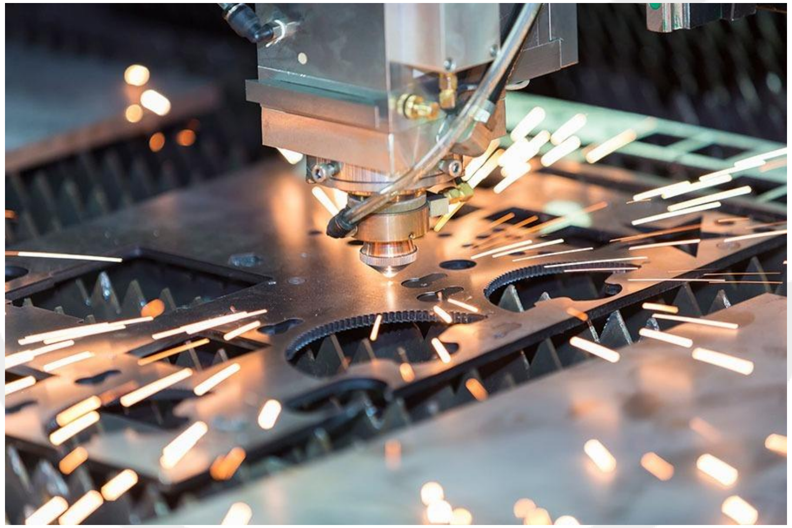
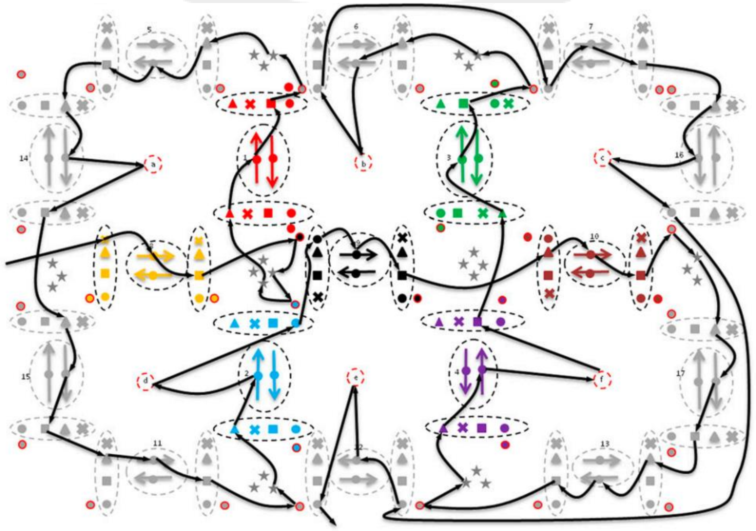
E. Glorieux, P. Franciosa, D. Ceglarek,
Coverage path planning with targeted viewpoint sampling for robotic free-form surface inspection,
Robotics and Computer-Integrated Manufacturing 61 (2020) 101843.

Example from literature: laser cutting



- Application: laser cutting
- Problem model
  - Decisions: task sequencing + selection of cut directions
  - Side constraints: precedences
  - Objective: minimal cycle time
  - Detailed process model, e.g. piercing, pre-cut placing, sharp angles etc.

- Mathematical model: PCGTSP – Precedence-constrained GTSP
- Algorithm: Construction heuristics



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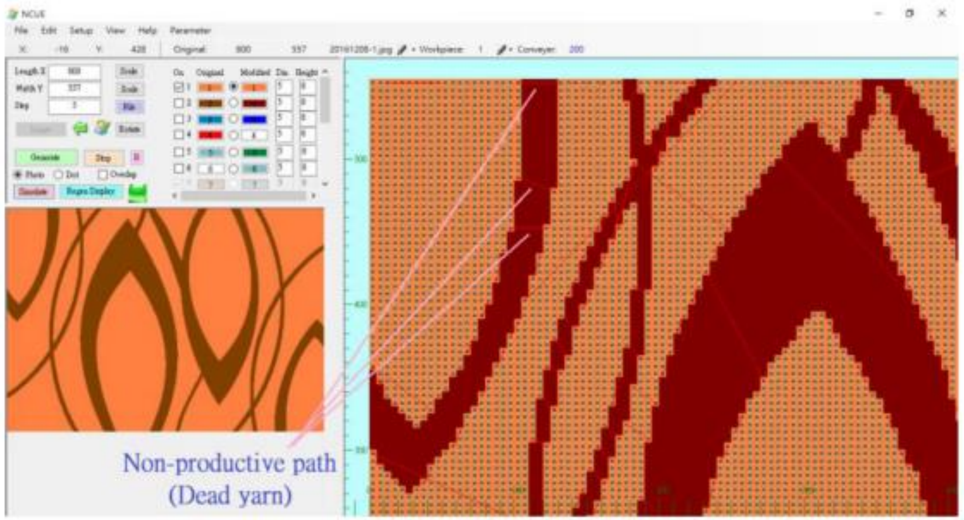
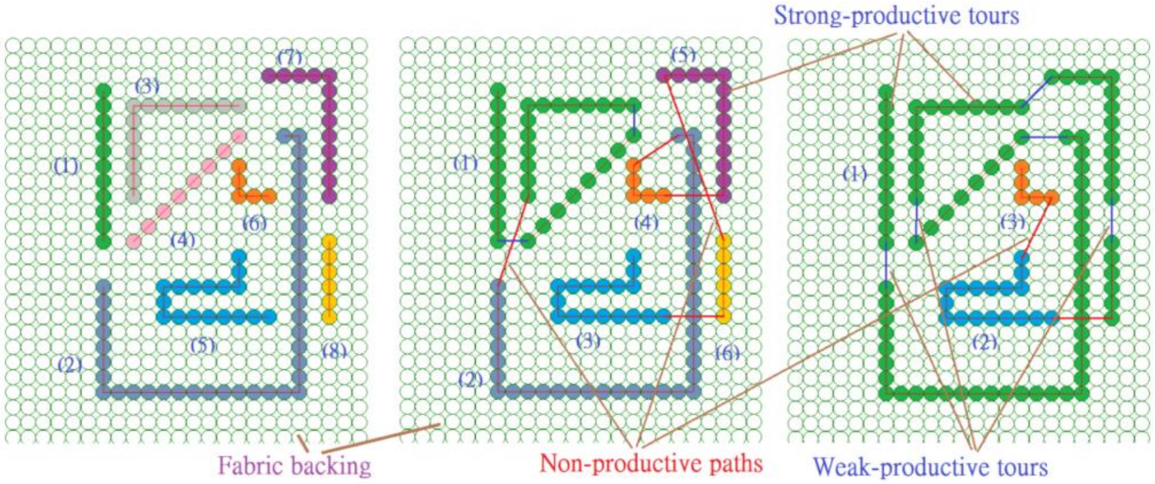
R. Dewil, P. Vansteenwegen, D. Cattrysse,
Construction heuristics for generating tool paths for laser cutters,
International Journal of Production Research 52 (20) (2014) 5965–5984.

Example from literature: carpet tufting

- Application: carpet tufting
- Problem model:
    - Decisions: task sequencing (tuft sequencing)
    - Objective: min. cycle time (tufting, positioning, and needle switching times)



- Mathematical model: TSP
- Algorithm: genetic algorithm



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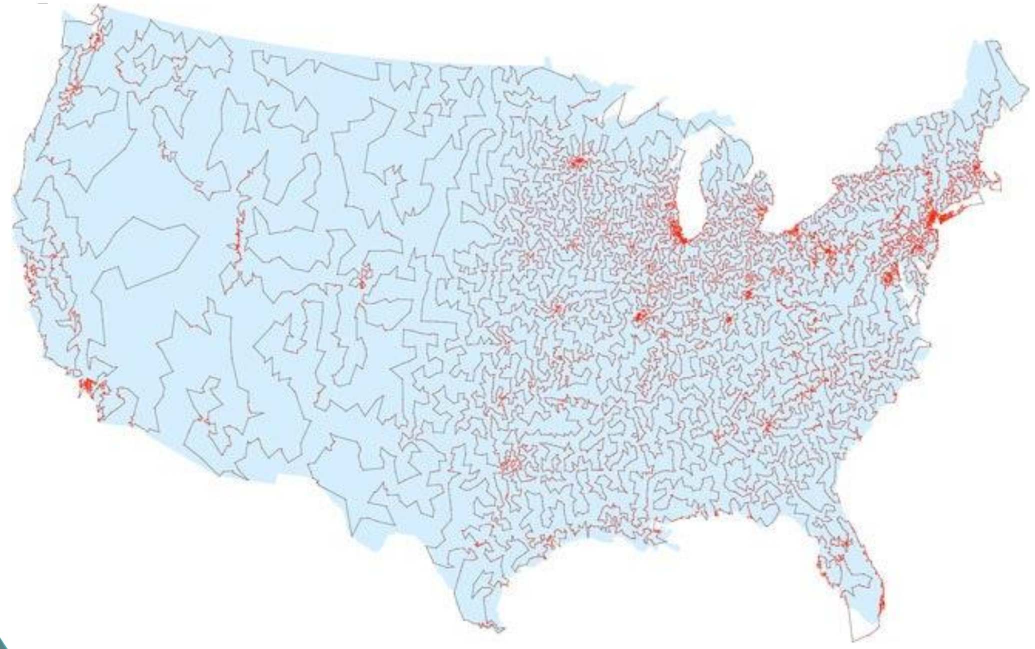
Y.-L. Lai, P.-C. Shen, C.-C. Liao, T.-L. Luo,
Methodology to optimize dead yarn and tufting time for a high-performance CNC by heuristic and genetic approach,
Robotics and Computer-Integrated Manufacturing 56 (2019) 157–177.

Mathematical models: TSP

- TSP – Travelling Salesman Problem
- "Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?„
- $G(V, E, W)$

  $V = \{v_1, v_2, \dots, v_n\}$ $\mathrm{E} = \{e_{1,1}, \dots, e_{ij}, \dots, e_{n,n}\}$

  $\mathrm{W} = \{w_{1,1}, \dots, w_{ij}, \dots, w_{n,n}\}$
- Minimum weight Hamiltonian cycle
- NP-hard problem
- Variant with precedence constraints:
  - SOP – Sequential Ordering Problem



Salesman in the USA

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Mathematical models: TSP

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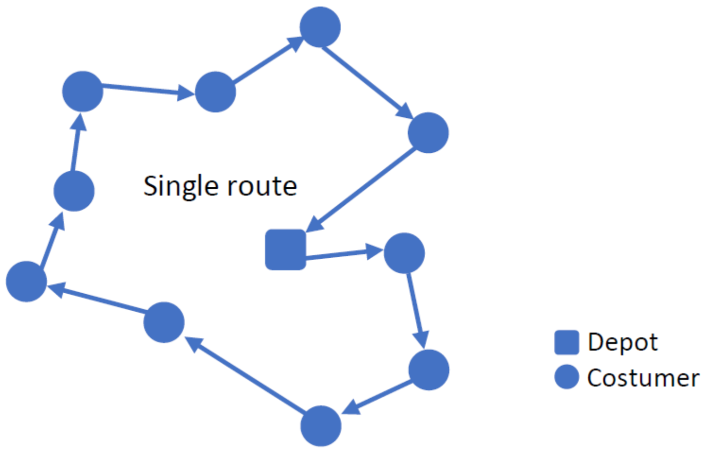

Travelling Salesman Problem

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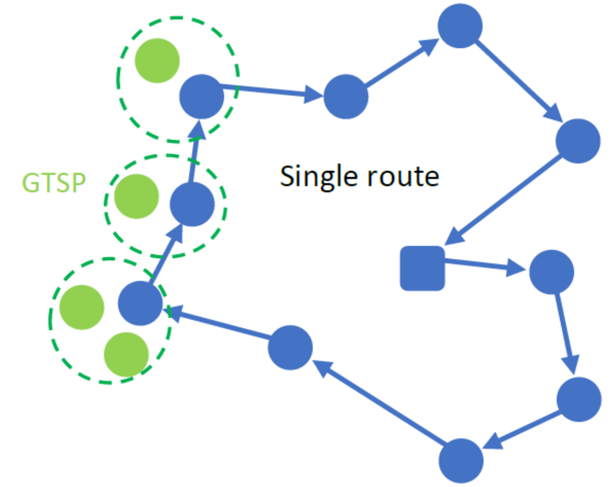
Mathematical models: GTSP

- GTSP – Generalized Travelling Salesman Problem
- "Given a list of cities, assigned to regions, and the distances between each pair of cities, what is the shortest possible route that visits each region exactly once and returns to the origin city?„
- $G(V, E, W, C)$

  $V = \{v_1, v_2, \dots, v_n\}$ $\mathrm{E} = \{e_{1,1}, \dots, e_{ij}, \dots, e_{n,n}\}$

  $\mathrm{W} = \{w_{1,1}, \dots, w_{ij}, \dots, w_{n,n}\}$ $C = \{c_1, \dots, c_2, \dots, c_m\}$
- NP-hard problem
- Variant with precedence constraints between regions:
  - PCGTSP – Precedence-constrained GTSP



Generalized Travelling Salesman Problem

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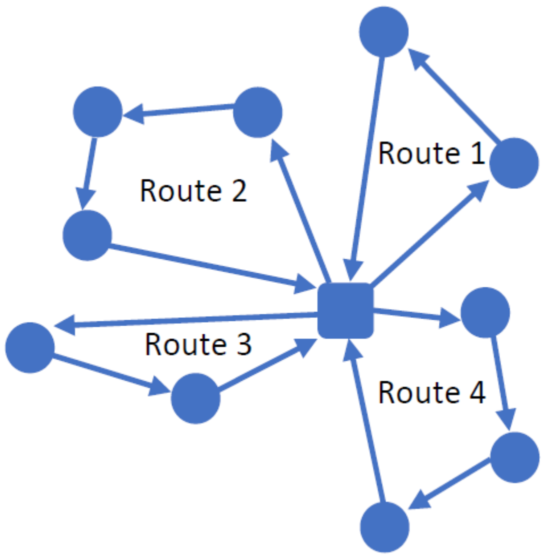
Mathematical models: VRP



Vehicle Routing Problem

- VRP – Vehicle Routing Problem
- "What is the optimal set of routes for a fleet of vehicles to traverse in order to deliver to a given set of customers?"
- $G(V, E, W)$

  $V = \{v_1, v_2, \ldots, v_n\}$ $\mathrm{E} = \{e_{1,1}, \ldots, e_{ij}, \ldots, e_{n,n}\}$

  $\mathrm{W} = \{w_{1,1}, \ldots, w_{ij}, \ldots, w_{n,n}\}$ k – Number of vehicles
- NP-hard Problem
- DHL - Greenplan algorithm exceeds efficiency of existing planning tools and saves up to 20 per cent costs.

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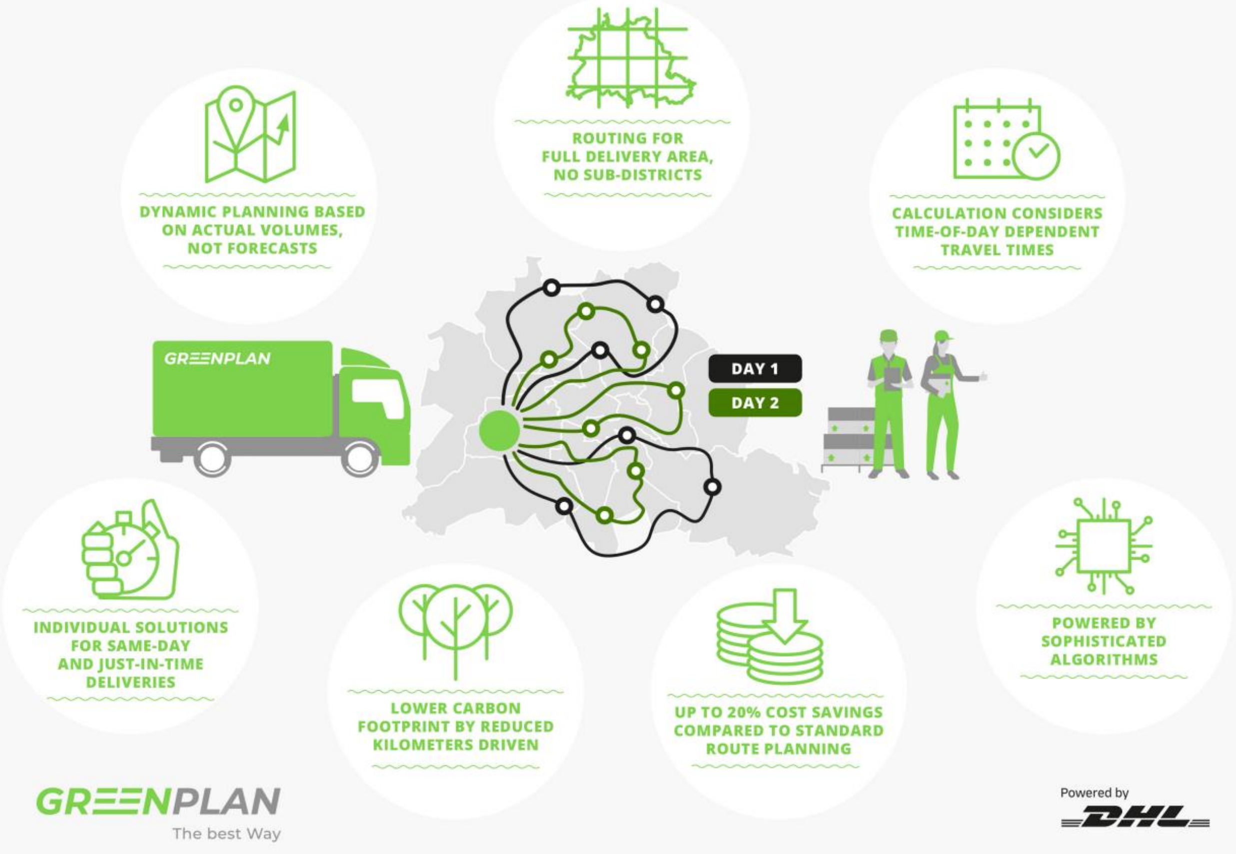
Mathematical models: VRP



- VRP – Vehicle Routing Problem
- "What is the optimal set of routes for a fleet of vehicles to traverse in order to deliver to a given set of customers?“
- $G(V, E, W)$
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ProSeqqo:
- General representation
- Design in task space and joint space, in any dimension
- Consideration of side constraints (e.g. precedences), resources
- Managing alternatives
- Near-optimal plans
- Calculation time suitable for online planning
- Integration, server service

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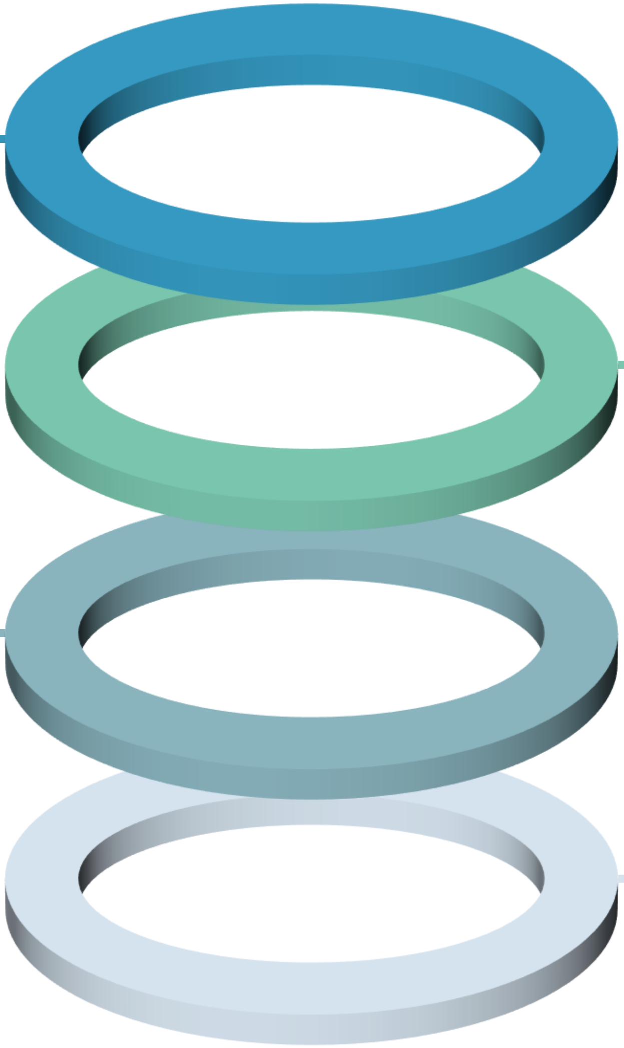
Solution approach



Problem description
Easy-to-use description language,
manageable by industrial specialists

Mathematical model
Generalized TSP (GTSP)
One node has to be selected in a class

Custom algorithms
Compact GTSP representation,
handling precedence constraints

Google OR-Tools
Open-source solver, C++ implementation,
several interfaces, VRP and MIP solver

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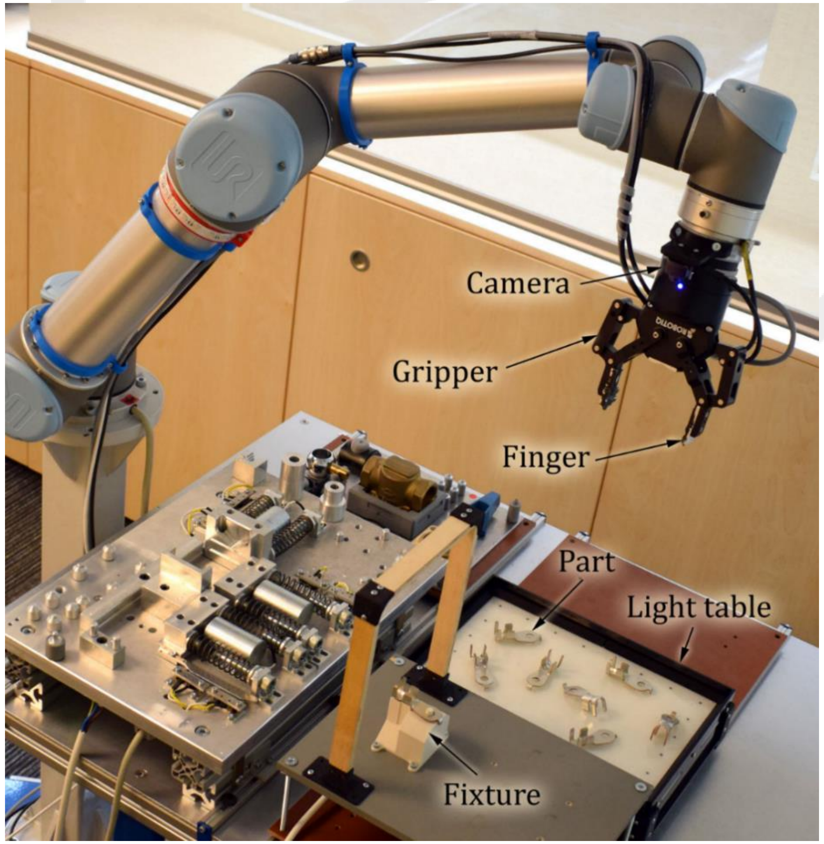
Case study: camera-based pick-and-place

- **Challenge:** Handling of parts arriving in bulk to the input points of an automated manufacturing system
- **Process**:
  - Parts on the lighting table
  - Localization via camera image
  - Grasp planning
  - **Sequence planning**
  - Path planning
  - Take the parts one by one
- **Goal**:
  - Plan the task process sequence
  - Select grasps and IK solutions
  - Close-to-optimal plan
  - Online planning



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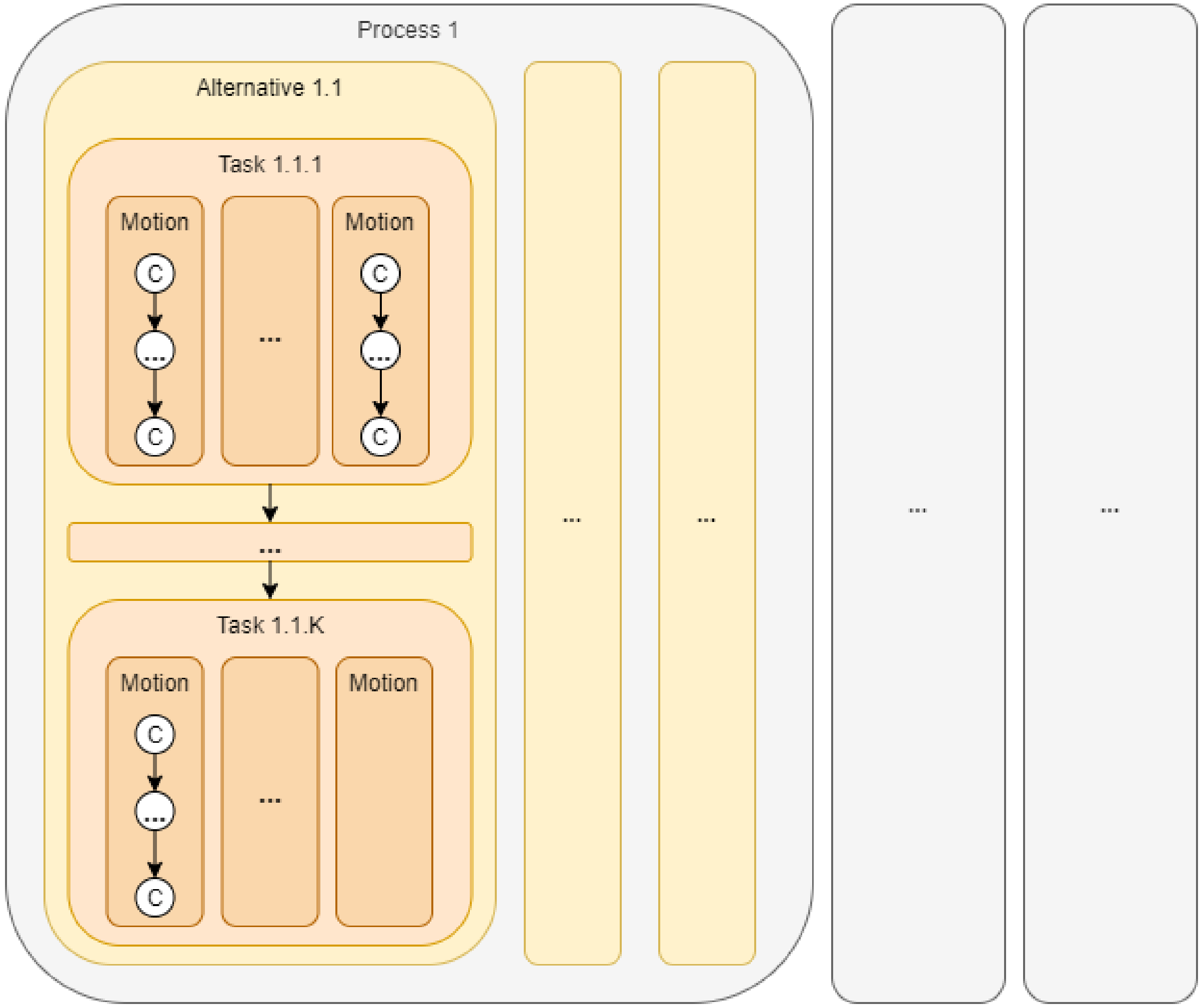
Bence Tipary and Gábor Erdős.
Generic development methodology for flexible robotic pick-and-place work cells based on Digital Twin
Robotics and Computer-Integrated Manufacturing, 2021.

Problem representation

Five-level hierarchical representation

- Process
  - Every process must be sequenced & executed
  - P&P: complete handling of a part + taking camera image
- Alternative
  - Alternative ways of executing a process, choose one
  - P&P: grasps for a given part
- Task
  - Given sequence of tasks in each alternative
  - P&P: picking task, placing task
- Motion
  - Alternative ways of executing a task, choose one
  - P&P: IK solutions for a given picking/ placing task
- Configuration
  - Sequence of locations visited during a motion
  - P&P: single configuration in 6D robot configuration space



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Problem representation

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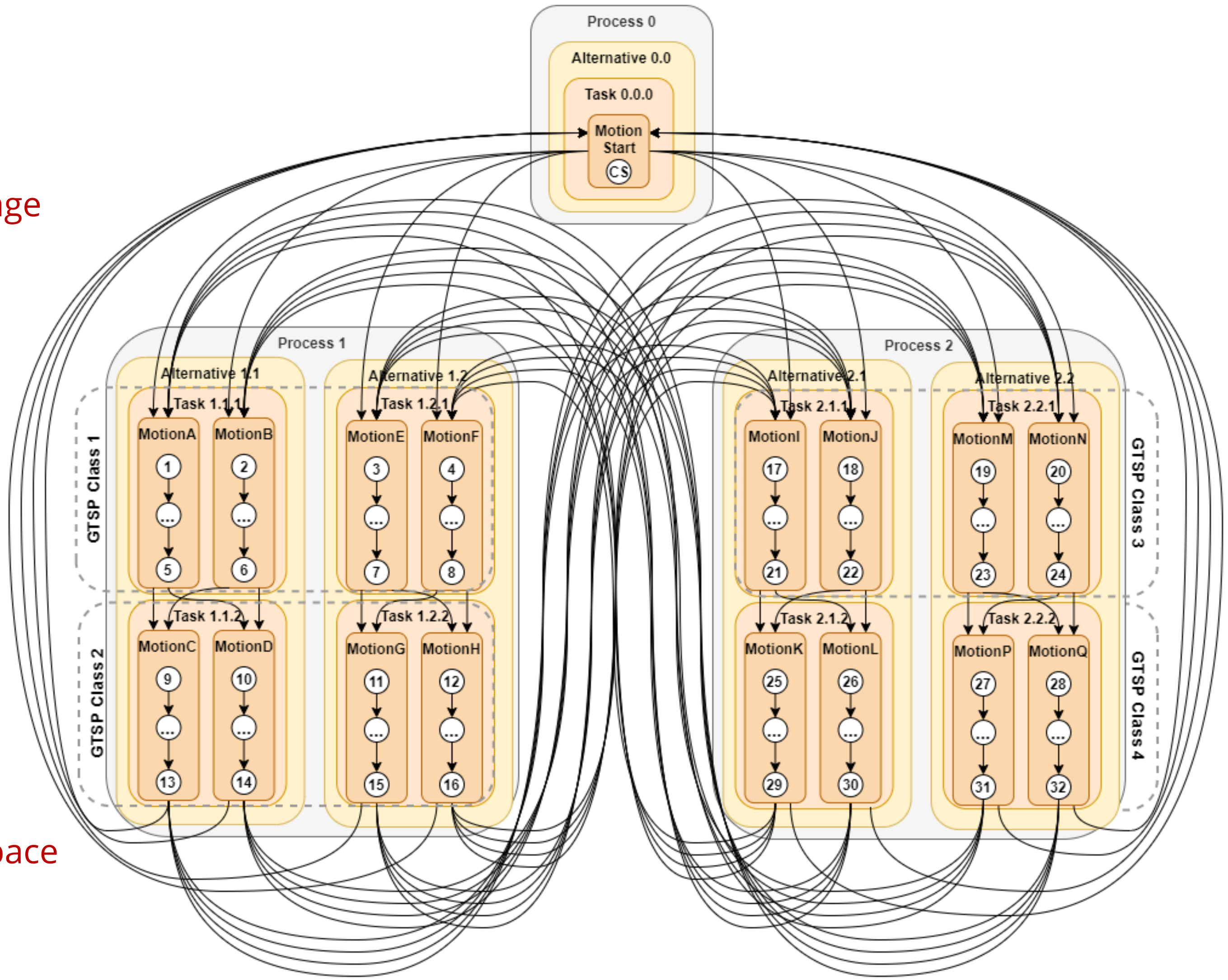

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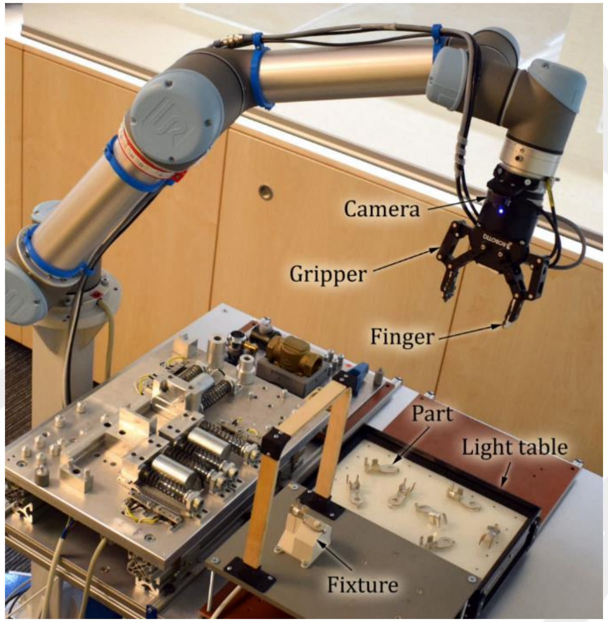
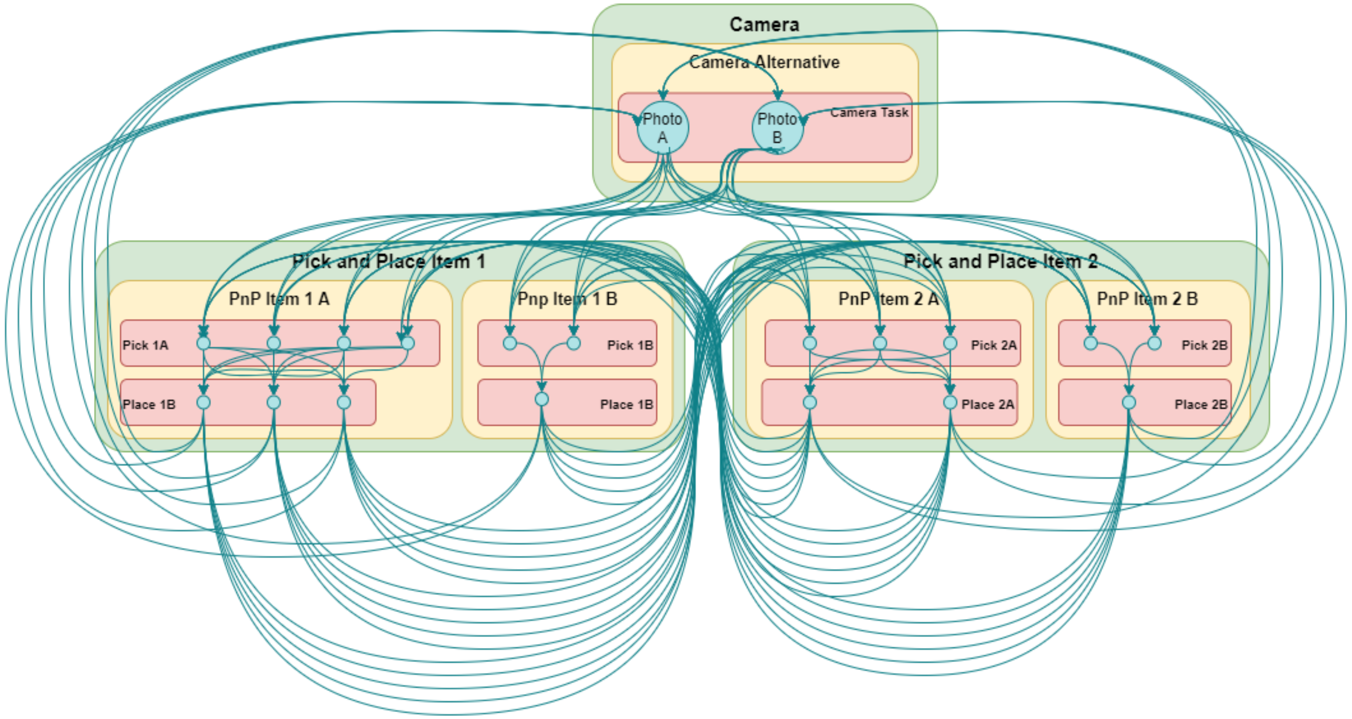
Problem representation – Example

Camera-based pick-and-place

- Process
  - Complete handling of a part
- Alternative
  - Grasping mode for a part
- Task
  - One picking and one placing task per alternative
- Motion
  - IK solution for executing a task
- Configuration
  - Single configuration for each point-like motion





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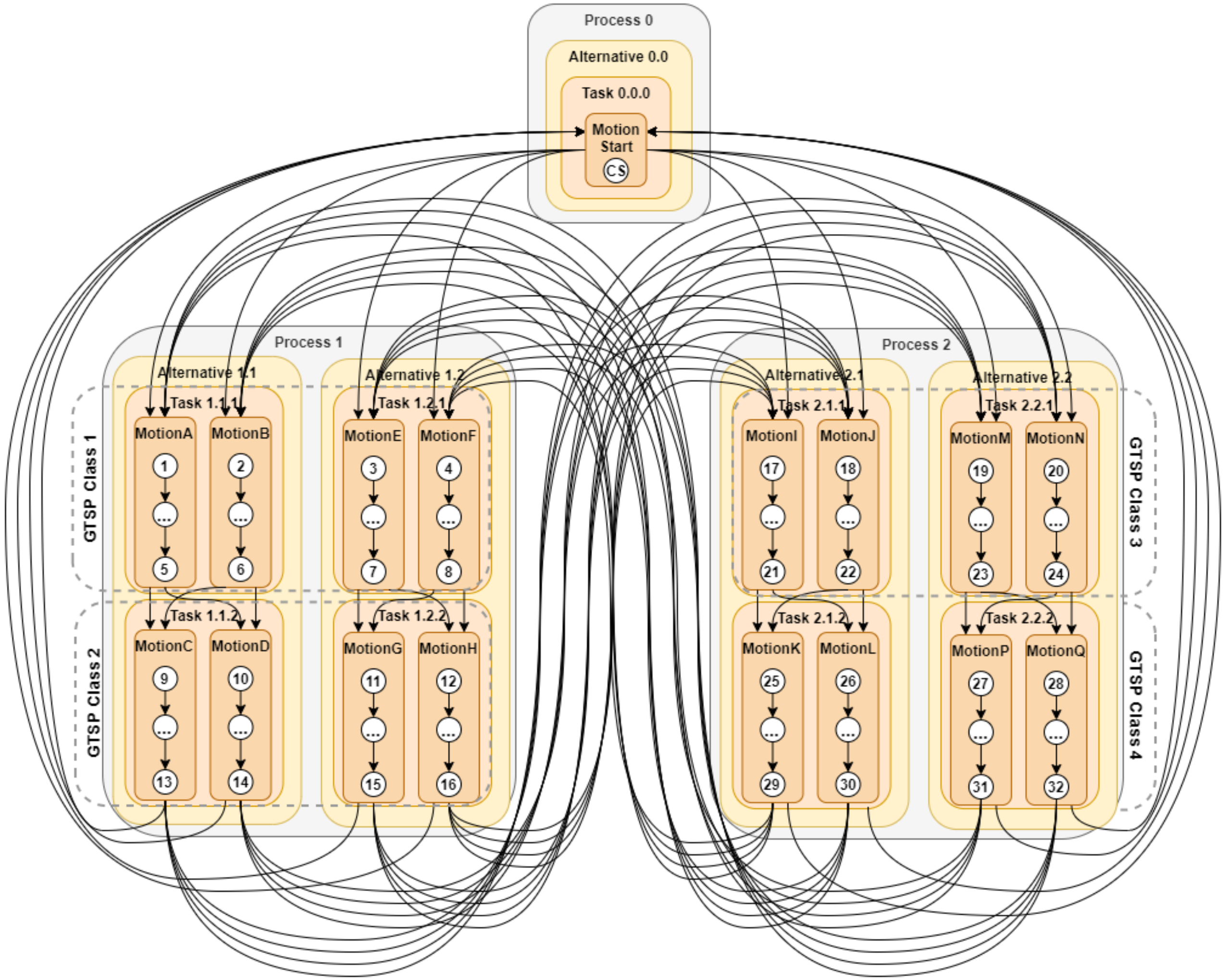
Problem representation

- Sequencing – Process level
- Selection – Alternatives, Motions
- Arbitrary configuration space
  - E.g. 2D/3D task space, 6D robot configuration
- Build-in distance functions
  - Descartes
  - Manhattan
  - Trapezoid time - $C[\varphi_0, \varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5]$
  - Individual cost matrix
- Mathematical representation:
  - GTSP with precedence constraints



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Problem representation – Trapezoid time

- Sequencing – Process level
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  - E.g. 2D/3D task space, 6D robot configuration
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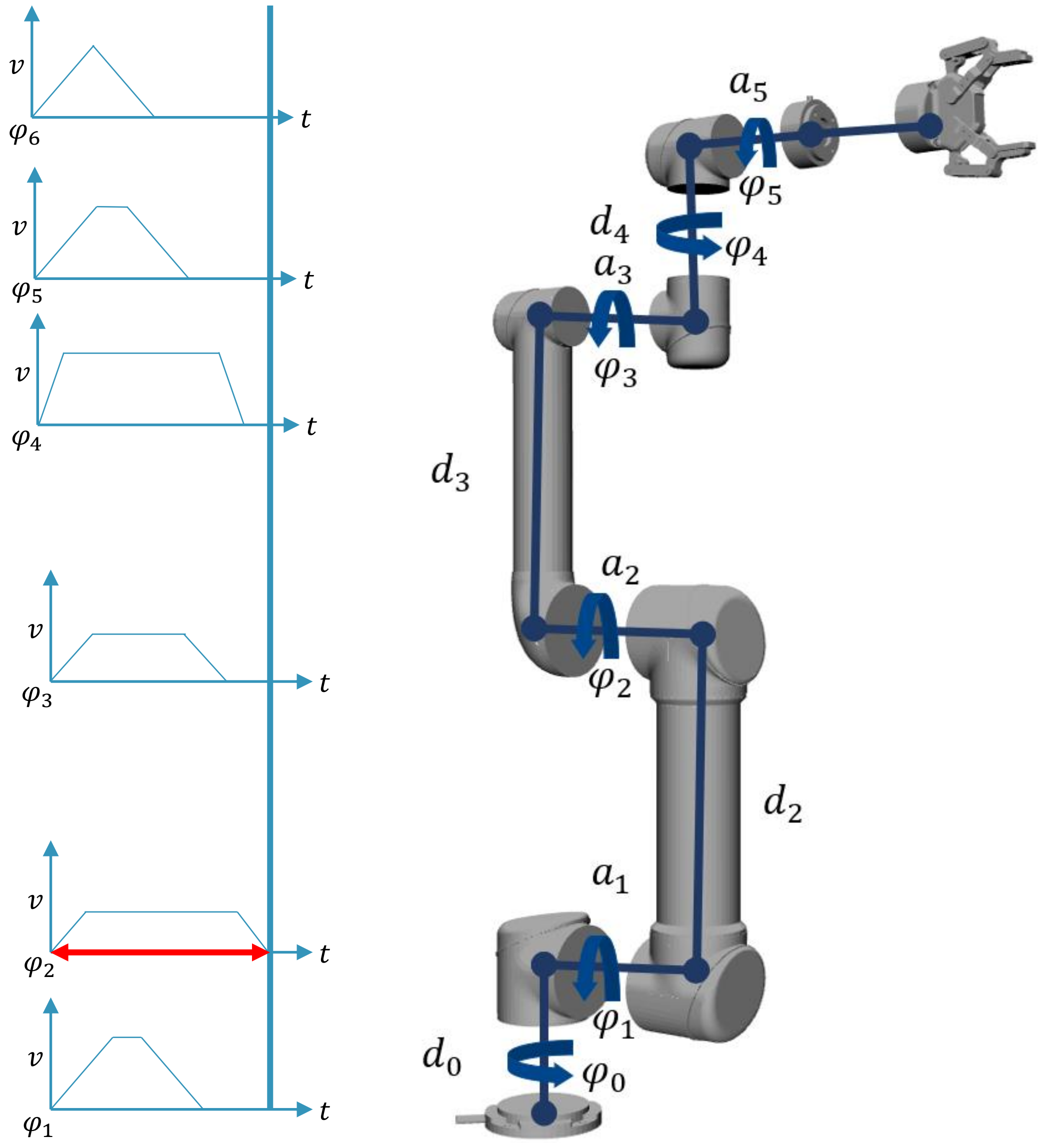

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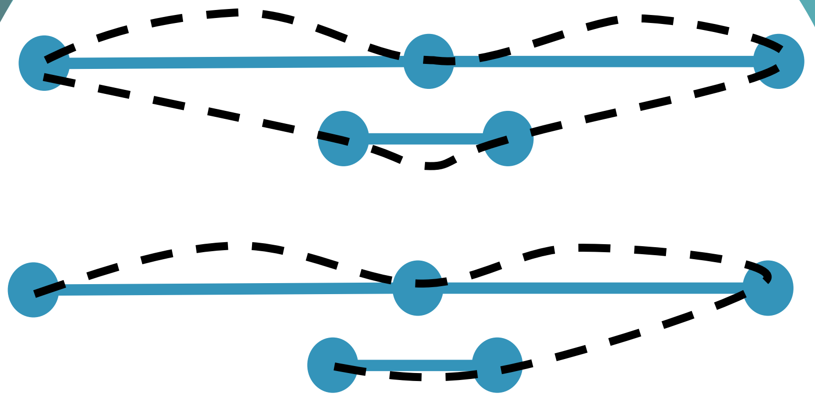
Problem representation – Features

- Cyclic and acyclic sequences
  - Return to start configuration needed or not
- Penalty for discontinuities
  - Add penalty in case of non-continuous steps
  - E.g. Laser welding/cutting, painting, drawing
- Resource changes
  - Resource change cost matrix defined
  - Resources defined for configurations
  - Drilling, painting, pick and place
- Precedence constraints
  - Defined on two levels
    - Processes
    - Motions



Cyclic and acyclic sequences

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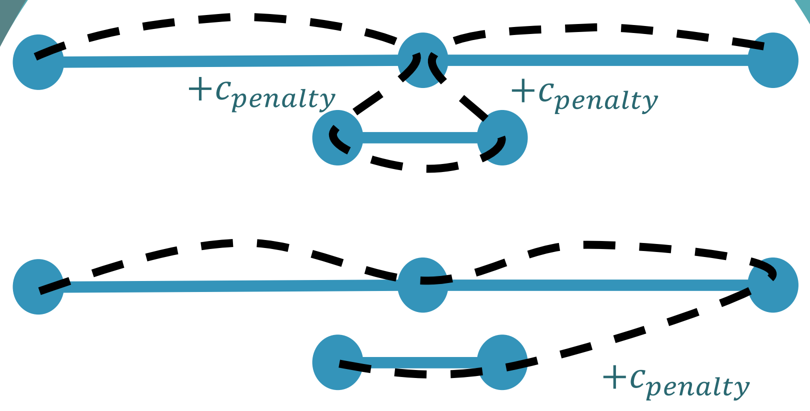

Avoid discontinuities

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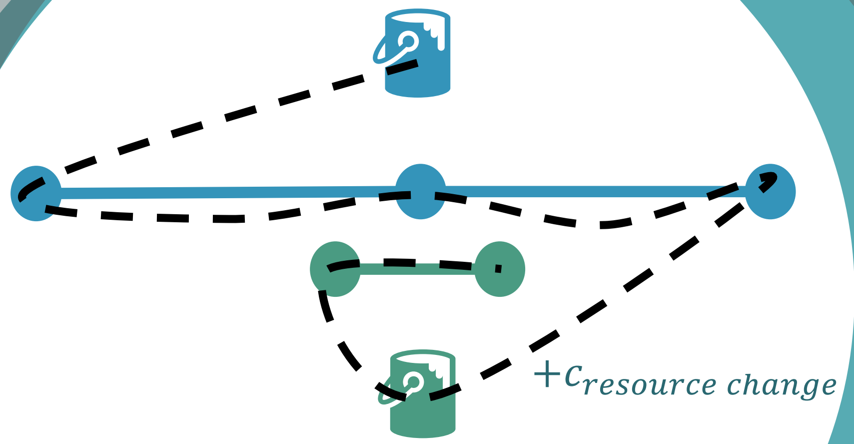

Resources

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Problem representation – Features

- Cyclic and acyclic sequences
  - Return to start configuration needed or not
- Penalty for discontinuities
  - Add penalty in case of non-continuous steps
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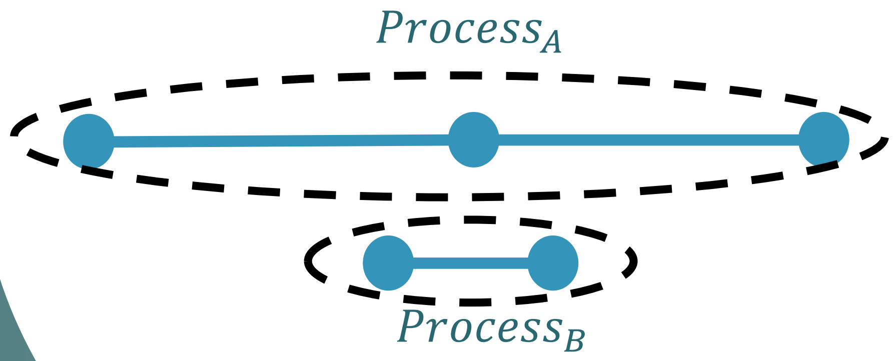
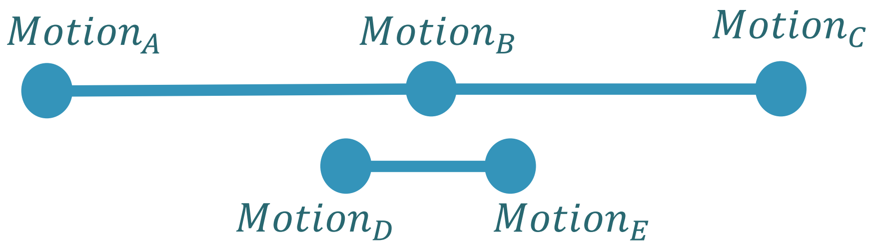


Process precedence constraints

$Process_A \longrightarrow Process_B$



Motion precedence constraints

$Motion_D \longrightarrow Motion_E$

$Motion_C \longrightarrow Motion_A$

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Problem representation – Description language

- Easy-to-use description
- Problem-centric approach
- Formats
    - SEQ
    - JSON
    - XML

```
Cyclic:                      True
StartDepot:                  1
TimeLimit:                   3000
DistanceFunction:            TrapezoidTime
TrapezoidSpeed:              [2,269;  2,269; 2,269; 3,316; 3,316; 3,316]
TrapezoidAcceleration:       [10,472;10,472;10,472;10,472;10,472;10,472]
LocalSearchStrategy:         GuidedLocalSearch
UseMIPprecedenceSolver:      True
ResourceChangeover:          Off
UseShortcutInAlternatives:   False

ConfigList:
1; [-1,868; -1,4441; 1,69802; -1,99163; -1,5198;-0,293486];Camera
2; [ 1,572; -0,3077; 0,46288; -4,92137; 2,44224;-1,6411]; Grasp1_1
3; [ 1,572;  5,9754; 0,46288; -4,92137; 2,44224;-1,6411]; Grasp1_2
4; [ 1,572; -0,3077; 0,46288;  1,36181; -3,8409;-1,6411]; Grasp1_3
5; [-1,501;  3,5196;-0,43442; -2,38683; 1,54423;-3,1638]; Grasp2_1
6; [ 1,383; -0,3857; 0,45309; -0,78662;-1,79213; 2,9516]; Grasp2_2
7; [-1,501; -2,7635;-0,43442; -2,38683; 1,54423; 3,1193]; Grasp_3
17;[ 1,228;  4,6728;-2,04866; -0,40084; 1,72721;-0,2865]; Inter1_1
18;[ 1,228;  4,4296;-1,45343;  2,38873;-1,72721; 2,8550]; Inter1_2
21;[ 1,228;  4,6728;-2,04866; -0,40084; 1,72721;-0,2865]; Inter2_1
22;[ 1,228;  4,4296;-1,45343;  2,38873;-1,72721; 2,8550]; Inter2_2

ProcessHierarchy:
0;  0;  0;  1;  [1]
1;  0;  0;  2;  [2]
1;  0;  0;  3;  [3]
1;  0;  0;  4;  [4]
1;  0;  1;  17; [17]
1;  0;  1;  18; [18]
2;  0;  0;  7;  [5]
2;  0;  0;  8;  [6]
2;  0;  0;  9;  [7]
2;  0;  1;  21; [21
2;  0;  1;  22; [22]
```

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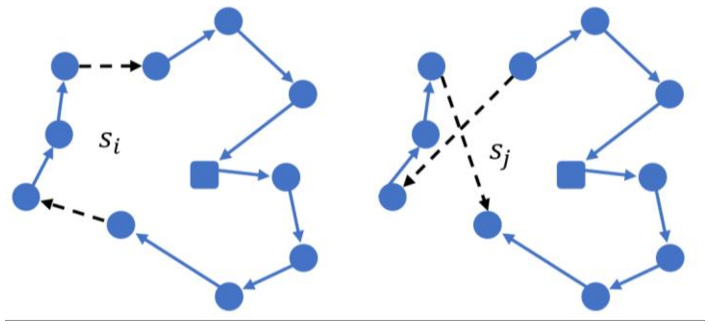
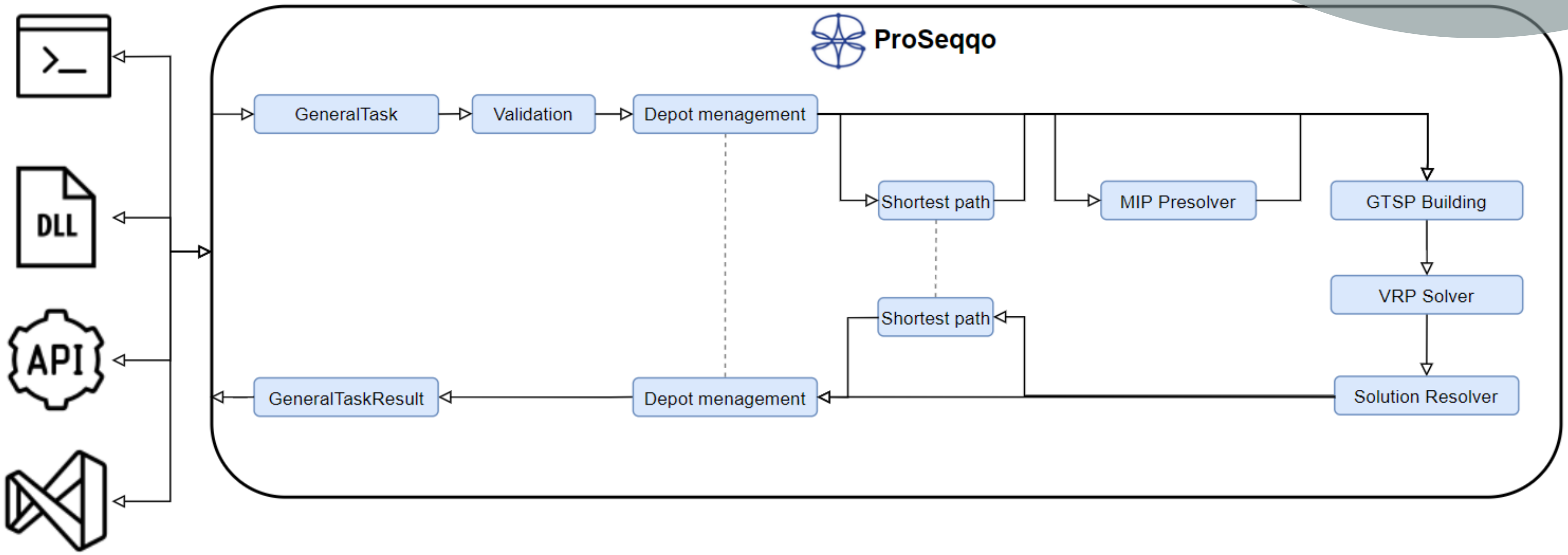
Solution approach

- Compile the representation into a GTSP problem
  - GTSP distance matrix and class definition
  - Precedence constraints
- OR-Tools local search
  - Meta-heuristics: greedy, tabu, simulated annealing, guided local search
  - GTSP-specific neighbourhood functions, e.g., 3-opt, 2-opt, OR-opt



2-opt neighbourhood



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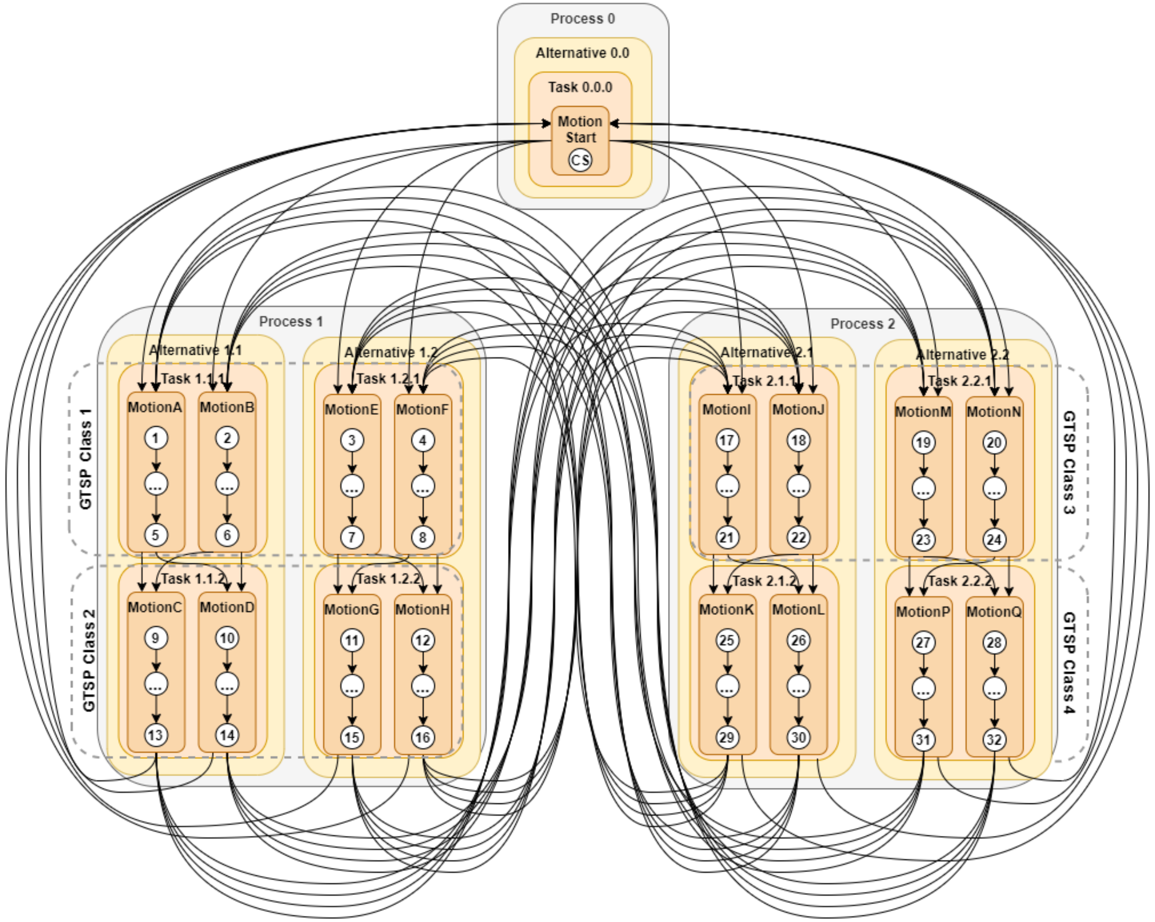
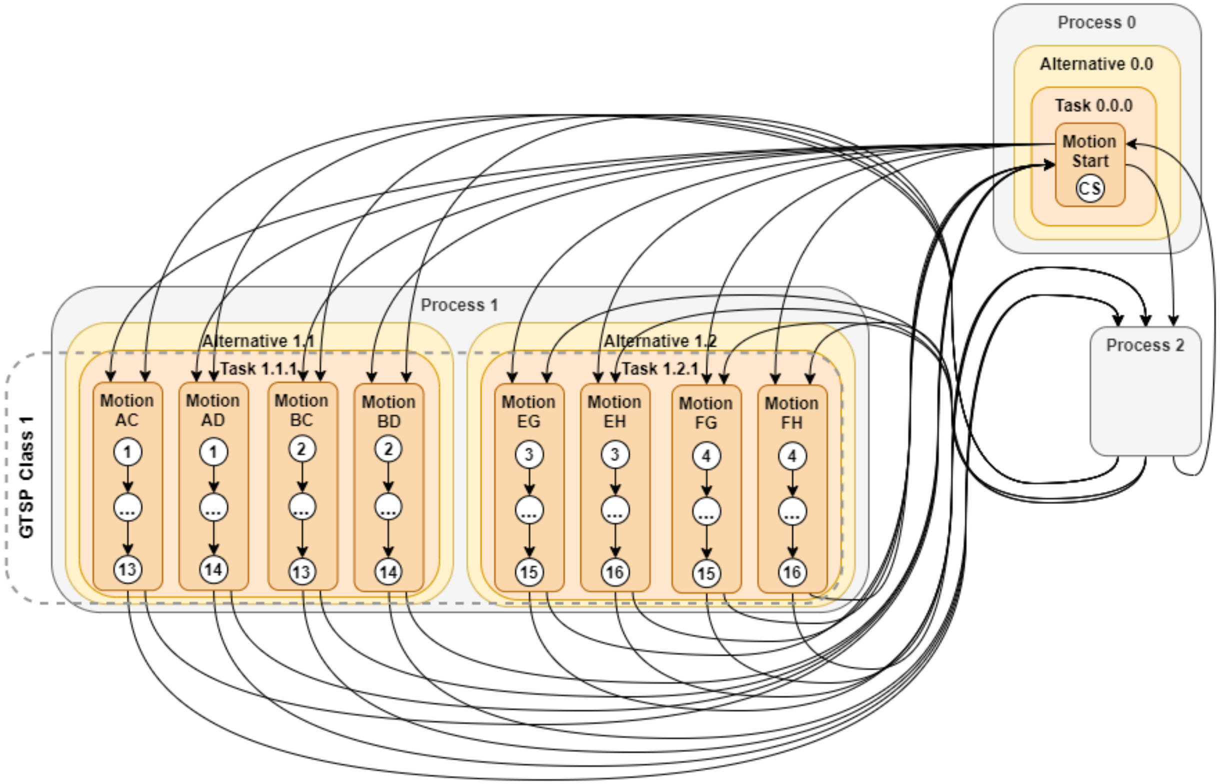
Solution approach – Shortest paths

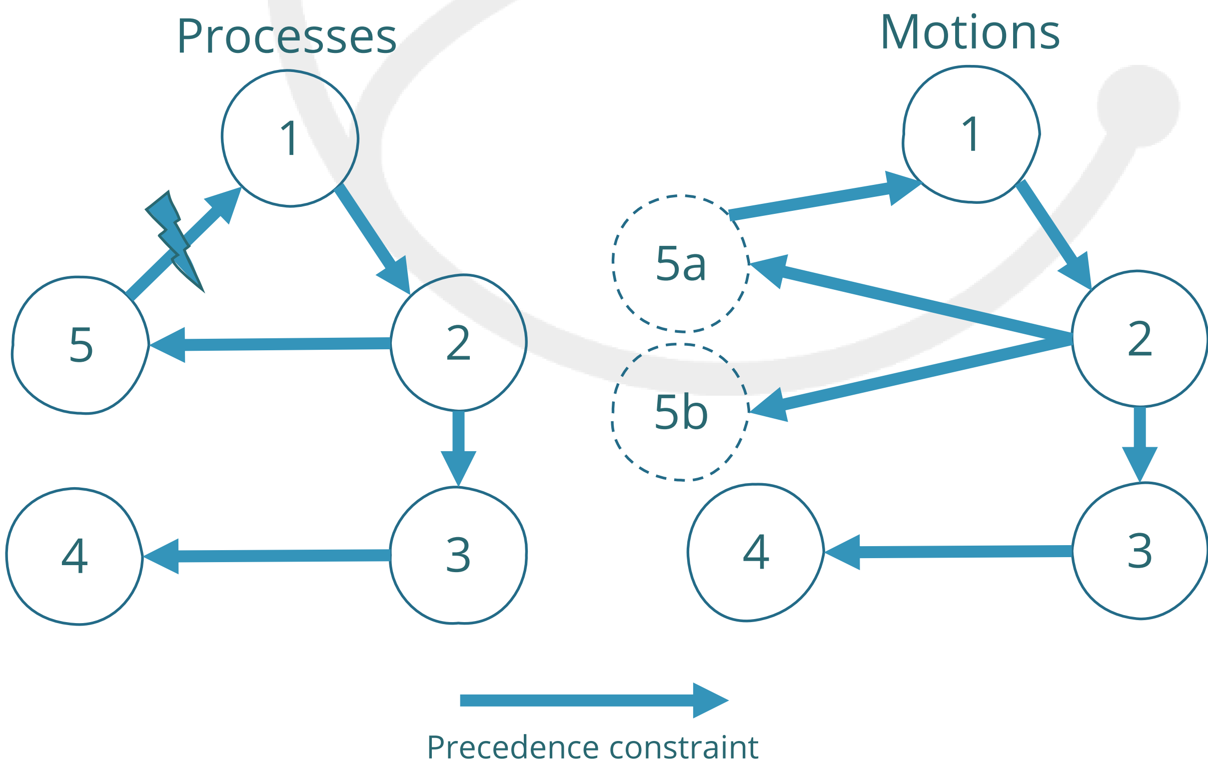
- Pre-computed shortest paths in the GTSP representation
- Each possible shortest path within an alternative encoded into a single node
- Leads to a wide but shallow GTSP representation that can be searched more





Solution approach – Initial solution via MIP

- Precedence constraints are important in industrial applications
- Precedence constraints on two levels
  - Processes
  - Motions
- Process precedence constraints
  - Cycle detection → Infeasible problem
- Motion precedence constraints
  - Motion may or may not be selected →
    Cycles do not imply infeasibility →
    Difficult to detect →
    Initial solution not found →
    MIP for feasible initial solution

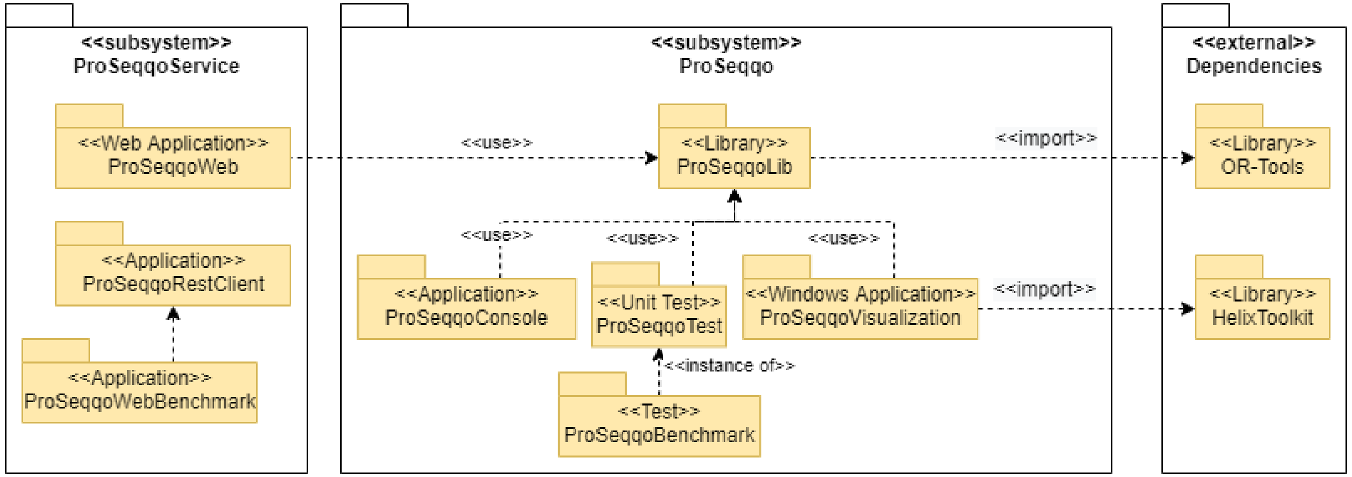


EPIC InnoLabs

Implementation – Core

ProSeqqo Library

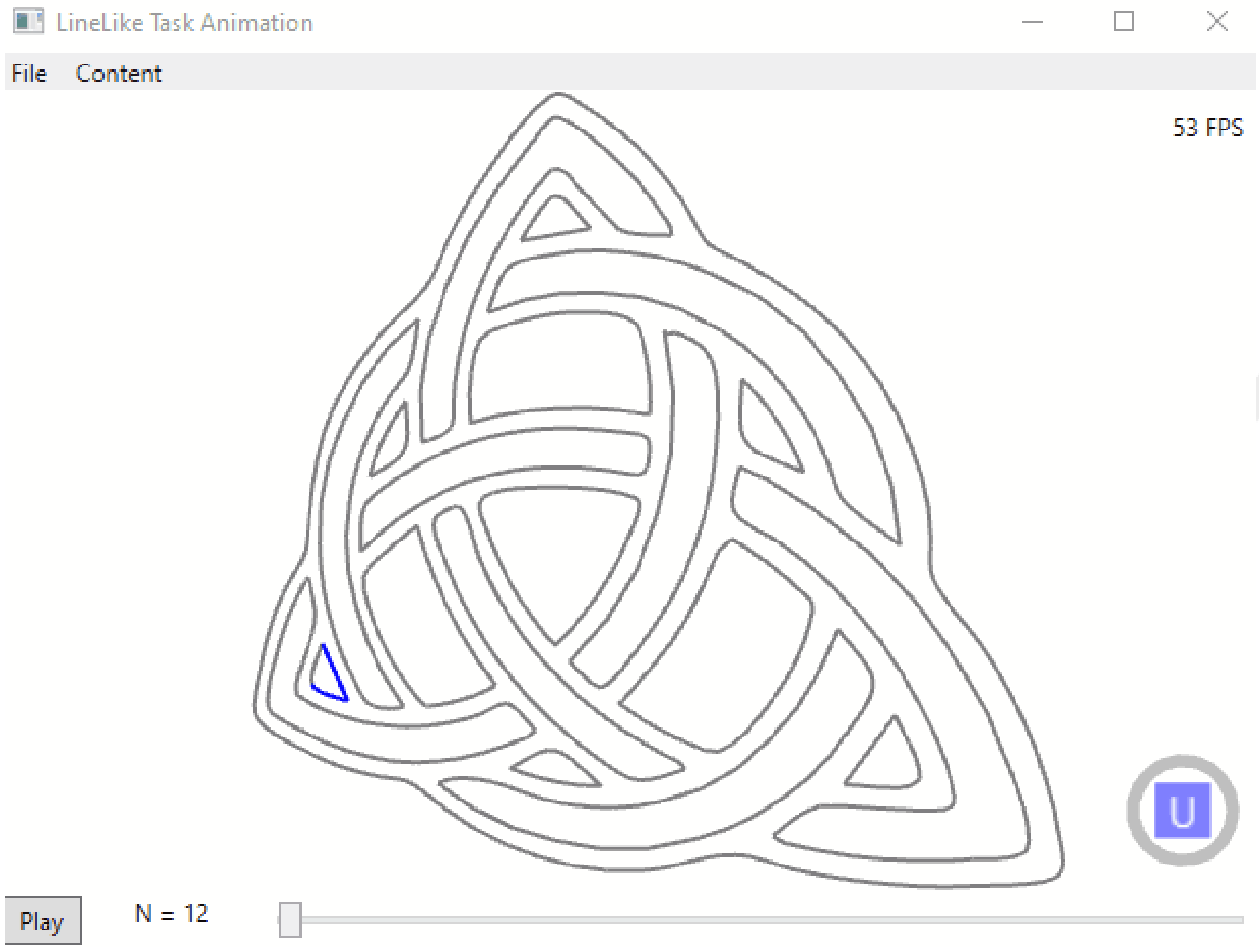
- Core component
  - Import, export problem definitions (SEQ, JSON, XML)
  - Process and transform problems to formal definition
  - Parameter configuration
  - Implemented algorithms: MIP initial solver and shortest path
  - Built on OR-Tools VRP C++ Solver
- Visual Studio Solution – C#
- Platform independent .NET Core class library
- Console application, .dll assembly, visualizer



EPIC InnoLabs

Implementation – Visualizer

- Visual Studio WPF application
- Helix Toolkit
- Visual validation in 2D, 3D
- Effective and idle sections

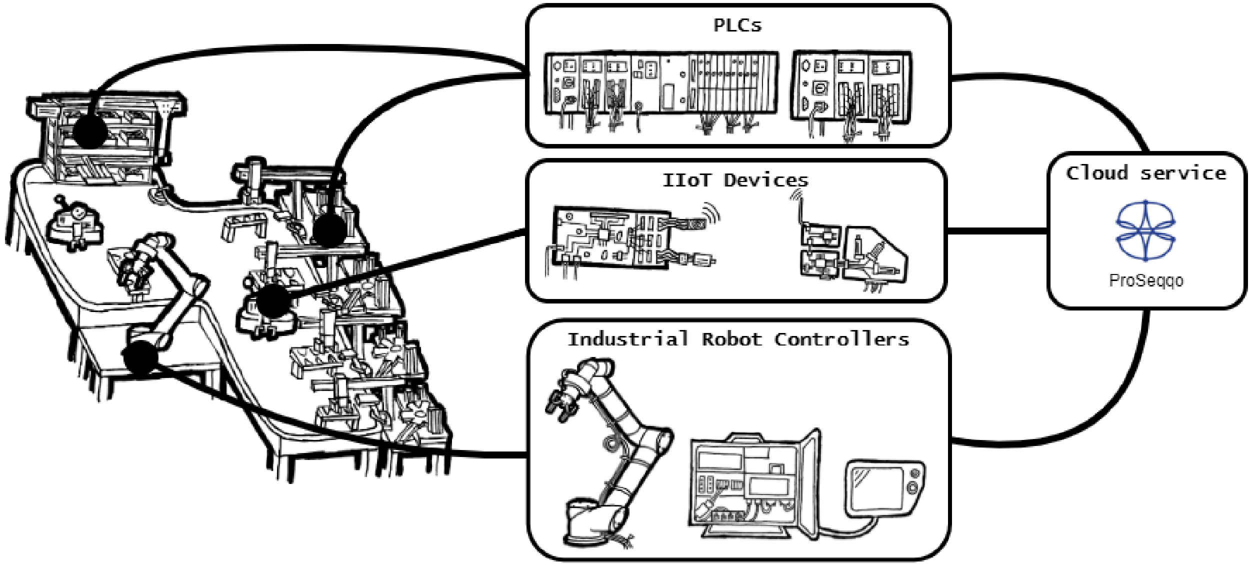


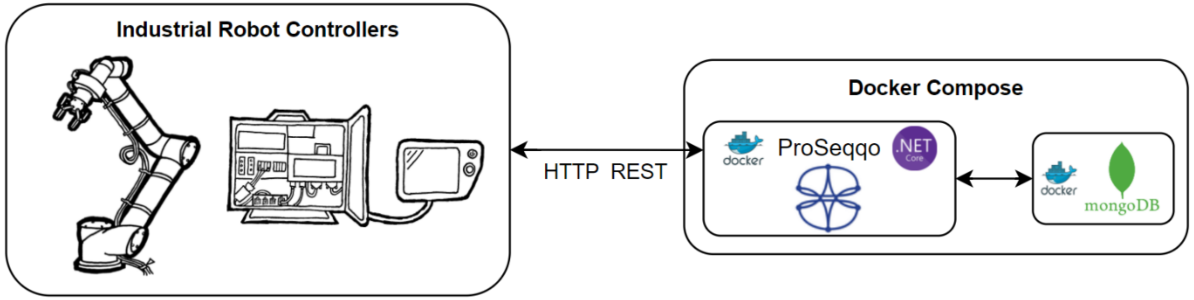
EPIC InnoLabs

Implementation – Cloud

ProSeqqo Web Service for Cloud integration

- Use shared resources
  - Edge computing
  - Cloud computing
- Visual Studio Project
- HTTP REST-based communication
- JSON, XML format
- Docker image, docker-compose operation
- MongoDB NoSQL database
- MQTT, OPC UA as development possibility

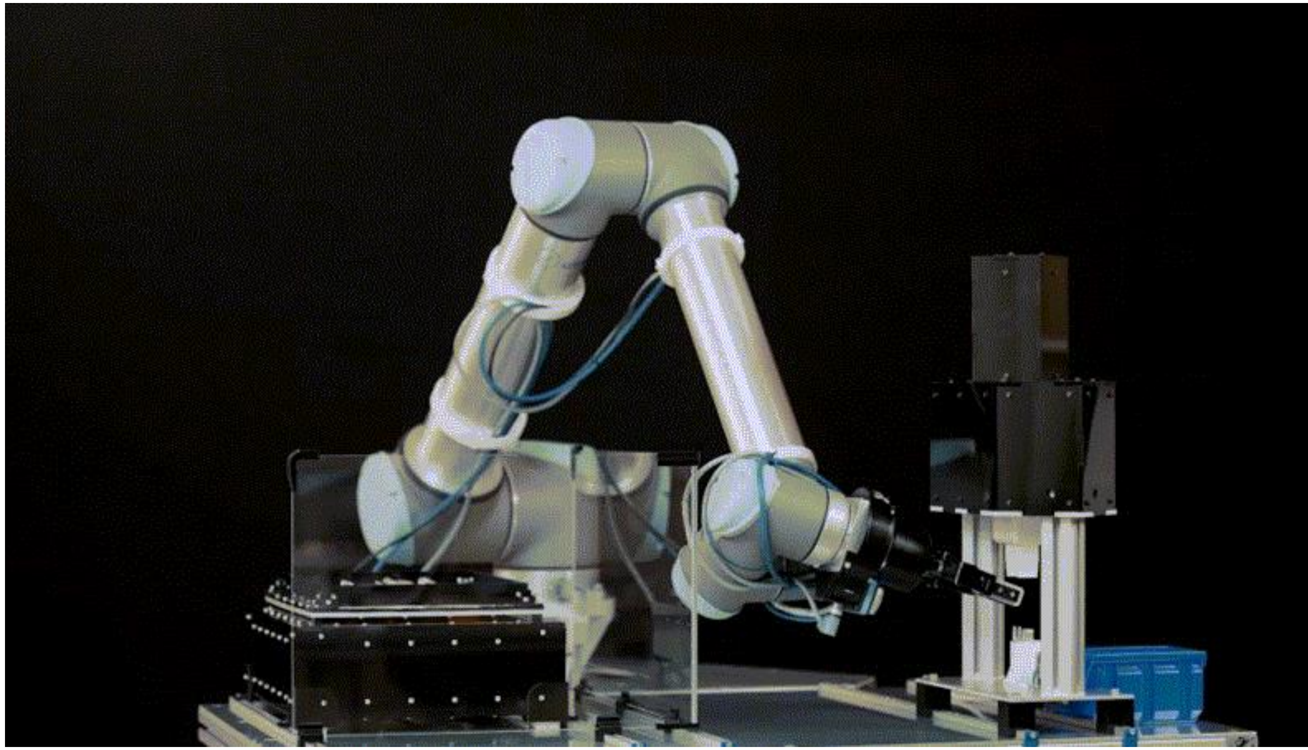




EPIC InnoLabs

Case Study – Camera-based pick-and-place

- Goal: pick and place the 3 - 30 parts lying in random poses
- Problem: sequencing the parts, selection of IK solutions
- Distance function: trapezoid time profile over 6D configurations
- Representation:
  - 3 - 30 processes (parts)
  - 1 alternative (single grasp)
  - 2 tasks (pick, place)
  - 1 – 10 motions (collision-free IK solutions)



EPIC InnoLabs

Bence Tipary and Gábor Erdős.
Generic development methodology for flexible robotic pick-and-place work cells based on Digital Twin
Robotics and Computer-Integrated Manufacturing, 2021.
YouTube - https://www.youtube.com/watch?v=9novNg8sIN4

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```
Cyclic:                     True
StartDepot:                 1
TimeLimit:                  3000
DistanceFunction:           TrapezoidTime
TrapezoidSpeed:             [2,269;  2,269; 2,269; 3,316; 3,316; 3,316]
TrapezoidAcceleration:      [10,472;10,472;10,472;10,472;10,472;10,472]
LocalSearchStrategy:        GuidedLocalSearch
UseMIPprecedenceSolver:     True
ResourceChangeover:         Off
UseShortcutInAlternatives: False

ConfigList:
1; [-1,868; -1,4441; 1,69802; -1,99163; -1,5198;-0,293486];Camera
2; [ 1,572; -0,3077; 0,46288; -4,92137; 2,44224;-1,6411]; Grasp1_1
3; [ 1,572;  5,9754; 0,46288; -4,92137; 2,44224;-1,6411]; Grasp1_2
4; [ 1,572; -0,3077; 0,46288;  1,36181; -3,8409;-1,6411]; Grasp1_3
5; [-1,501;  3,5196;-0,43442; -2,38683; 1,54423;-3,1638]; Grasp2_1
6; [ 1,383; -0,3857; 0,45309; -0,78662;-1,79213; 2,9516]; Grasp2_2
7; [-1,501; -2,7635;-0,43442; -2,38683; 1,54423; 3,1193]; Grasp_3
17;[ 1,228;  4,6728;-2,04866; -0,40084; 1,72721;-0,2865]; Inter1_1
18;[ 1,228;  4,4296;-1,45343;  2,38873;-1,72721; 2,8550]; Inter1_2
21;[ 1,228;  4,6728;-2,04866; -0,40084; 1,72721;-0,2865]; Inter2_1
22;[ 1,228;  4,4296;-1,45343;  2,38873;-1,72721; 2,8550]; Inter2_2

ProcessHierarchy:
0;  0;  0;  1;  [1]
1;  0;  0;  2;  [2]
1;  0;  0;  3;  [3]
1;  0;  0;  4;  [4]
1;  0;  1;  17; [17]
1;  0;  1;  18; [18]
2;  0;  0;  7;  [5]
2;  0;  0;  8;  [6]
2;  0;  0;  9;  [7]
2;  0;  1;  21; [21
2;  0;  1;  22; [22]
```

EPIC InnoLabs

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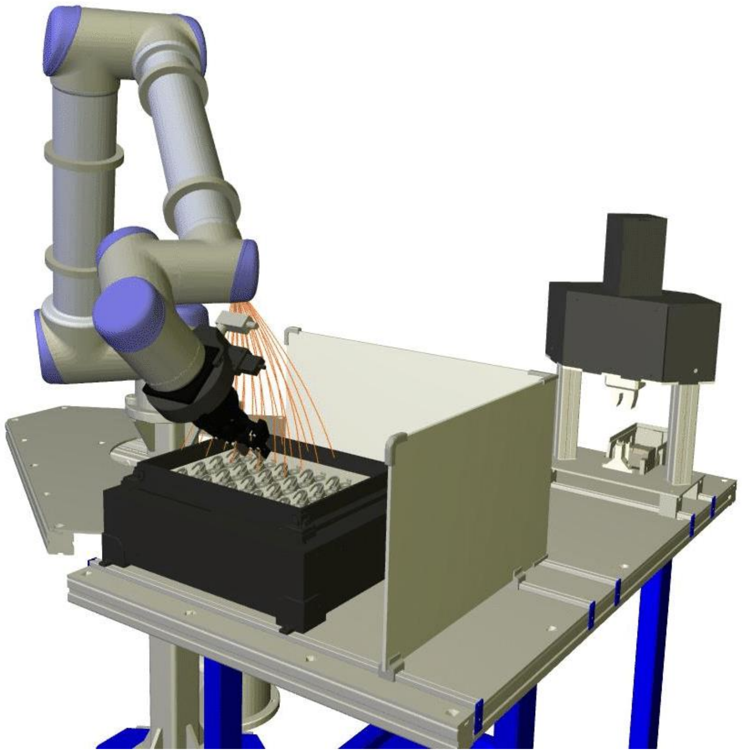
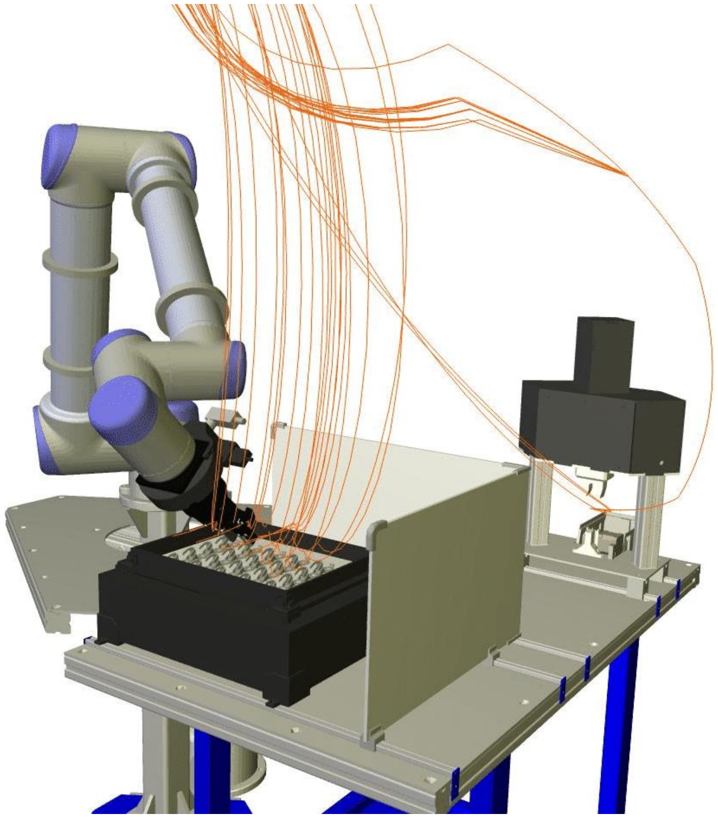
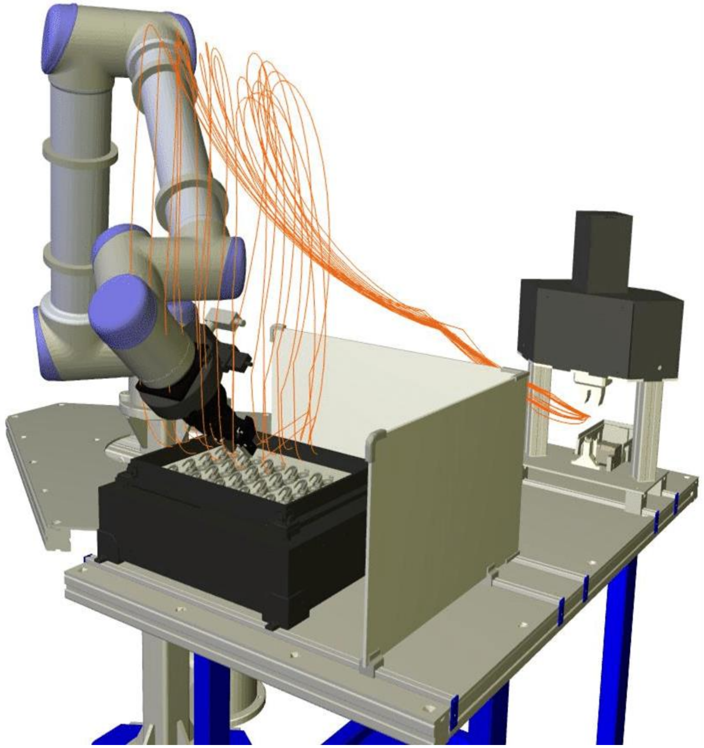
Case Study – Camera-based pick-and-place







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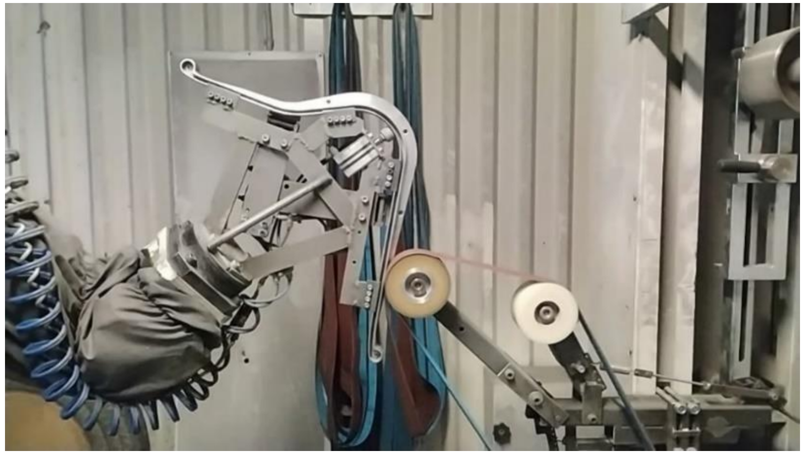
Case Study – Camera-based pick-and-place

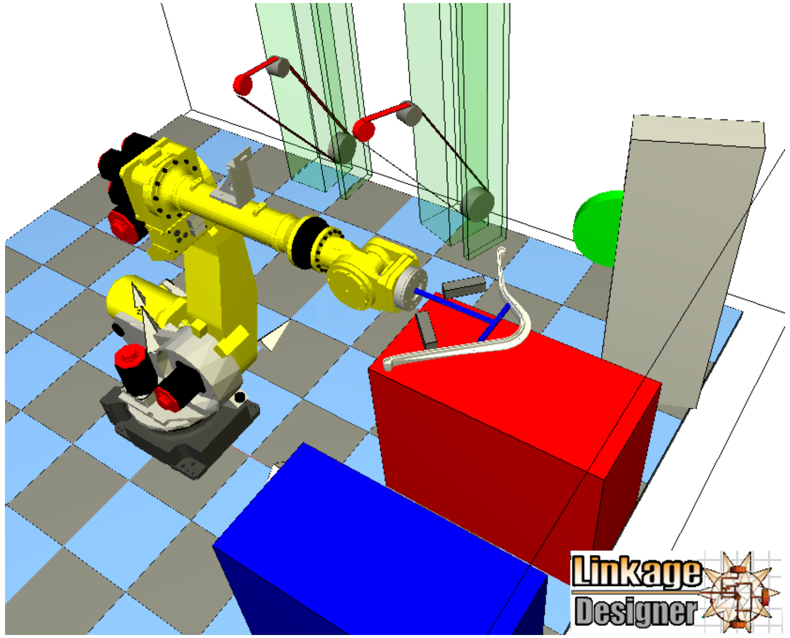
- Results:
  - Suitable for online planning
  - GTSP representation matters:
    - Very efficient with pre-computed shortest paths
    - 30 parts in 0.2s
    - 3% difference to the best
    - GLS algorithm used

Parts	PSP	GTSP vertices	GD		GLS 0.1 s	GLS 1 s	GLS 10 s	GLS 1 min
3	N	28.8	10.73	(0.02 s)	9.73	9.73	9.73	9.73
4		36.0	15.64	(0.03 s)	12.65	12.60	12.60	12.60
5		54.3	18.88	(0.05 s)	15.44	15.38	15.38	15.38
10		117.5	37.72	(0.08 s)	31.01	30.75	30.09	29.90
15		180.0	57.11	(0.15 s)	45.59	45.27	44.44	43.36
20		249.8	75.29	(0.34 s)	61.40	61.18	60.25	58.32
25		305.0	94.58	(0.46 s)	76.26	75.63	75.34	74.11
30		358.2	114.64	(0.57 s)	92.35	91.64	91.16	88.39
3	Y	61.2	9.78	(0.00 s)	9.73	9.73	9.73	9.73
4		74.0	12.73	(0.00 s)	12.63	12.60	12.60	12.60
5		131.2	15.44	(0.01 s)	15.40	15.38	15.38	15.38
10		304.0	30.66	(0.03 s)	30.64	30.39	30.16	30.02
15		474.0	45.02	(0.05 s)	44.93	44.58	43.93	43.56
20		673.2	60.58	(0.09 s)	60.58	60.26	59.67	58.79
25		814.0	75.57	(0.12 s)	75.76	75.43	75.15	73.67
30		946.8	90.76	(0.18 s)	91.59	90.61	89.27	87.61

Case Study – Grinding and polishing of furniture parts

- Goal: rough grinding, fine grinding, and polishing
- Problem: task sequencing, choosing directions
- Distance function: individual cost matrix based on collision-free path planning
- Representation:
  - 19 processes (machining)
  - 1 alternative
  - 1 task
  - 2 motions (directions)
  - + 280 precedence constraints





EPIC InnoLabs

G. Erdős, I. Paniti, B. Tipary,
Transformation of robotic workcells to digital twins,
CIRP Annals – Manufacturing Technology 69 (1) (2020) 149–152.

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    - 1 task
    - 2 motions (directions)
    - + 280 precedence constraints

```
Cyclic:                      False
DistanceFunction:            Matrix
BidirectionMotionDefault:    True
AddMotionLengthToCost:       False
LocalSearchStrategy:         GuidedLocalSearch
TimeLimit:                   120000
UseMIPprecedenceSolver:      True
UseShortcutInAlternatives:   False
ResourceChangeover:          Off

ConfigMatrix:
0;   1;   2;   3;   ...
0;   2.4; 1.5; 2.2; ...
2.4; 0  ; 2.4; 2.7; ...
1.5; 2.4; 0;   2.7; ...
2.2; 1.9; 2.7; 0;   ...
...

ProcessHierarchy:
0;  0;  0;  19;   [0;1 ];; P1A
1;  1;  1;  1;    [2;3 ];; P1B
2;  2;  2;  2;    [4;5 ];; P1C
3;  3;  3;  3;    [6;7 ];; P2A
4;  4;  4;  4;    [8;9 ];; P2B
5;  5;  5;  5;    [10;11];;P2C
6;  6;  6;  6;    [12;13];;P3A
7;  7;  7;  7;    [14;15];;P3B
8;  8;  8;  8;    [16;17];;P3C
9;  9;  9;  9;    [18;19];;P4A
10; 10; 10; 10;   [20;21];;P4B
11; 11; 11; 11;   [22;23];;P4C
12; 12; 12; 12;   [24;25];;P5A
13; 13; 13; 13;   [26;27];;P5B
14; 14; 14; 14;   [28;29];;P5C
15; 15; 15; 15;   [30;31];;P6C
16; 16; 16; 16;   [32;33];;P7C
17; 17; 17; 17;   [34;35];;P8C
18; 18; 18; 18;   [36;37];;P9C

MotionPrecedence:
#A->B
3;  1
6;  1
12; 1
...
#B->C
1  ;2
1  ;5
```

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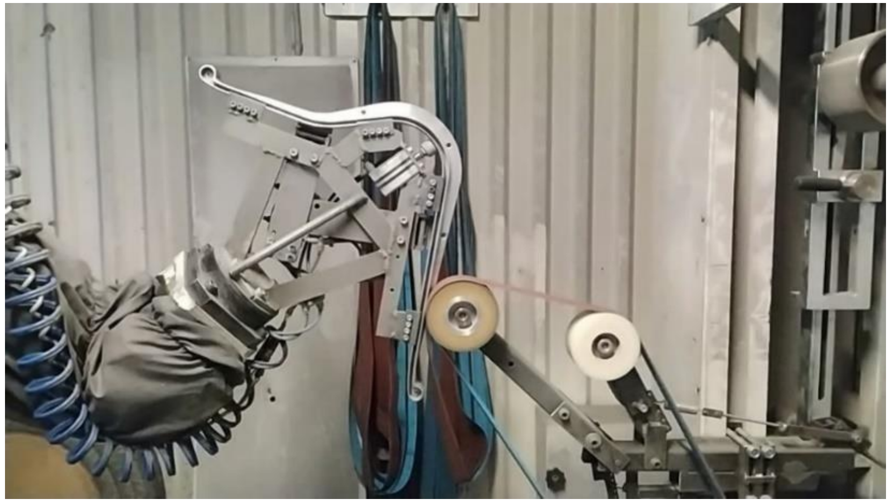
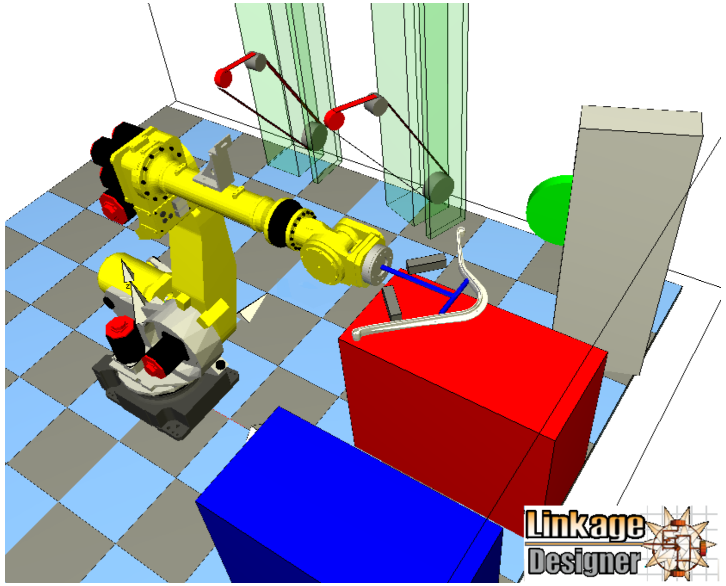
Case Study – Grinding and polishing of furniture parts

- Results:
  - Offline planning
  - Initial solution that satisfies precedence constraints with MIP
  - Transition time 24% lower than human expert solution
  - Best solution using GLS, Tabu search
  - Result approved by an expert in simulation



Time limit	Human expert	GD	GLS	TS
5 s	38.93	35.16	32.47	29.79
10 s	(one working day)	(0.27 s)	32.47	29.79
1 min			32.47	29.79
10 min			29.70	29.79
30 min			29.70	29.79



EPIC InnoLabs

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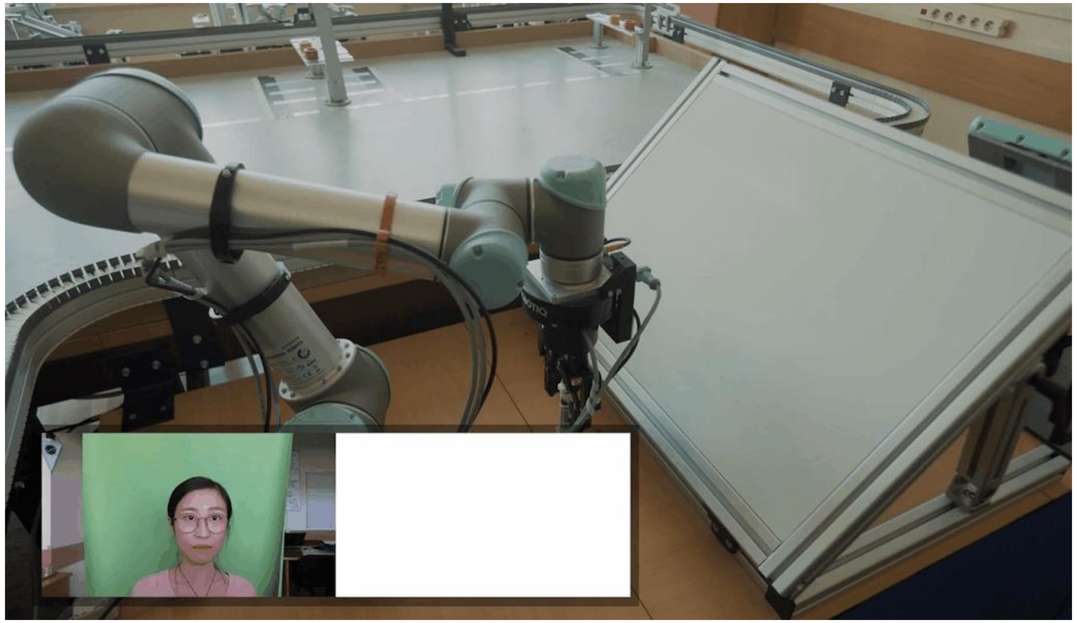
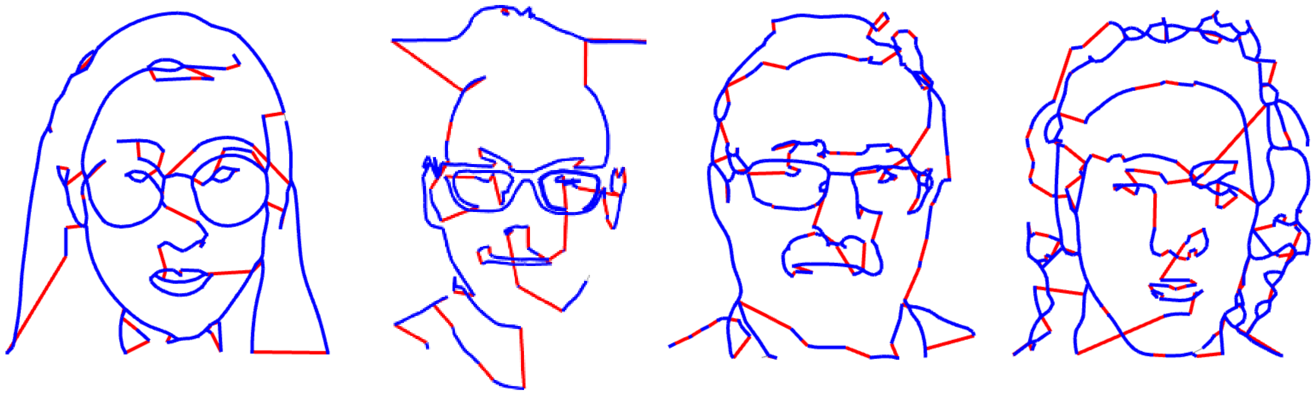
Case Study – Robotic cartoon drawing

- Goal: cartoon drawing by robot arm
- Problem: sequencing the lines, selection of directions
- Distance function: Euclidian distance of 2D coordinates

  + penalties for discontinuity of the lines
- Representation:
  - 265-643 processes (lines)
  - 1 alternative
  - 1 task
  - 2 motions (direction)





EPIC InnoLabs

Tamás Cserteg, János Csempesz
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  - 265-643 processes (lines)
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  - 1 task
  - 2 motions (direction)

```
Cyclic:                   False
TimeLimit:                80 000
DistanceFunction:         Euclidian
LocalSearchStrategy:      GuidedLocalSearch
IdlePenalty:              10
BidirectionMotionDefault: True
ResourceChangeover:       Off

ConfigList:
1; [14.2087; 16.63323]; Point_1
2; [12.7673; 16.58287]; Point_2
3; [11.4878; 16.53255]; Point_3
4; [9.94235; 16.60115]; Point_4
5; [9.50211; 16.64757]; Point_5
6; [5.70371; 16.61334]; Point_6
7; [4.98491; 16.82752]; Point_7
8; [4.18291; 17.12871]; Point_8
9; [3.57080; 17.42932]; Point_9
10;[2.64122; 17.75301]; Point_10
...

ProcessHierarchy:
1;1;1;1;[1;2];   ;Line_1[P1,P2]
2;2;2;2;[2;3];   ;Line_2[P2,P3]
3;3;3;3;[3;4];   ;Line_3[P3,P4]
4;4;4;4;[4;5];   ;Line_4[P4,P5]
5;5;5;5;[5;6];   ;Line_5[P5,P6]
6;6;6;6;[6;7];   ;Line_6[P6,P7]
7;7;7;7;[7;8];   ;Line_7[P7,P8]
8;8;8;8;[8;9];   ;Line_8[P8,P9]
9;9;9;9;[9;10];  ;Line_9[P9,P10]
...
```

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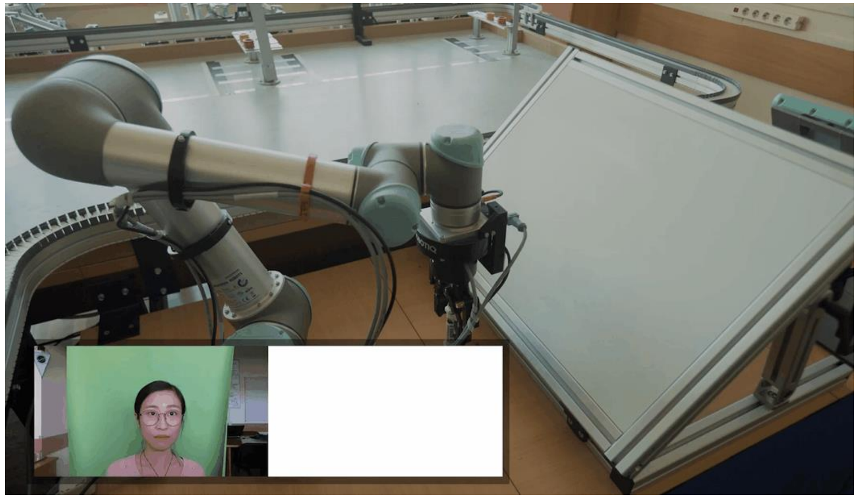
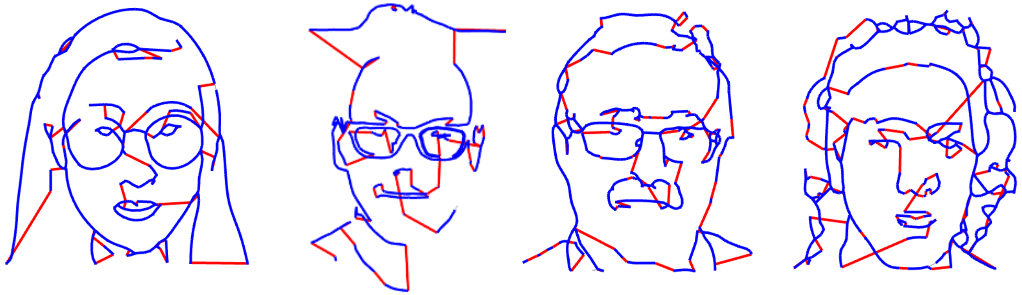
Case Study – Robotic cartoon drawing

Results

- Online planning
- Penalty controls trade-off between the quality and drawing time
- Good solution in 1 sec
- Local minimum in 1-7 sec



Cartoon	Lines	GD		GLS			
				1 s	10 s	1 min	10 min
A	265	811.83	(1.05 s)	811.83	790.55	764.02	751.80
B	485	3899.34	(4.47 s)	4081.54	3399.34	3387.65	3203.63
C	614	3970.43	(6.98 s)	4312.00	3970.43	3927.73	3818.12
D	643	5204.70	(7.18 s)	5364.63	5185.53	5074.26	5033.43
E	296	3502.24	(1.99 s)	3595.68	3476.95	3411.11	3310.68



EPIC InnoLabs

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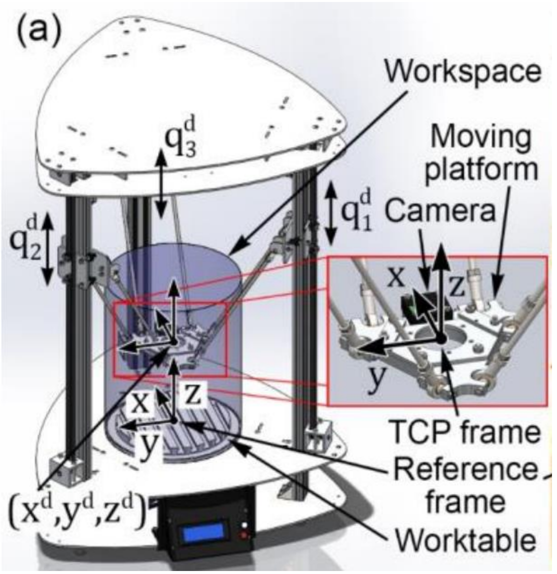
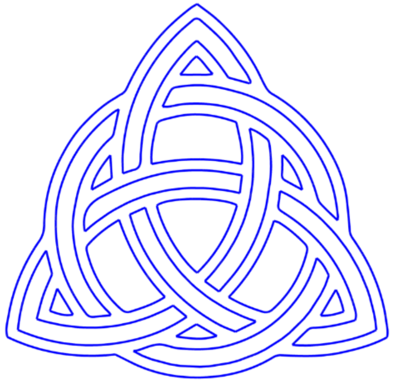
Case Study – Laser engraving

- Goal: laser engraving of a Celtic knot motif
- Problem: sequencing lines, selection of directions
- Distance function: Euclidian distance of 2D coordinates
- Representation :
    - 250 - 4048 processes (lines)
    - 1 alternative
    - 1 task
    - 2 motions (direction)





EPIC InnoLabs

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Industrial Robot-an International Journal (2022) 49 (1). pp. 168-176.

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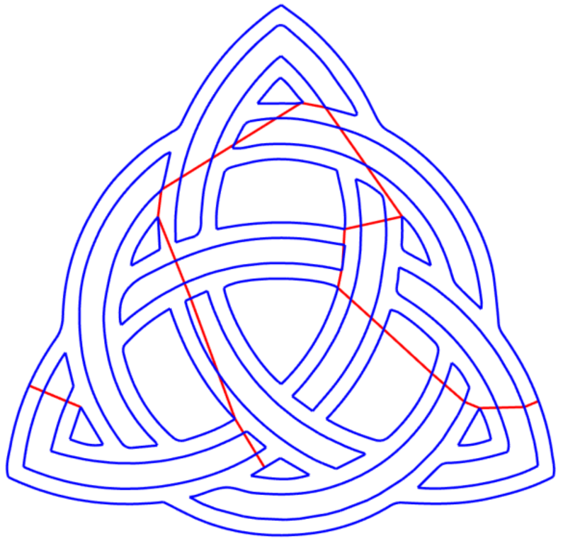

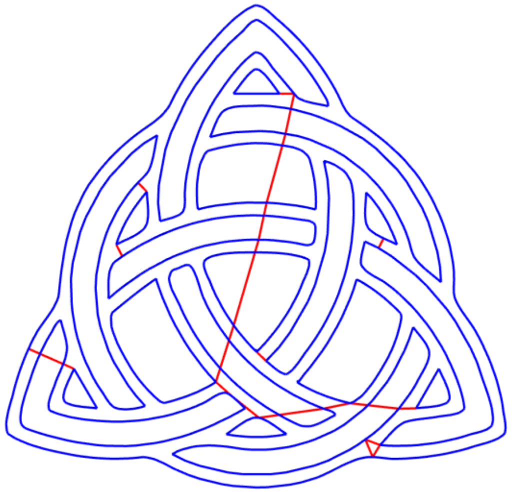

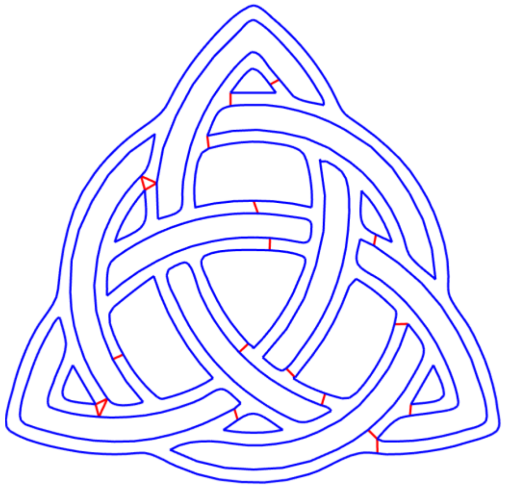

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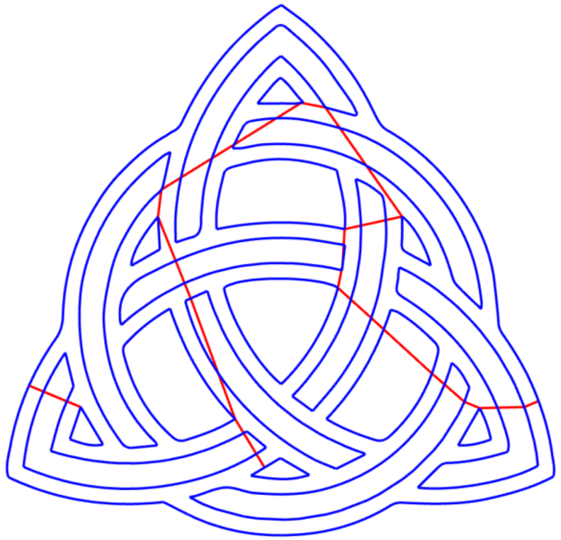
  - 1 task
  - 2 motions (direction)

```
Cyclic:                    False
DistanceFunction:          Euclidian
BidirectionMotionDefault:  True
TimeLimit:                 180 000
LocalSearchStrategy:       GuidedLocalSearch
ResourceChangeover:        Off

ConfigList:
1;  [-1.1226863; 9.8689459];  Point_1
2;  [0.87634620; 10.290004];  Point_2
3;  [-0.0298332; 11.102733];  Point_3
4;  [-0.9035854; 10.158098];  Point_4
5;  [-1.1226862; 9.8689459];  Point_5
#NewContour
6;  [9.18254487; -3.938683];  Point_6
7;  [8.42045842; -5.265297];  Point_7
8;  [8.56477699; -5.875849];  Point_8
9;  [9.71774896; -5.464493];  Point_9
#NewContour
12; [-7.967819; -5.929423];  Point_12
13; [-8.740734; -4.603991];  Point_13
14; [-9.343613; -4.419687];  Point_14
15; [-9.618377; -5.524891];  Point_15

ProcessHierarchy:
1;  1;  1;  1;  [1;2];  ;Line_1_2
2;  2;  2;  2;  [2;3];  ;Line_2_3
3;  3;  3;  3;  [3;4];  ;Line_3_4
4;  4;  4;  4;  [4;5];  ;Line_4_5
#NewContour
5;  5;  5;  5;  [6;7];  ;Line_6_7
6;  6;  6;  6;  [7;8];  ;Line_7_8
7;  7;  7;  7;  [8;9];  ;Line_8_9
#NewContour
10; 10; 10; 10; [12;13];;Line_12_13
11; 11; 11; 11; [13;14];;Line_13_14
12; 12; 12; 12; [14;15];;Line_14_15
...
```

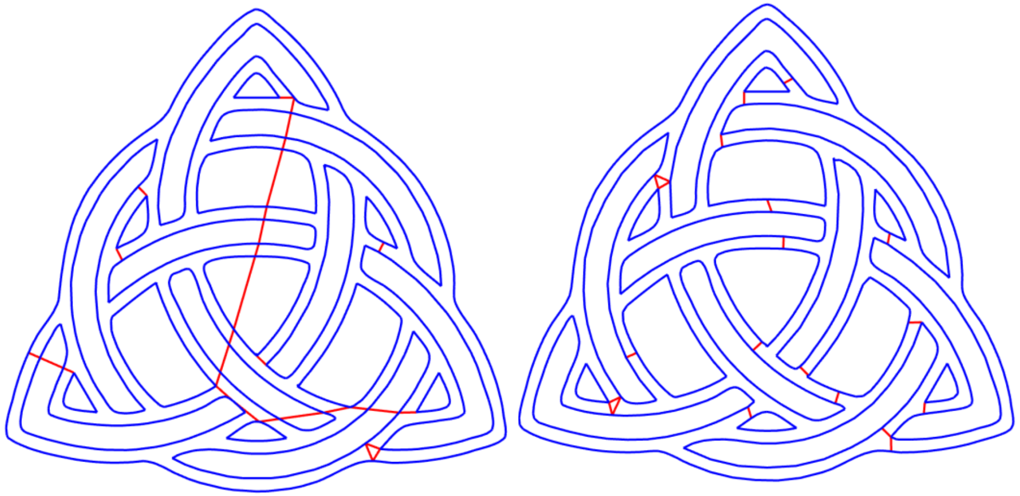
EPIC InnoLabs

Case Study – Laser engraving of Celtic knot

- Results
  - Offline planning with good results – for mass production
  - Online planning – custom heuristics for large problems to be developed
  - Penalty controls trade-off between the quality and drawing time
  - Total travel distance decreased by 10% (1 sec vs 30 min)



Lines	GD		GLS				
			1 s	10 s	1 min	10 min	30 min
250	485.59	(1.15 s)	485.59	481.84	468.93	465.45	464.27
466	493.43	(4.56 s)	507.80	493.43	488.37	464.76	463.28
883	485.33	(33.50 s)	514.10	510.13	485.17	470.68	463.37
1800	480.43	(89.91 s)	515.03	512.55	481.38	480.43	480.43
4048	491.42	(546.19 s)	-	501.28	496.27	491.42	491.42



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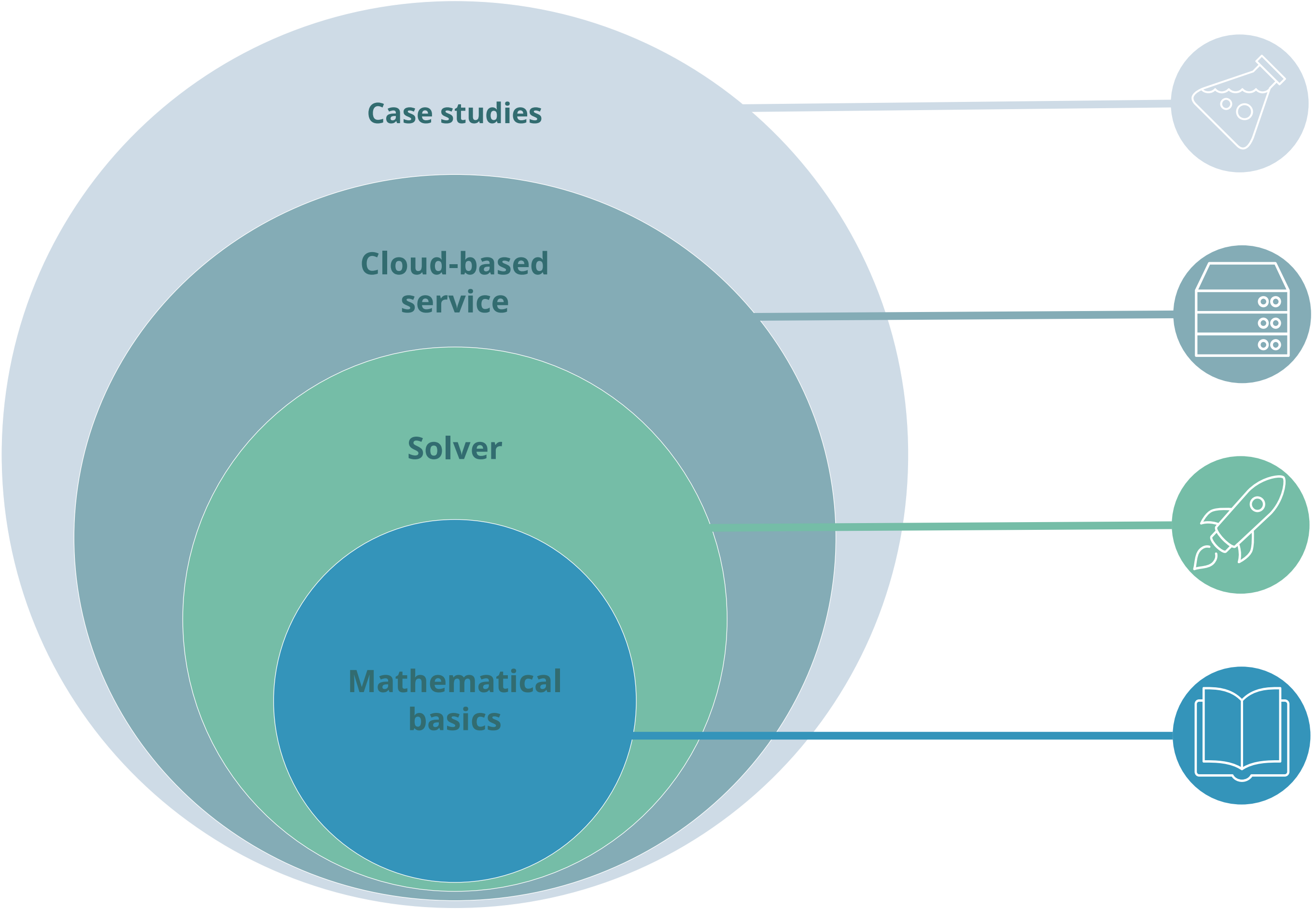
Tipary, Bence, Erdős Gábor
A novel, low-cost technique for modeless calibration of a 3-axis parallel kinematic machine.
Industrial Robot-an International Journal (2022) 49 (1). pp. 168-176.

Work performed



Case studies
5 industrial and demonstration case studies to prove expressiveness and computational efficiency

Cloud service
Solving problems on a remote computer,
based on HTTP REST,
measuring multi-user service

Model, language, algorithms
General model and language (SEQ, JSON, XML),
GTSP model, MIP initial solver, local search, OR-Tools

Mathematical basics
Literature review, typical sequencing problems, mathematical models

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Reference

Available open-source: github.com/sztaki-hu/ProSeqqo

Credits:

András Kovács, Gábor Erdős, Bence Tipary, János Csempesz, Tamás Cserteg, Mátyás Hajós

Further reading:

László Zahorán and András Kovács. Proseqqo: A generic solver for process planning and sequencing in industrial robotics. Robotics and Computer-Integrated Manufacturing, submitted manuscript, 2021.

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Thank you for your attention!

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