51st CIRP Conference on Manufacturing Systems

CMS special session: Smart and Evolvable Production Systems

A software platform for supporting the design and reconfiguration of versatile assembly systems

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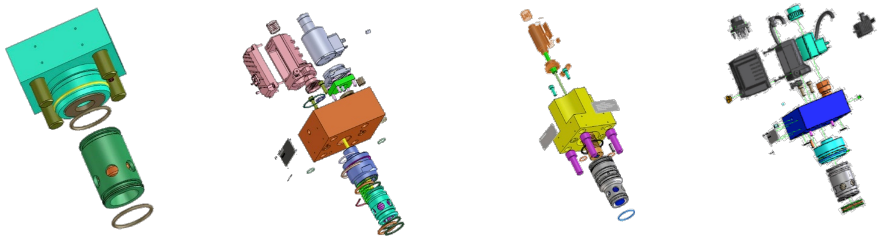
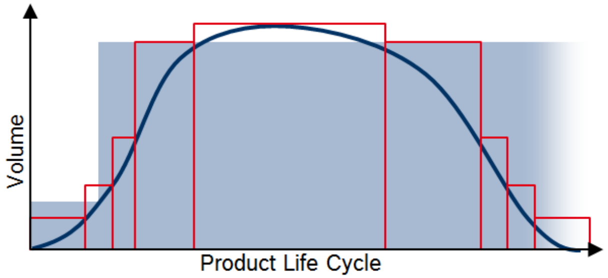
Problem context

- Assembly for mass customization, high number of product families, small lot sizes



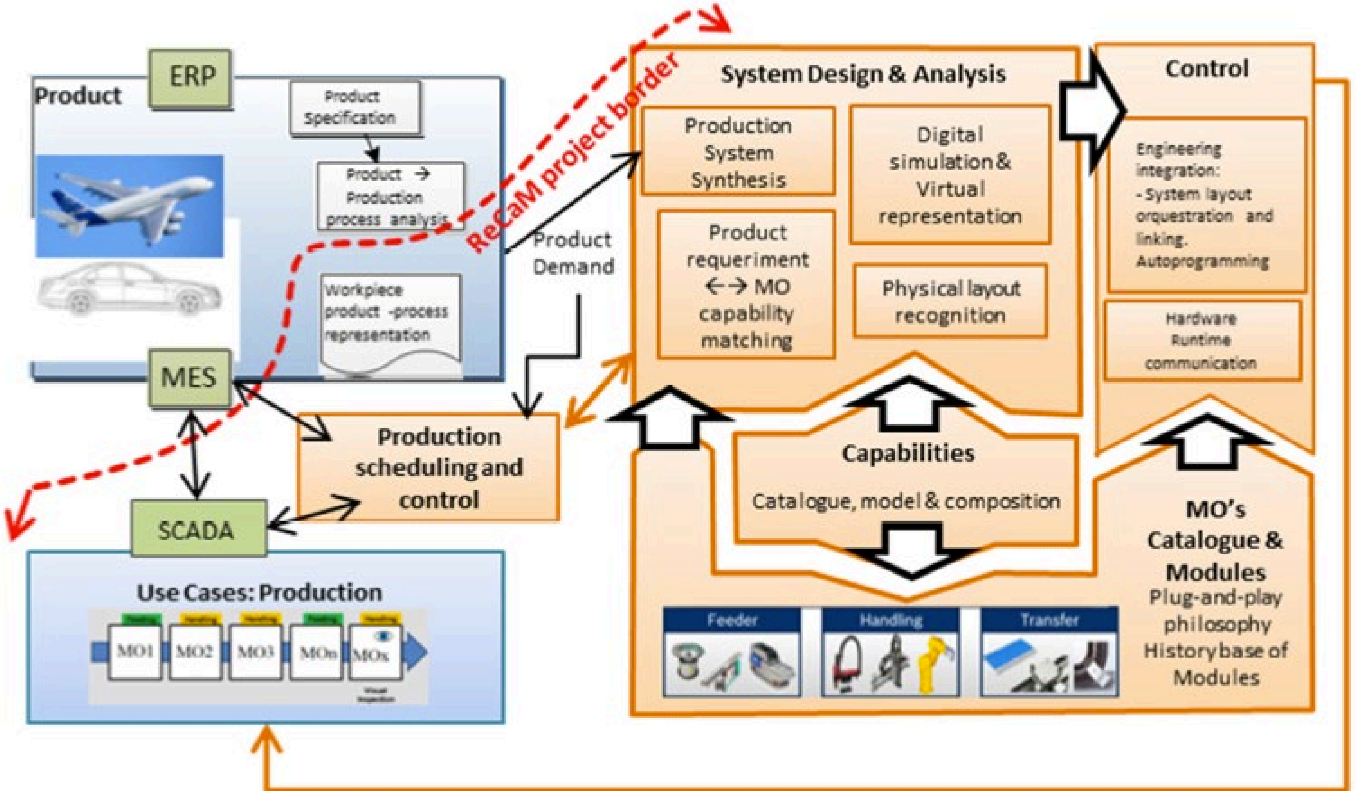
- Short product life-cycles, changing product-mix and high demand fluctuations



- Product varieties require different assembly processes that must be adapted through the use of modular resources

Design goals

The goal is to develop a system engineering platform connected to the mechatronic object catalogue, which allows the user to explore several potential configurations based on the capabilities of the Mechatronic Objects (MOs).



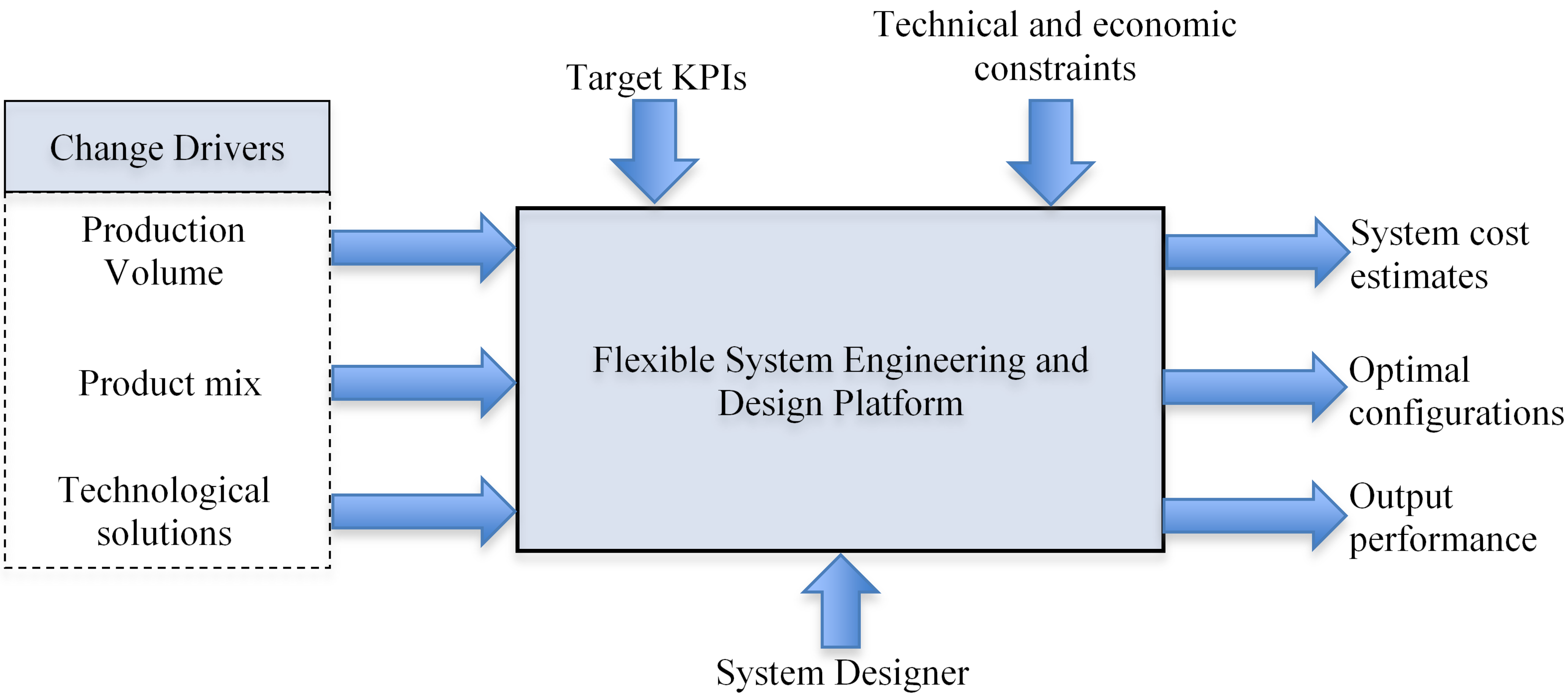
- System evolution according to future and uncertain scenarios
- Easy reconfigurability and flexibility
- Guarantee efficiency while producing low batch sizes
- Allow a fast introduction of new product types and ramp up time

Main challenges

The main design challenges under the given context include:

1. The input design parameters are not stable quantities, therefore they vary throughout the system life cycle.
   - E.g.: Product-mix and product volume change from period to period.
2. The design method needs to capture uncertainty related to future scenarios as the basis of the problem.
   - The evolution of scenarios and their occurrence cannot be predicted with certainty in advance.
3. Multiple aspects need to be considered into an integrated set of methodologies and tools that support the entire design problem.
   - E.g.: Equipment selection, workload balancing, equipment reliability, logistics performance, cost etc. should be measured during the analysis.

The design platform



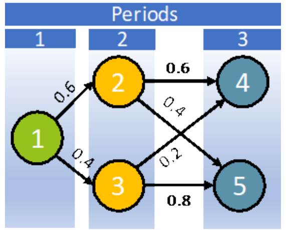
Overall architecture

Resource catalogues

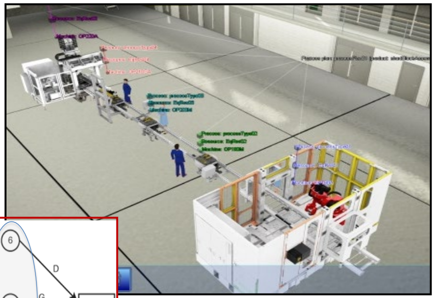
Matching algorithms

Product requirements

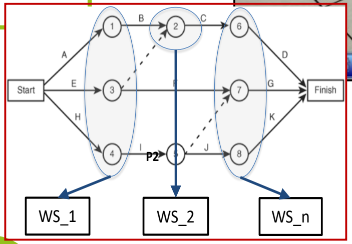
Multi-period:
- Product mix
- Demand



- Assembly system model generation
- Transportation modelling
- Processing station modelling
- System visualisation tool



- Reliability parameters
- Cycle times
- System topology



Performance evaluation tools

System configuration

Performance

mode FRONTIER

Multi-objective optimiser

Optimized layout and parameters → Robustness and simulation analysis

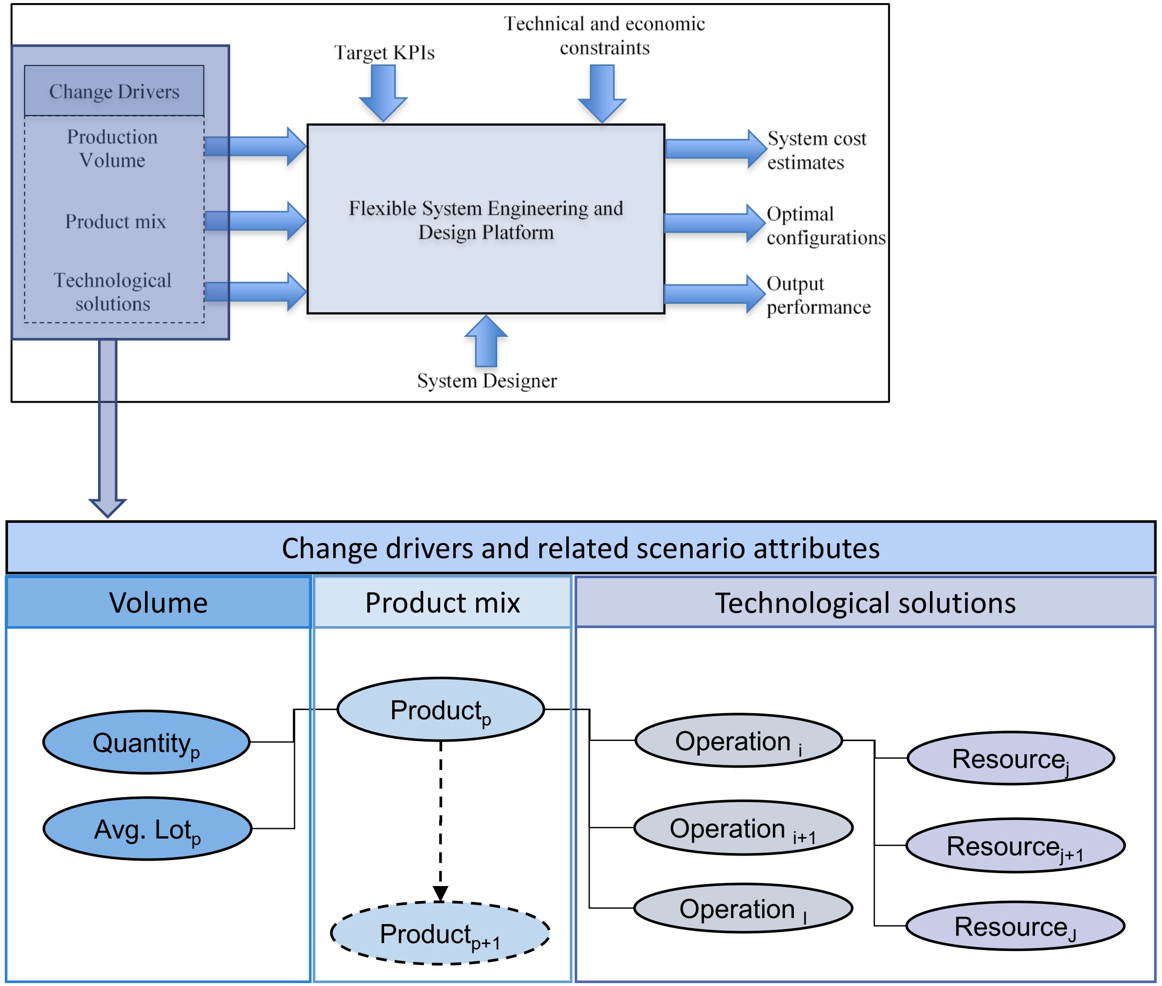
User– Platform Interaction

Optimal System Configuration

- ✓ MOs
- ✓ Optimal Configurations
- ✓ Performances

- Installation and testing of design solutions

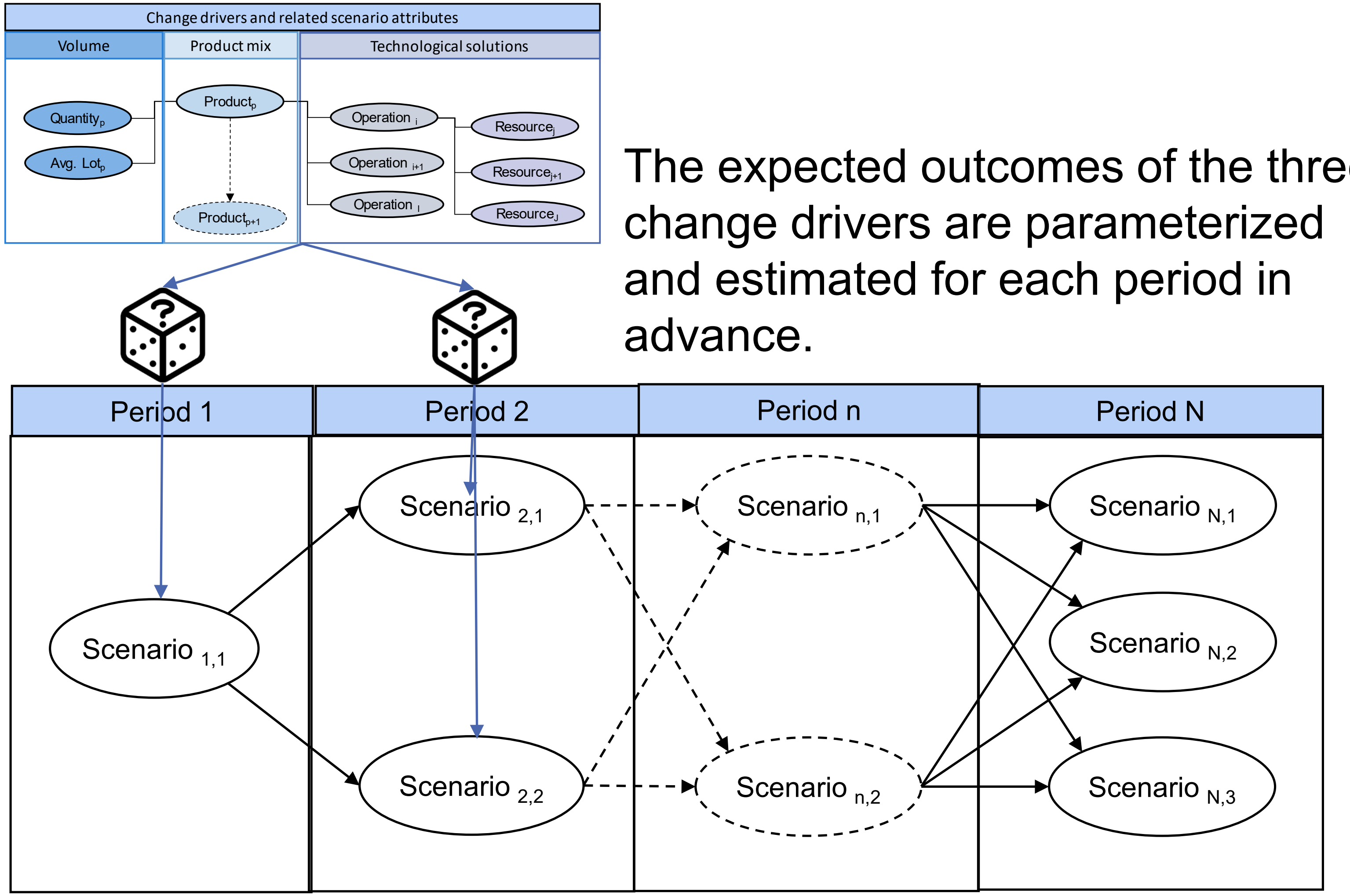
Scenario parameters definition



The input information consist of long term forecast about:

- Product mix, production volumes, expected volume changes and average lot sizes
- Product structure and the bill of materials and required assembly operations are provided by pre-processing tools.
- The outputs of these tools provide the list of candidate resources (Modules) capable of performing each operation.
- Each resource is associated to its parameters; technical (processing speed, reliability, setup times) and economic (purchase costs and operating costs).

Scenario parameters definition



The expected outcomes of the three change drivers are parameterized and estimated for each period in advance.

- As many as necessary number of scenarios can be defined in each period.
- The probability to transit between a preceding scenario and a following scenario are also estimates.
- The final output of this step generates the entire scenario tree of the problem.

Internal workflow of the platform

3.6.1 Single-scenario Objective Function

The single-scenario $o \in O$ objective function:

$$
\begin{aligned}
Z_o \;=\; & \sum_{s\in S}\sum_{m\in M} \mathbb{I}_{v,o}\, \Delta v\, \xi_{m,s,o} \left[CMbusy_m \cdot \bar{u}_{s,m,o} + CMfail_m \cdot \bar{f}_{s,m,o} + CMidle_m \cdot (1 - \bar{u}_{s,m,o} - \bar{f}_{s,m,o})\right] && (12)\\
& + \left[\sum_{p\in P}\sum_{k\in K} CBhold_{p,k} \cdot \overline{WIP}_{p,k,o})\right] && (13)\\
& + \sum_{m\in M} (CMinv_m + CMinstall_m) \cdot (Nline_{m,o}) + \sum_{k\in K}\sum_{b\in B} (CBinv_b + CBinstall_b) \cdot n_{b,k,o} && (14)\\
& + \sum_{m\in M}\sum_{s\in S} CF_m \cdot NF_{m,s} && (15)
\end{aligned}
$$

3.4 Non-linear quantities of the model

- The throughput of the assembly system in scenario o:

$$TH^o = \mathcal{F}(x_{i,p,s,o}, \xi_{m,s,o}, n_k, \mu_{i,p,?,o}, MTBF_m, MTTR_m, CMinv_m, \ldots)$$

- The utilization of each MO associated to a station in scenario o:

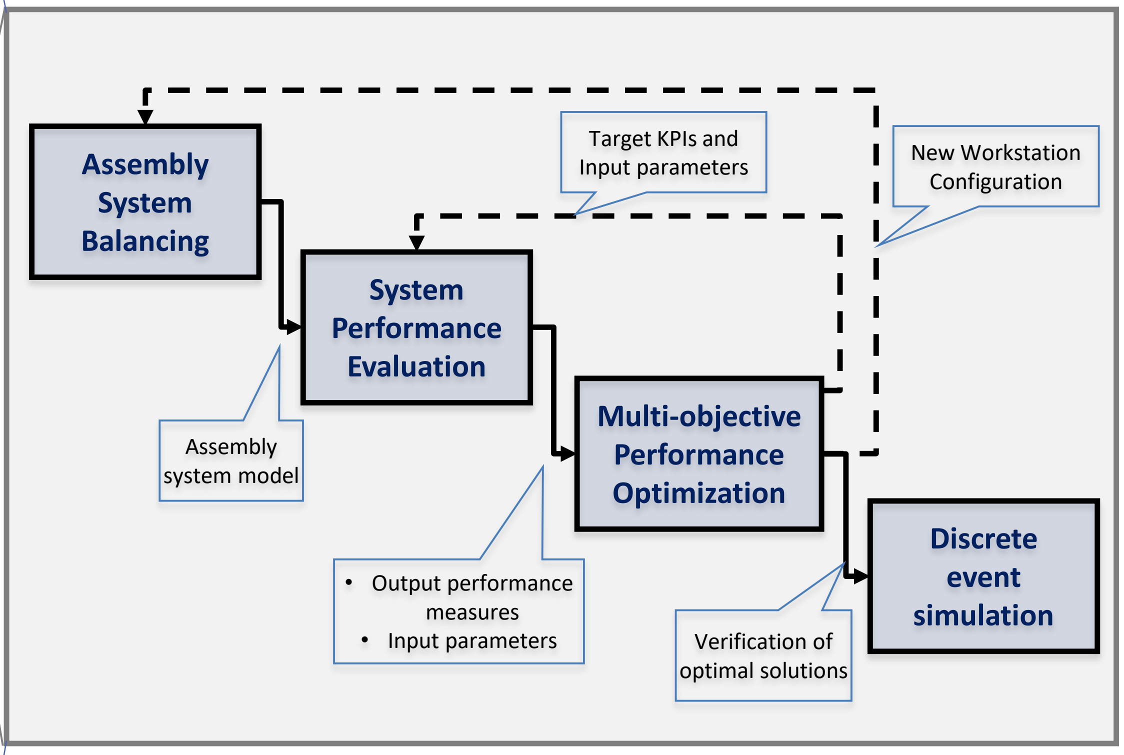
$$u_{s,m,o} = \mathcal{F}(x_{i,p,s,o}, \xi_{m,s,o}, n_k, \mu_{i,p,?,o}, MTBF_m, MTTR_m, CMinv_m, \ldots)$$

- The probability of being in failure of each MO associated to a station in scenario o:

$$f_{s,m,o} = \mathcal{F}(x_{i,p,s,o}, \xi_{m,s,o}, n_k, \mu_{i,p,?,o}, MTBF_m, MTTR_m, CMinv_m, \ldots)$$

- The number of failure of each MO associated to a station in scenario o:

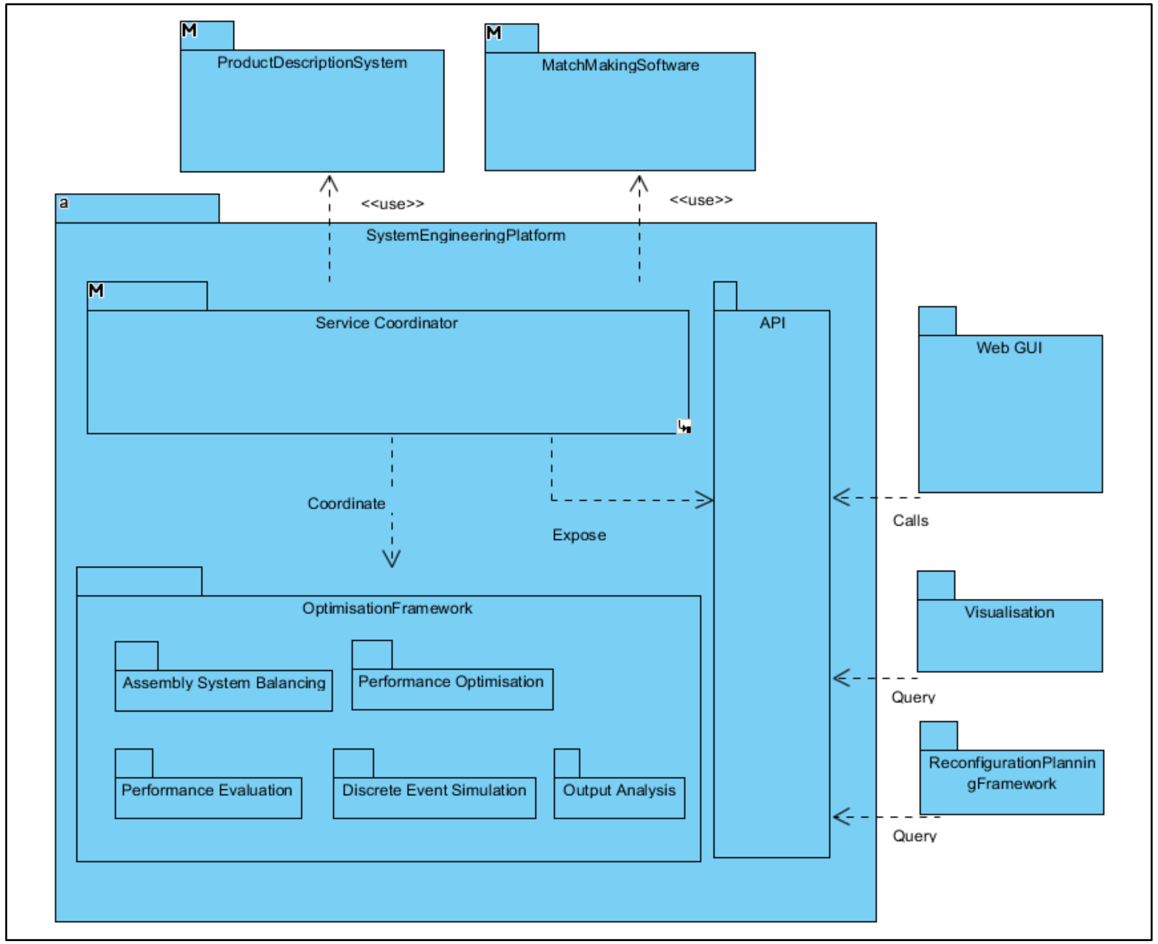
$$NF_{s,m,o} = \mathcal{F}(x_{i,p,s,o}, \xi_{m,s,o}, n_k, \mu_{i,p,?,o}, MTBF_m, MTTR_m, CMinv_m, \ldots)$$



Implementation and software components

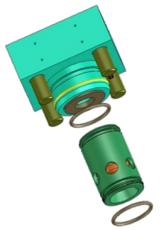
Optimization Framework

- Assembly System Balancing
  - SCIP + Soplex, ZIMPL
- Performance Evaluation
  - MATLAB Runtime 9.0 libraries, C++
- Performance Optimisation
  - modeFRONTIER 2016, Python
- Output Analysis
  - MATLAB
- Discrete Event Simulation
  - External tool (ARENA, etc.)



Test case – Bosch assembly system

- The **Bosch Case** regards the production of hydraulic valves for industrial applications.
- The test focuses on the assembly process of the production system.



- Fundamental characteristics are:
  - High number of product variants: only 6 products are investigated.
  - Dynamic and fluctuating production scenarios: spanning multiple periods need to be considered.
- The design of a flexible assembly system is based on reconfigurable mechatronic objects (MOs) with different capabilities to be selected for carrying out different tasks requested by the technological process of each product type.
- The system engineering methodology analyses the satisfaction of the requirements expected under each scenario, considering the overall cost of the output design.

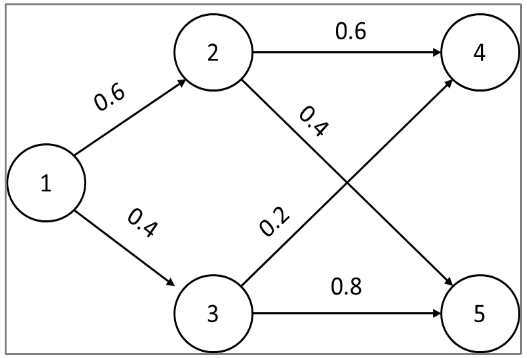
Test case – Bosch assembly system

Expected products' demand

For each of the scenarios, the demand of the different products has to be estimated and inserted as input.

Scenario	LFR	RKP	DAU	ZDC	FESX	WFCE	Min. throughput [JPH]
01	4500	1200	450	850	750	1500	4.478045
02	5500	1600	550	1000	850	3500	6.453214
03	1800	500	200	280	250	2000	2.468005
04	1500	400	180	250	230	3000	2.733978
05	7500	2000	900	1300	1000	6000	9.339882

To scenario specification

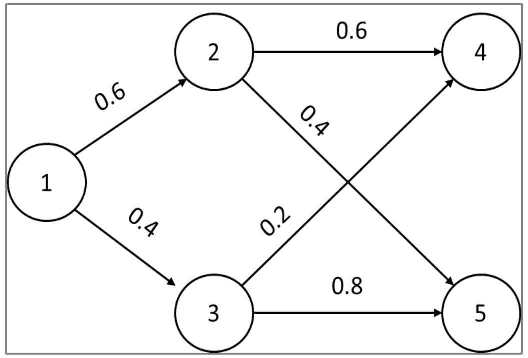


Test case – Bosch assembly system

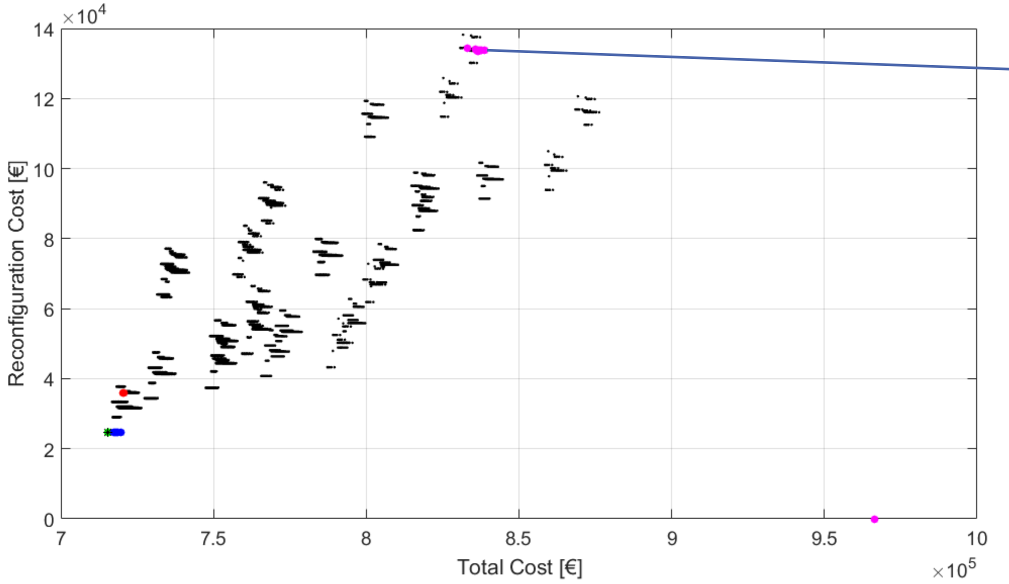
Processing technologies- Candidate Modules are the result of feasible combinations of MOs into workstations. Different modules have different costs and offer different levels of automation.

	Candidate Modules	M1	M 2	M3	M 4*	M 5*	M 6	M 7	M 8	M 9	M 10	M 11	M 12
	Operator	1	1	1	0	0	1	1	1	1	1	1	1
Mechatronic Objects	Universal fixture	1	0	1	0	0	1	1	1	0	1	0	0
	Classic fixture	0	1	0	0	0	0	0	0	1	0	1	1
	Fixture integrated to calibration	1	1	1	1	0	0	0	1	0	0	0	1
	Fixture integrated to leakage testing	1	1	0	0	1	0	1	0	0	0	0	0
	Fixture integrated to Press	1	1	0	0	0	0	0	0	0	0	0	0
	Fixture integrated to Laser engraving	0	0	0	0	0	0	0	0	0	0	0	0
	Automatic torque setting screw driver	1	1	1	0	0	1	1	1	1	1	1	1
	Automatic torque setting screw driver with special guidance	1	1	1	0	0	0	1	1	0	0	1	1
	Ogiva O-ring mounting	1	0	1	0	0	1	1	1	1	1	1	1
	Hammer	1	1	1	0	0	0	1	1	1	1	1	1
	Pressing gun	1	1	1	0	0	0	1	1	1	1	1	1
	Press	0	1	1	0	0	1	1	1	1	1	1	1
	Leakage testing	0	0	1	1	0	0	0	1	1	0	1	1
	Calibration	0	0	0	0	0	0	0	0	1	0	1	0
	Intelligent riveting tool	0	0	1	0	0	0	0	0	0	0	1	0
	Laser engraving	0	0	0	0	0	0	0	0	0	0	0	0
	Riveting tool	1	1	0	0	0	1	1	1	1	1	0	1

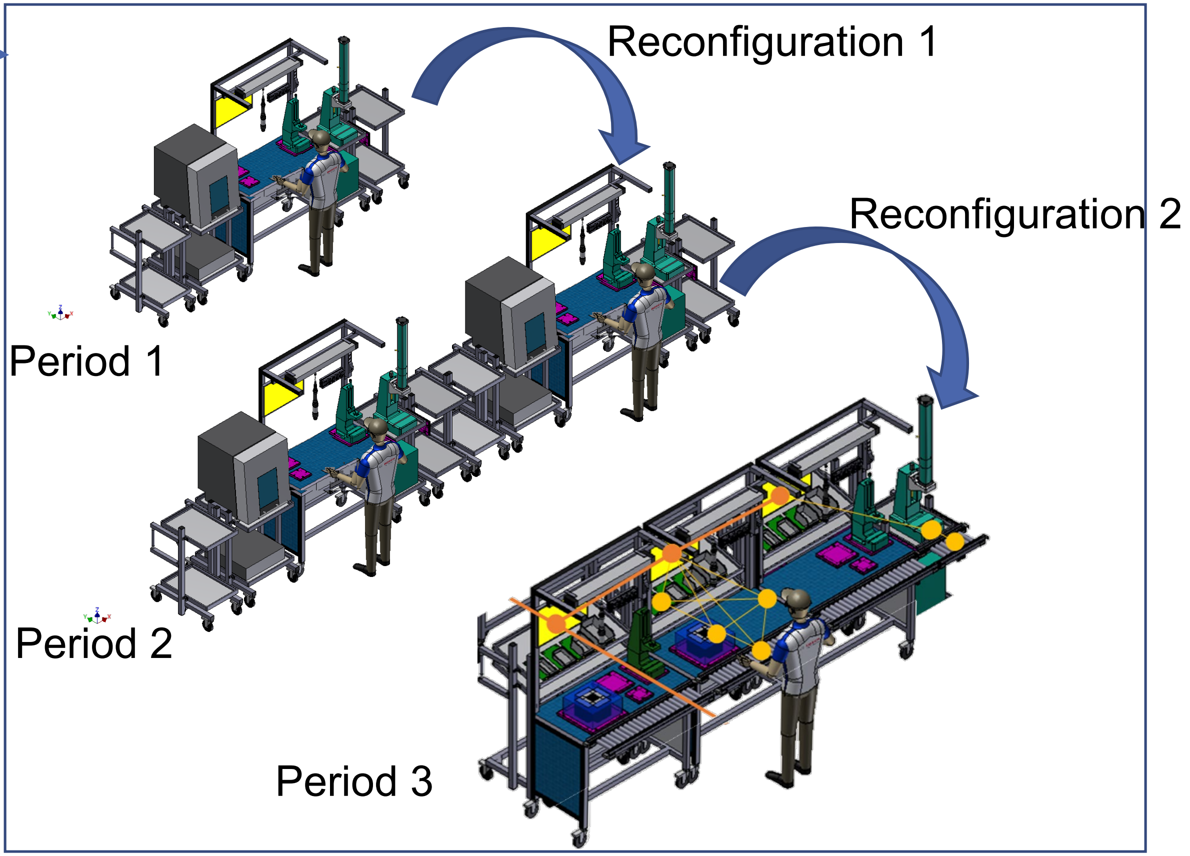
Assembly technological solutions are given by the match making tool



Test case – Bosch assembly system

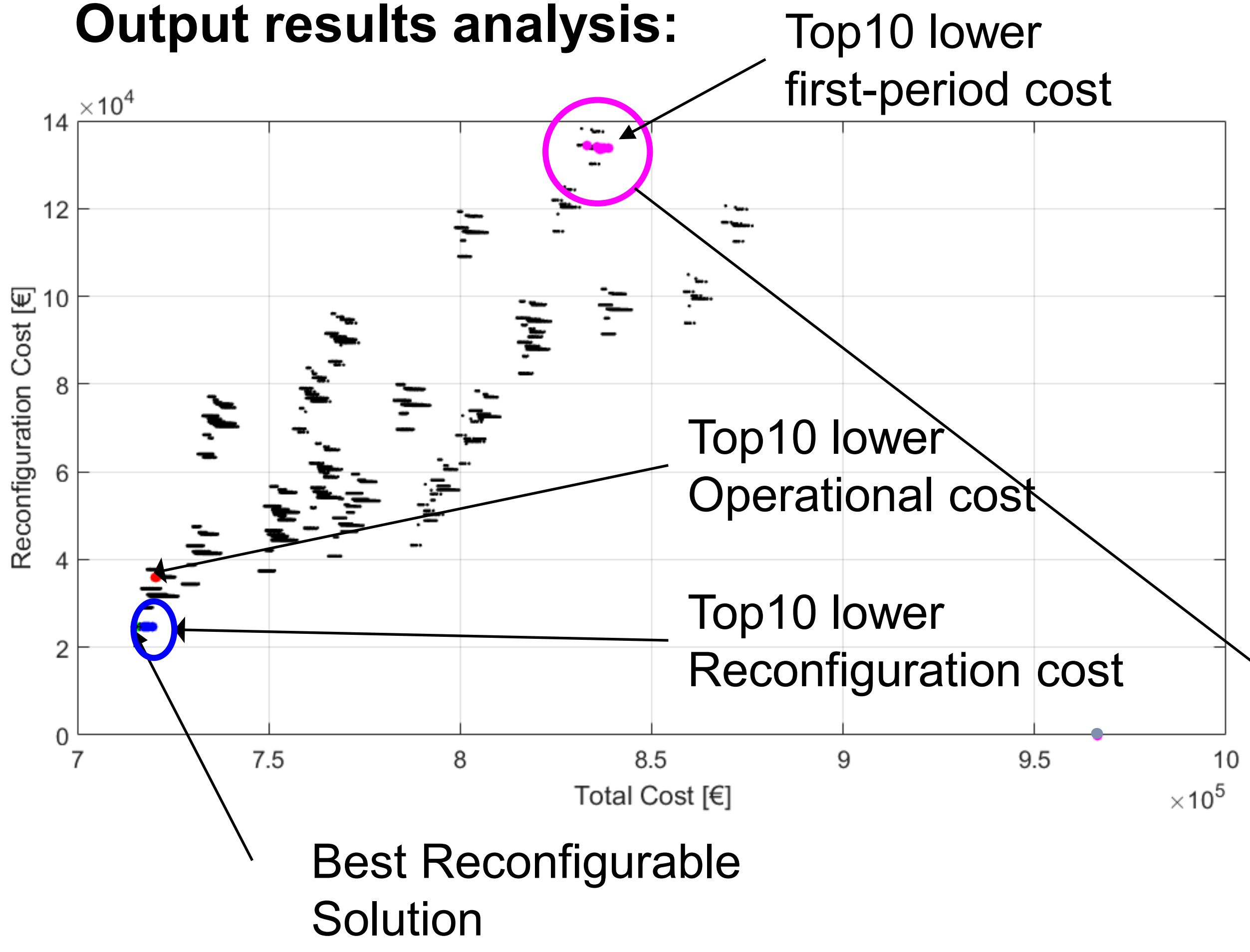


Each point in the solution list corresponds to a specific system design and reconfiguration throughout the system lifecycle



Test case – Bosch assembly system

Output results analysis:



- In total 161,051 solutions are explored
- The expected costs of some design solutions with respect to the «Best Reconfigurable Solution»

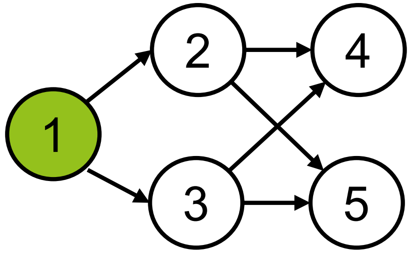
Cost Category	Total Expected Cost in (€)
Best Reconfigurable Solution	715,430
Flexible Solution for all scenarios	**+35%**
Solution that minimizes costs only for the initial period	**+23%**

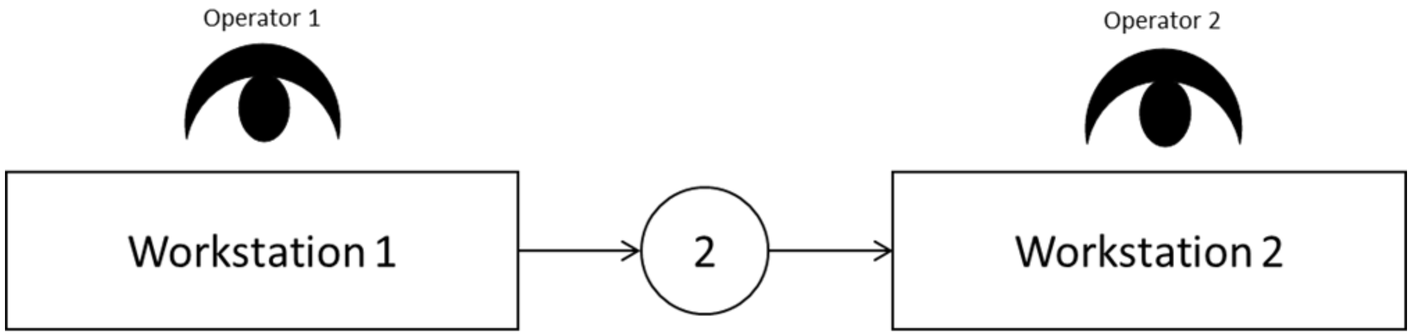
Compared to the solution that offers the minimum cost for the first period, the overall cost improvement of the reconfigurable solution is 23% lower.

Test case – Bosch assembly system

Output results interpretation

Optimal configuration analysis
Solution A – first period design



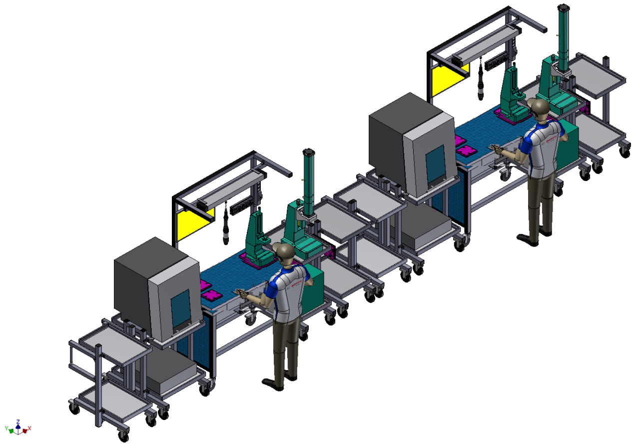


Workstation 1

- Classic fixture
- Fixture integrated to calibration
- Fixture integrated to leakage testing
- Fixture integrated to Press
- Automatic torque setting screw driver
- Automatic torque setting screw driver with special guidance
- Hammer
- Pressing gun
- Rivetting tool

Workstation 2

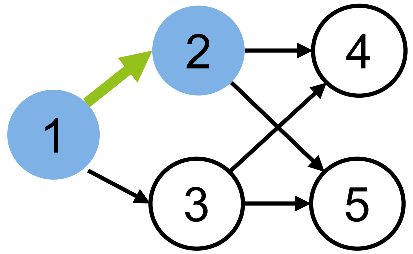
- Classic fixture
- Fixture integrated to calibration
- Automatic torque setting screw driver
- Automatic torque setting screw driver with special guidance
- Ogiva O-ring mounting
- Hammer
- Pressing gun
- Press
- Leakage testing
- Rivetting tool

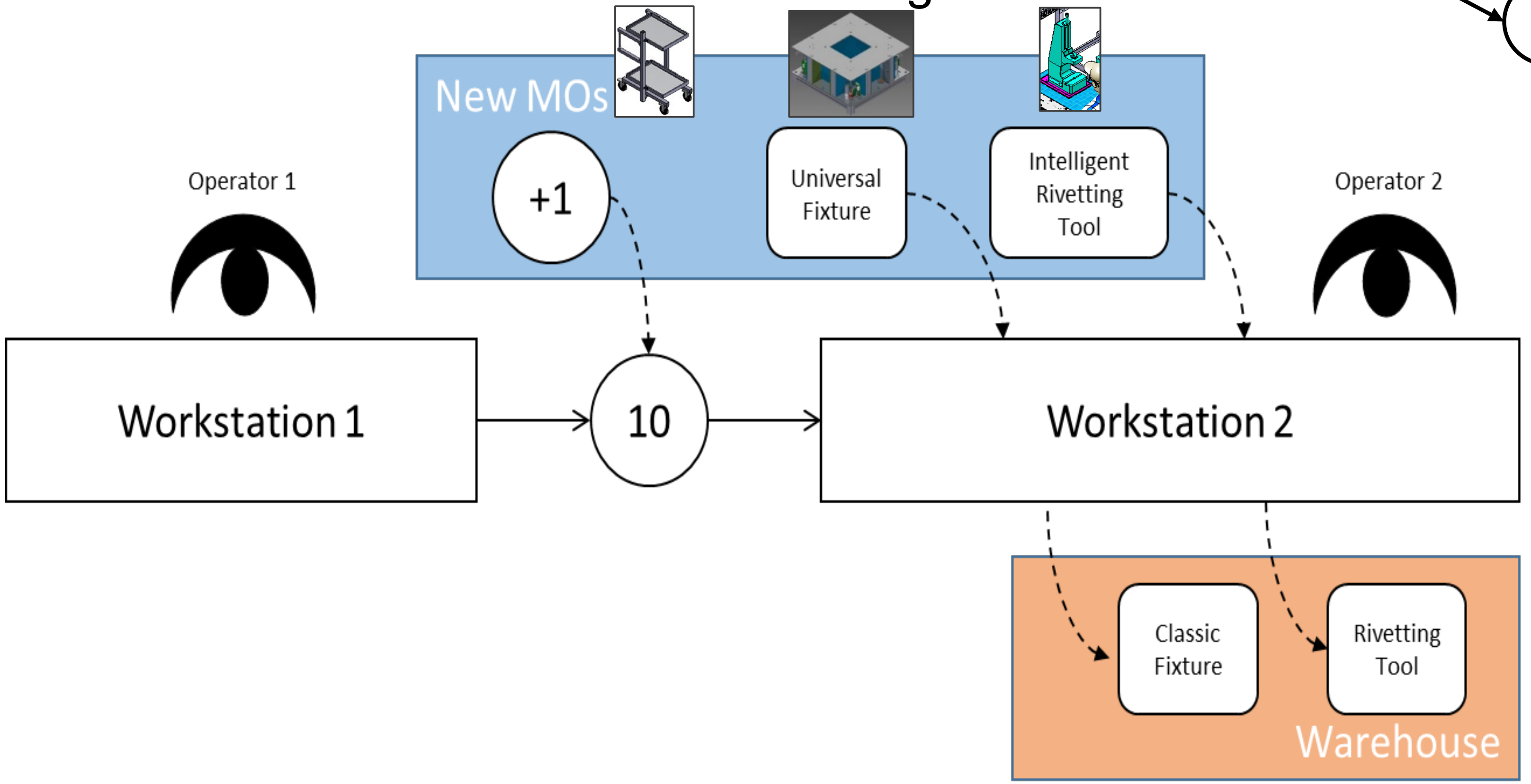


Test case – Bosch assembly system

Output results interpretation

Optimal configuration analysis
Solution A – reconfiguration 1-2

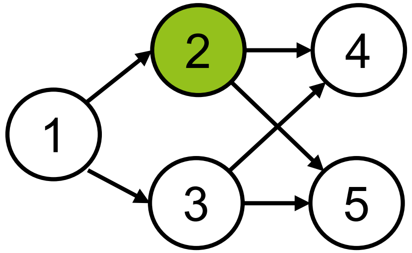


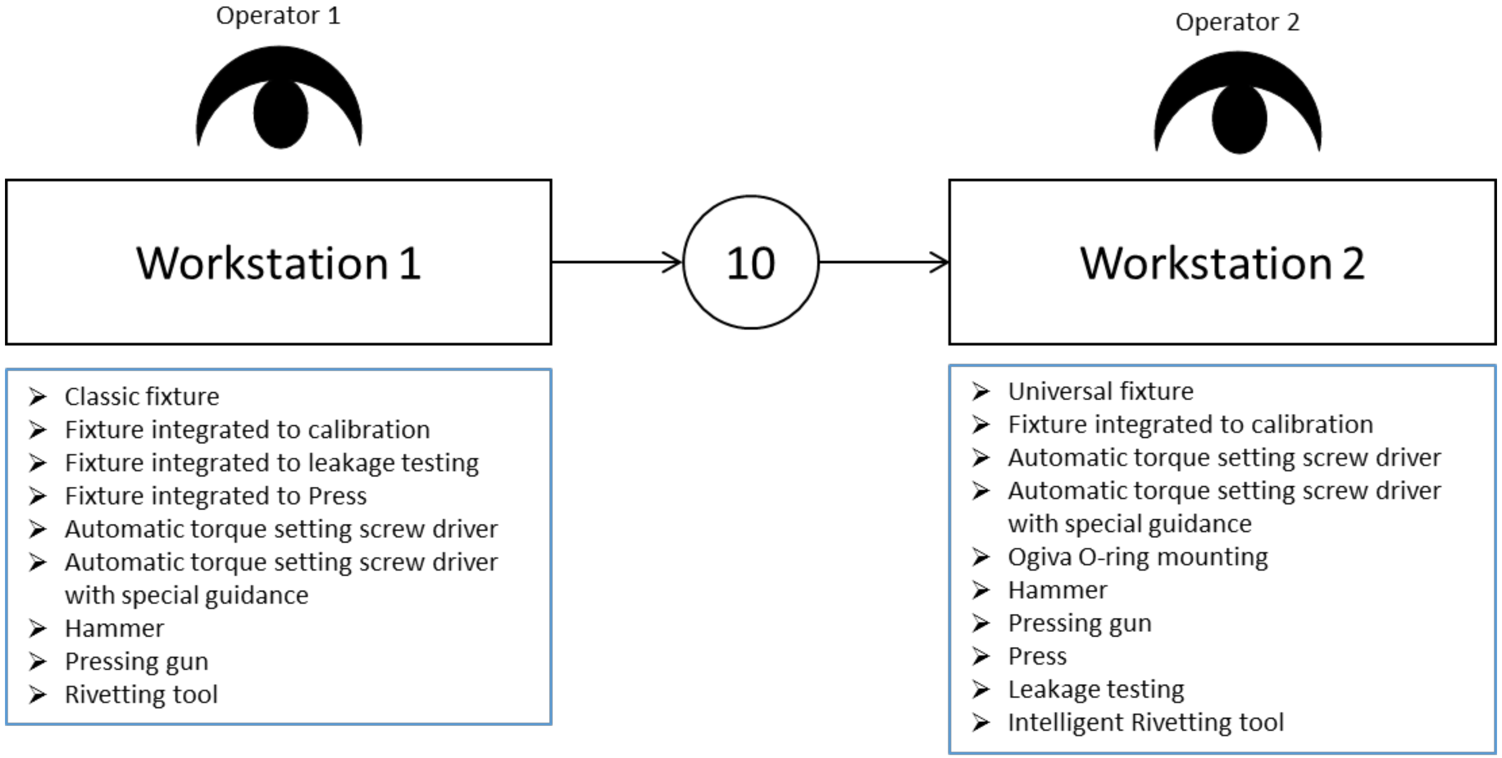


Test case – Bosch assembly system

Output results interpretation

Optimal configuration analysis
Solution A – second period design
(scenario 2)

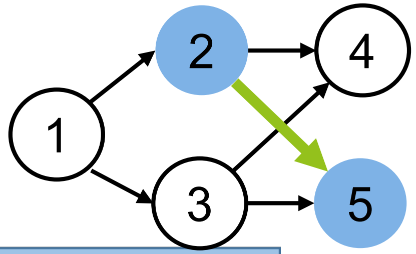


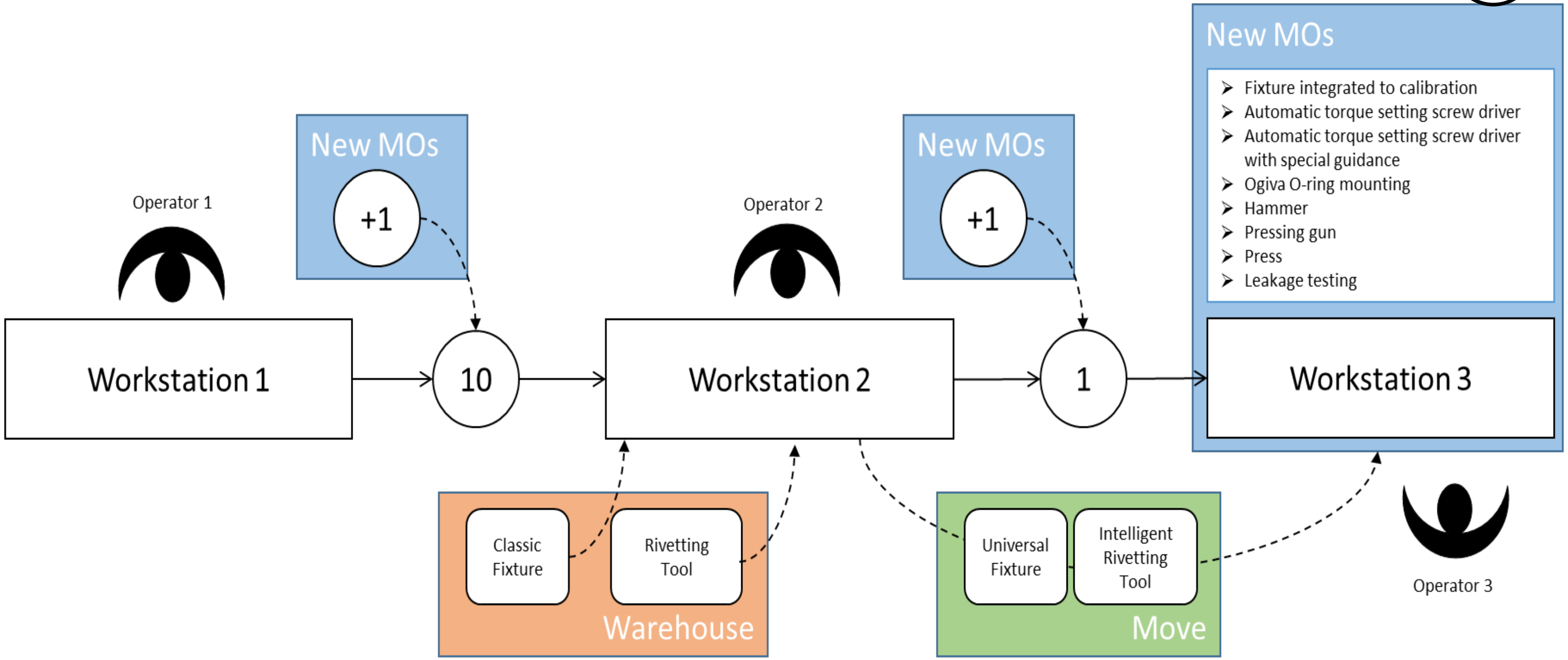


Test case – Bosch assembly system

Output results interpretation

Optimal configuration analysis
Solution A – reconfiguration 2-5

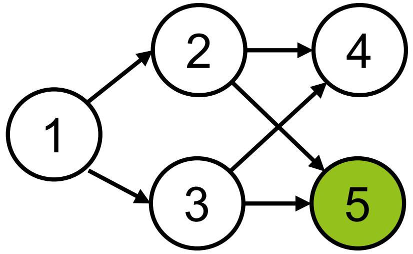


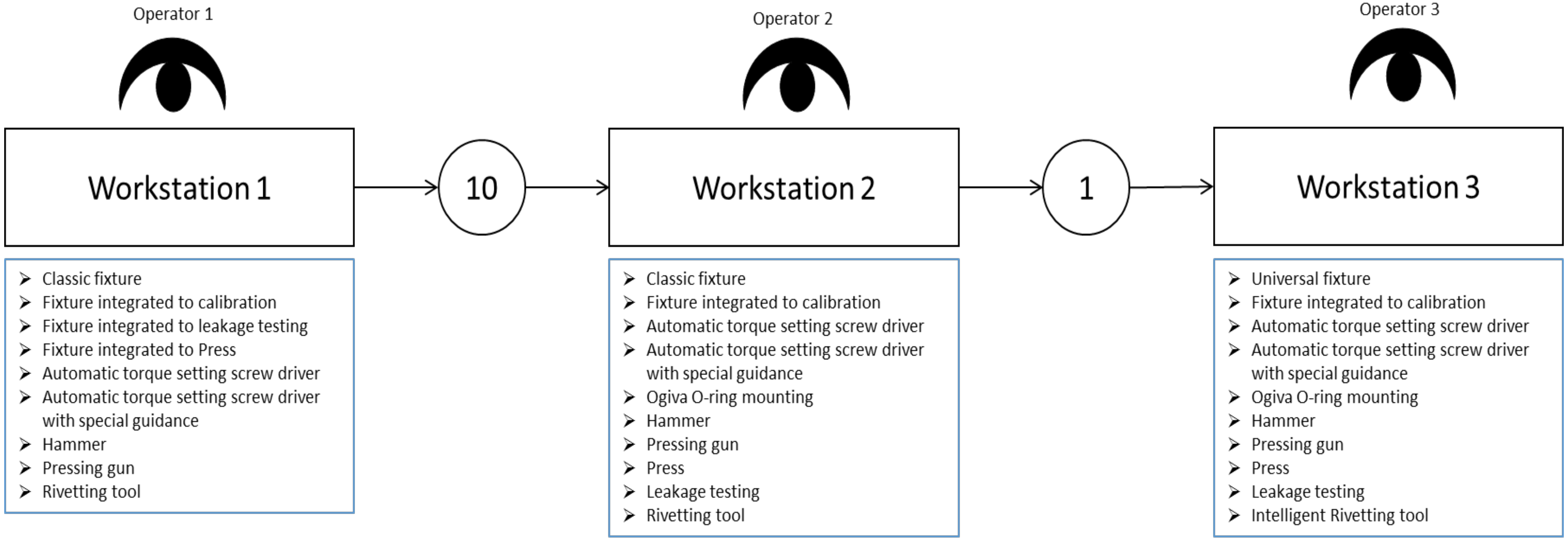


Test case – Bosch assembly system

Output results interpretation

Optimal configuration analysis
Solution A – third period design
(scenario 5)





Conclusions and Prospects

- A software platform considering a multi-period and multi-product problem with dynamic demand scenarios is developed.
- The platform allows to quantitatively evaluate the several reconfigurable system solutions that can adapt to anticipated future changes.
- The test case demonstrates that the optimal design solution is not necessarily the one that minimizes the total cost at the initial design period, but also the one that considers future changes over subsequent periods.
- The developed software platform can be generalized for an assembly design problem, enlarging the user basis of the tool, and improving it into a collaborative design environment for system designer, technology providers.

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Thank you for your kind attention!

Questions?