A Decision Support Methodology for the Design of Reconfigurable Assembly Systems

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June 11th 2018

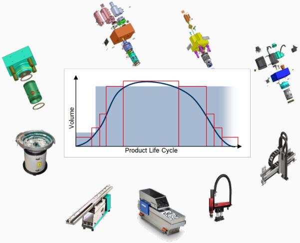
IFAC INCOM 2018 (Bergamo, Italy)

Introduction

Industrial Relevance

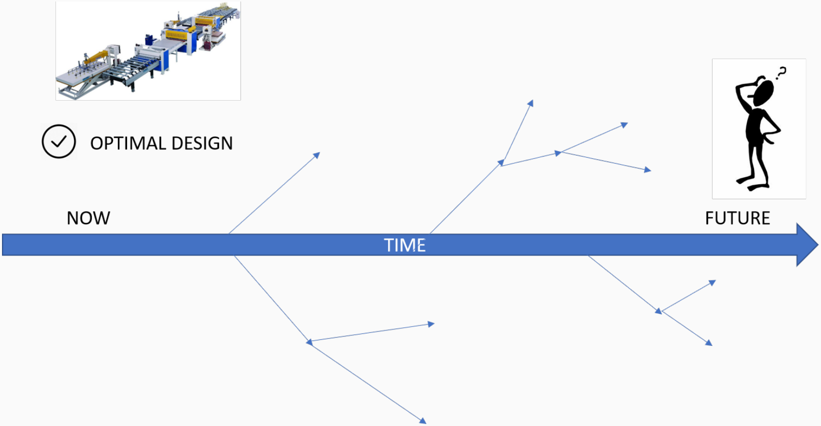
- Assembly for mass customization
- High number of product families
- Small lot sizes
- Short product life-cycles
- Changing product-mix and
- High demand fluctuations

The problem the manufacurers are facing is:



1. multi-period
2. multi-product
3. long-term
4. modular and complex system

Industrial Relevance



Scientific Relevance

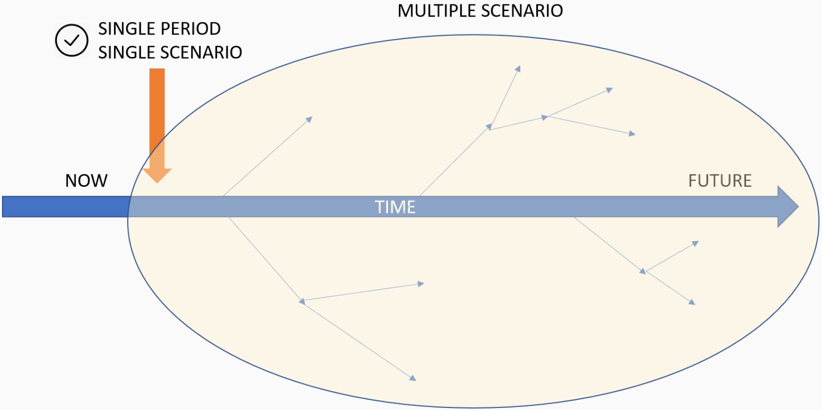
- Some of the main problems concerning system design of large-scale production systems include
  - Assembly Line Balancing (Becker and Scholl, 2006)
  - Buffer Allocation (Demir et al., 2014)
  - Capacity estimation (Wazed et al., 2010).
- Solving methods include:
  - Stochastic approaches play a central role in system design (Tolio, 2008)
  - Analytical approaches (Shabanpour and Colledani, 2018; Colledani et al., 2015; Colledani, 2013; Colledani and Gershwin, 2013; Colledani et al., 2014)
  - Stochastic Programming (J. R. Birge and F. Louveaux., 1997) is based on the assumption that the fluctuation of model parameters is governed by their probability distribution.
  - Alternative methodologies to deal with uncertainty include robust approaches, such as the ones proposed in (Ben-Tal, A. and Nemirovski, A., 2000) and reviewed in (Bertsimas et al., 2011).

In general

Methods applicable to real industrial problems characterized by complexity, multi-objective and multi-period decision making are not widely available.

Problem Statement

Problem


MULTIPLE SCENARIO
SINGLE PERIOD
SINGLE SCENARIO
NOW
TIME
FUTURE

Sub-problems

Single-period

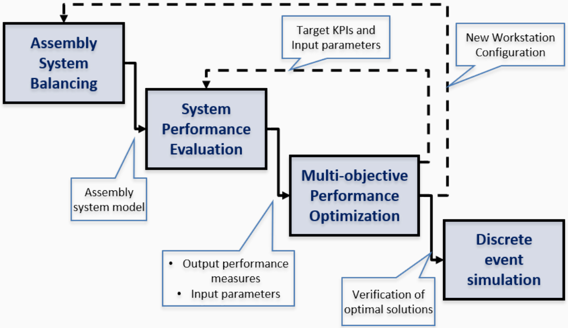
- Design solutions satisfying requirements defined within each scenario
- It is a greenfield design problem,
- Single-period problems can be solved independently
- It consists of:
    1. Multi-product Assembly Line Balancing (MALB)
    2. Buffer Allocation Problem (BAP)

Multiple-period

- System configurations taking into account **all** the possible paths along scenarios that the system might have to face

The RecaM Approach

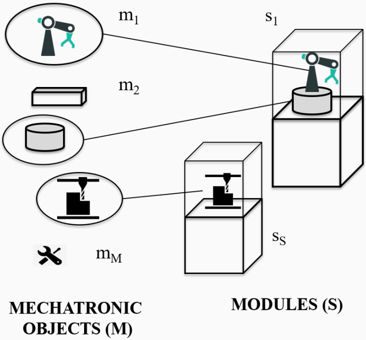
- The methodology is developed in the ReCaM project.
- Part of a software platform that supports engineers in the green field design phase of assembly systems.
- Composed of interconnected software building blocks that exchange information with both product and resource catalogues and the Manufacturing Execution Systems (MES).



The ReCaM Approach

Resources

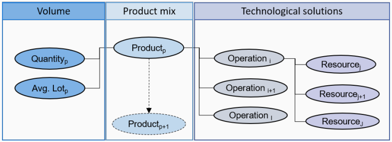
Modular and programmable resources called Mechatronic Objects (MOs) provide the processing capabilities required by the products.



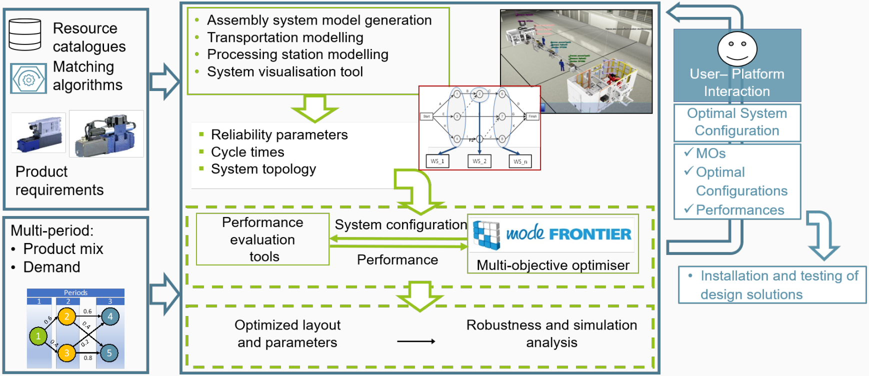
Products

The input information consist of long term forecasts:

- Product mix
- Production volumes
- Expected volume changes
- Average lot sizes



The ReCaM Approach



Methodology

Notation

Define:

$v \in V$ Set of discrete and finite time windows (i.e. periods)
$o \in O$ Scenarios Set of production forecast *scenarios*;
$p \in P$ Set of *product* variants to be produced over the entire planning horizon;
$i \in I$ Tasks of *tasks* to be executed (among all product $p \in P$);
$m \in M$ Set of *Mechatronic Objects* that can supply a certain set of capabilities;
$s \in S$ Set of *stations* that are instantiated;
$b \in B$ Buffer types (technological choice of buffer system)

Δv Period length [h]
π_{o_i,o_j} Transition probability between scenarios
$CMinv_m$ cost of module m
$CBinv_b$ Cost of buffer b
$CMbusy_m$ working Cost
$CMidle_m$ starving and blocking cost
$CMfail_m$ Failure Cost
CF_m Cost per failure event

$CBhold_{p,k}$ Inventory Cost
$CMstock_m$ Inventory Cost
$CMinstall_m$ Installation Cost of MO type m at a certain station.
$CMuninstall_m$ Uninstallation Cost
$CBinstall_b$ Installation Cost of buffer-type b

Single-period problem

Objective: minimize: single-period objective function Z_o

Decision variables

- Tasks-stations assignments ($x_{i,p,s,o}$)
- MOs-stations assignments ($\xi_{m,s,o}$)
- Instances of MO type m assigned ($Nline_{m,o}$)
- Capacity of k-th buffer ($\beta_{b,k,o}$)
- Buffer slots of type b installed ($n_{b,k,o}$)

Constraints

- Demand satisfaction constraints (i.e. minimum throughput)
- Line Balancing constraints (e.g. precedences)
- Buffers-related constraints (e.g. maximum capacity)

Some quantities in the model are non-linear

- The throughput of the assembly system in scenario o (TH^o)
- The utilization of each MO associated to a station in scenario o ($u_{s,m,o}$)
- The probability of failure for a MO in a station in scenario o ($f_{s,m,o}$)
- The average inventory of product p in the buffer k in scenario o ($WIP_{p,k,o}$)

Objective Function Z_o - Single-period

The objective function Z_o includes:

Operating costs

$$CMbusy_m \cdot \bar{u}_{s,m,o}$$

Failures costs

$$CMfail_m \cdot \bar{f}_{s,m,o}$$

Idle times costs

$$CMidle_m \cdot (1 - \bar{u}_{s,m,o} - \bar{f}_{s,m,o})$$

Inventory costs

$$\sum_{p \in P} \sum_{k \in K} CBhold_{p,k} \cdot \bar{WIP}_{p,k,o})$$

Investment costs of MOs

$$\sum_{m \in M} (CMinv_m + CMinstall_m) \cdot (Nline_{m,o})$$

Investment costs of buffers

$$\sum_{k \in K} \sum_{b \in B} (CBinv_b + CBinstall_b) \cdot n_{b,k,o}$$

Failures costs (events)

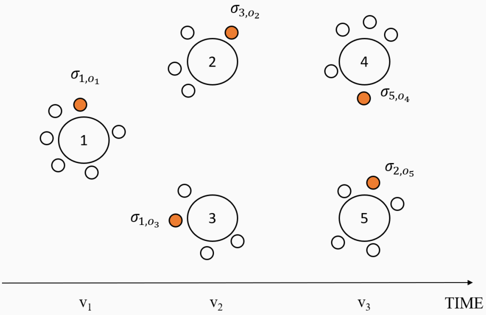
$$\sum_{m \in M} \sum_{s \in S} CF_m \cdot NF_{m,s}$$

Objective Function - Multiple-period

Notation

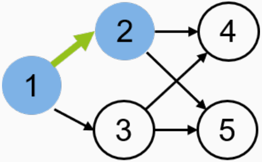
- $\sigma_{r,o} \in \Sigma$: r^{th} solution found for the single-period, single-scenario problem for scenario $o \in O$.
- Ψ: set of all the permutations of feasible solutions.
- $\gamma \in \Gamma(\psi_i)$ is a path through a set of solutions. It represents a feasible sequence over time periods for the i-th permutation ψ_i.

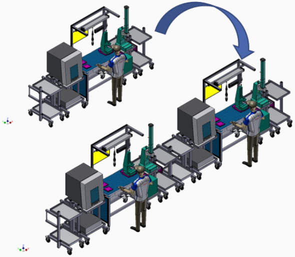
$$\phi_i = \{\sigma_{1,o_1}, \sigma_{3,o_2}, \sigma_{1,o_3}, \sigma_{5,o_4}, \sigma_{2,o_5}\}$$



Objective Function - Multiple-period

Suppose to go from scenario o_1 to o_2 from period v to $v + 1$.



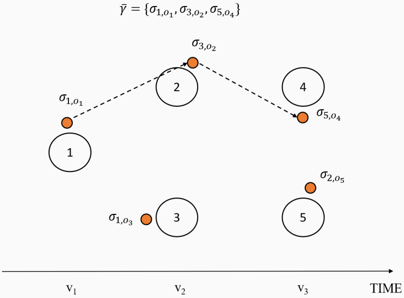


Reconfiguration actions may be taken:

- **Buy** a new module m on a station s;
- **Move** a module m from one station to another;
- **Store** a module m in a warehouse/stock;
- **Move back** module m from stock to the system.

Objective Function - Multiple-period

$\rightarrow$ The total cost Z_{tot,ψ_i} depends on the particular permutation of solutions:



Total cost

$$Z_{tot,\psi_i} = \sum_{\gamma \in \Gamma(\psi_i)} Z_\gamma \cdot \pi_\gamma$$

$$Z_\gamma = \sum_{o \in \gamma} Z_o$$

$$\pi_\gamma = \prod_{\{i\} \in \Gamma(\psi_i)} \pi_{i,i+1}$$

$\rightarrow$ The multi-period, multi-scenario problem becomes:

$$\min_{\psi_i \in \Psi} Z_{tot,\psi_i}$$

That is, finding the permutation of solutions ψ_i that minimizes the total system cost, satisfying all the problem's constraints.

Solution method

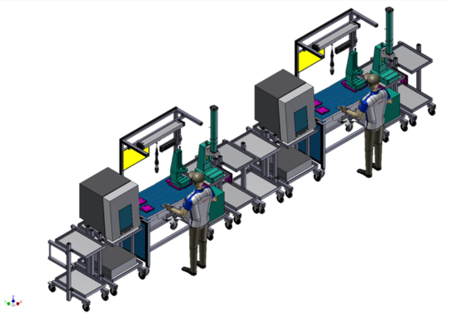
- The solution method is heuristic (complete enumeration).
- Each scenario is solved independently as single-period problem, and a certain number (user-specified) of near-optimal solutions are generated .
- By sampling one solution from each single scenario, a permutation of solutions at the scenario level is generated. The result is a set of solutions Σ, and the corresponding set of permutations Ψ.
- From this point, the heuristic follows an exhaustive enumeration over all the $\psi_i \in \Psi$.

  a) List all the permutations $\psi_i \in \Psi$.
  b) Calculate the set of feasible paths for each permutation $\Gamma(\psi_i)$.
  c) For each permutation, calculate the solution of single-scenario problems for all the scenarios along the feasible paths.
  d) For all the feasible paths, evaluate the expected total cost.
  e) Solve the global minimization problem.
  f) Enunerate the cost of solutions found and select the minimum ones.

Case-study

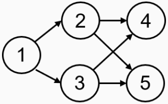
Case-study

The use case involves an assembly line for the production of hydraulic valves:



Data

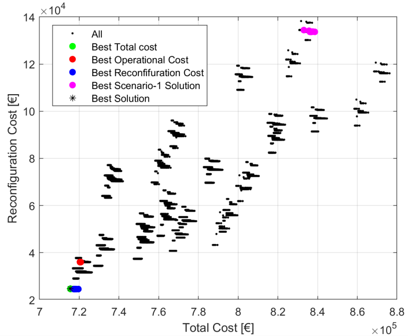
- 6 product types
- 19 modules
- 3 years horizon
- 5 scenarios

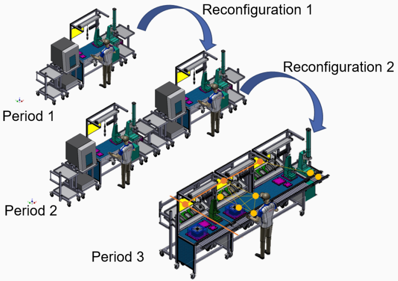


- 11 solutions have been drawn for each of the 5 single-scenario sub-problems, for a total of $|\Psi| = 161051$ permutations.
- Each of these solutions represent the configuration of an assembly line.
- The complete enumeration algorithm took around 10 minutes to be solved on a DELL XPS13 laptop with 8 GB memory and INTEL 2.3-GHz, i7 processor.

Case-study

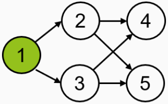
→ Each point in the solution list corresponds to a specific system design and reconfiguration throughout the system lifecycle.

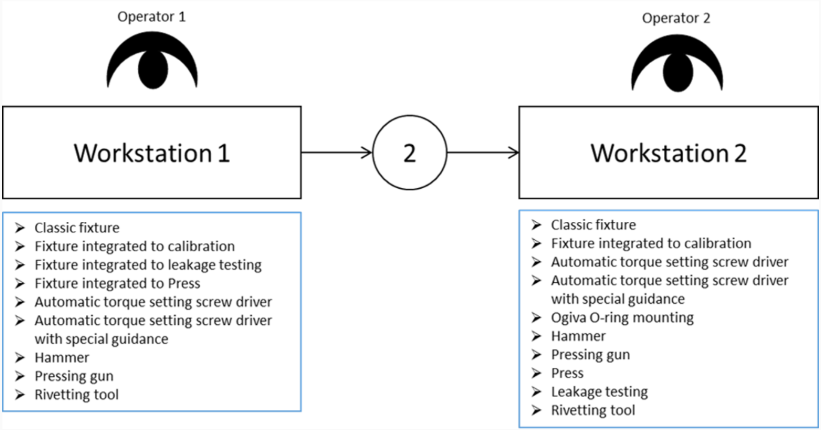




Cost Category	Total expected Cost [€]
Best Reconfigurable Solution	715,430
Flexible Solution for all scenarios	+ 35 %
Solution that minimizes costs only for the initial period	+ 23 %

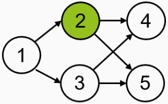
Results

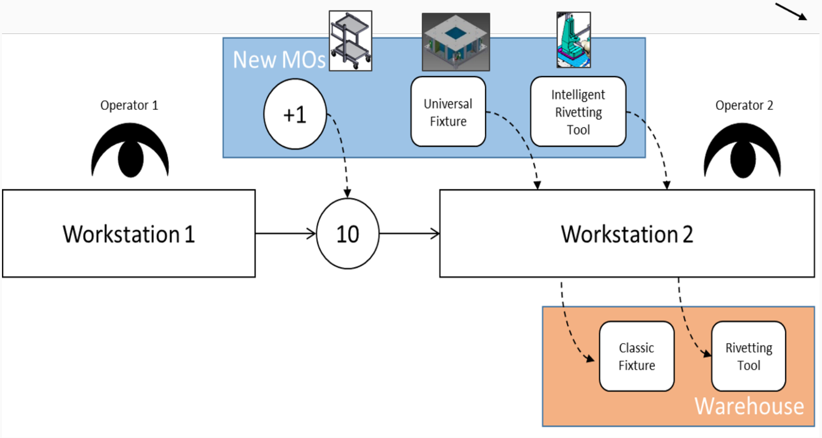




Solution A – first period design

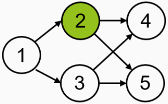
Results

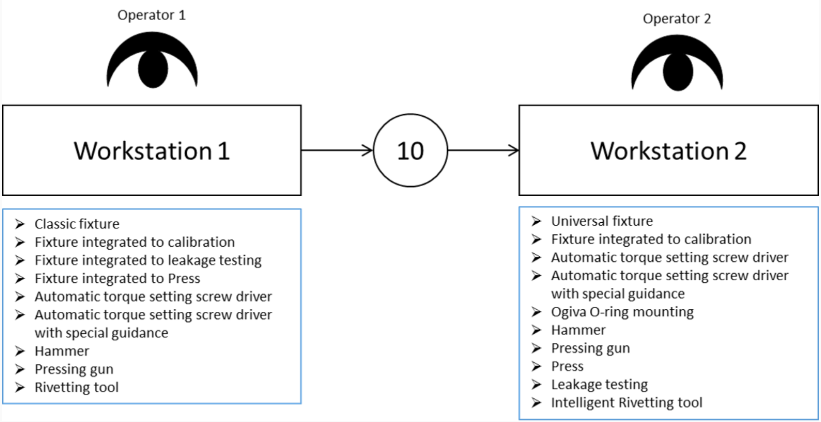




Solution A – reconfiguration 1-2

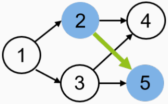
Results

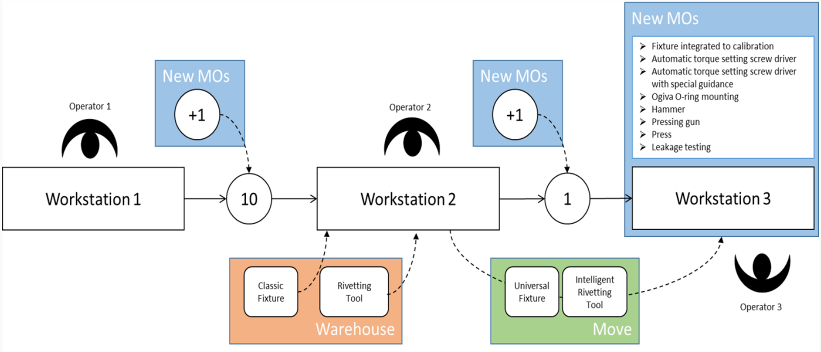




Solution A – second period design (scenario 2)

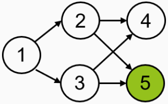
Results

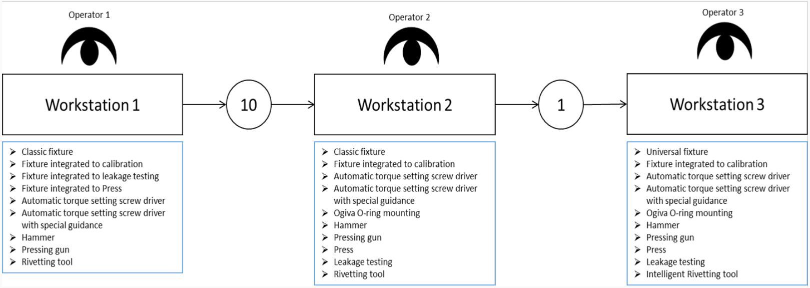




Solution A – reconfiguration 2-5

Results





Solution A – third period design (scenario 5)

Conclusions

Conclusions

- A methodology for supporting the green-field design of reconfigurable assembly systems by considering a multi-period problem, characterized by uncertain product-mix and demand scenarios.
- The system configuration decisions taken at the initial design phase can consider possible future system modifications that might be needed within the planning horizon.
- The approach identifies optimal designs capable of quickly and efficiently adapting towards product variant and production quantity changes.
- The optimal solution is not always the one that minimizes the total cost over a certain time horizon, but the system configuration that is more adaptable to the anticipated future changes.

Future research

→ Extend the formulation to include spatial constraints, product routing constraints, layout constraints, as well as specific user-defined constraints.

→ Efficient and faster solution techniques are needed. Candidates are genetic algorithms, branch-and-bound algorithms, and neural networks.

Thank You

ReCaM

Rapid reconfiguration of flexible Production Systems

recam-project.eu

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Assumptions

- It is assumed that the set of *scenarios* are finite and describe possible forecasts of product-mix and quantities.
- All reconfiguration actions happen only between two consecutive periods, and include:
    1. the **upgrade** of a station in terms of installation/uninstallation of resources,
    2. the **purchase** of a new resource
    3. the **storing** of a resource in a warehouse because it is not required for production.
- once an instance of a certain resource (MO, buffer) is uninstalled from the layout, it is moved to a warehouse to be stored.
- The reconfiguration costs are considered as the costs of reconfiguring the system between two scenarios in sequential periods
- Unused MOs are stored in a warehouse.