# Design Optimization of Time- and Cost-Constrained Fault-Tolerant Distributed Embedded Systems

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## Motivation

- Hard real-time applications
  - Timing constraints
  - Cost constraints

- **Faults**
  - Predictable
  - **Transient**
  - Intermittent

- Hardware solutions
  - MARS, TTA, X-by-Wire
    - Permanent faults
    - Costly for transient faults

**vs.**

- **Software solutions**
  - Re-execution/rollback recovery
  - Checkpointing/rollback recovery
  - Replication, primary-backup…

- Online preemptive
  - Flexible

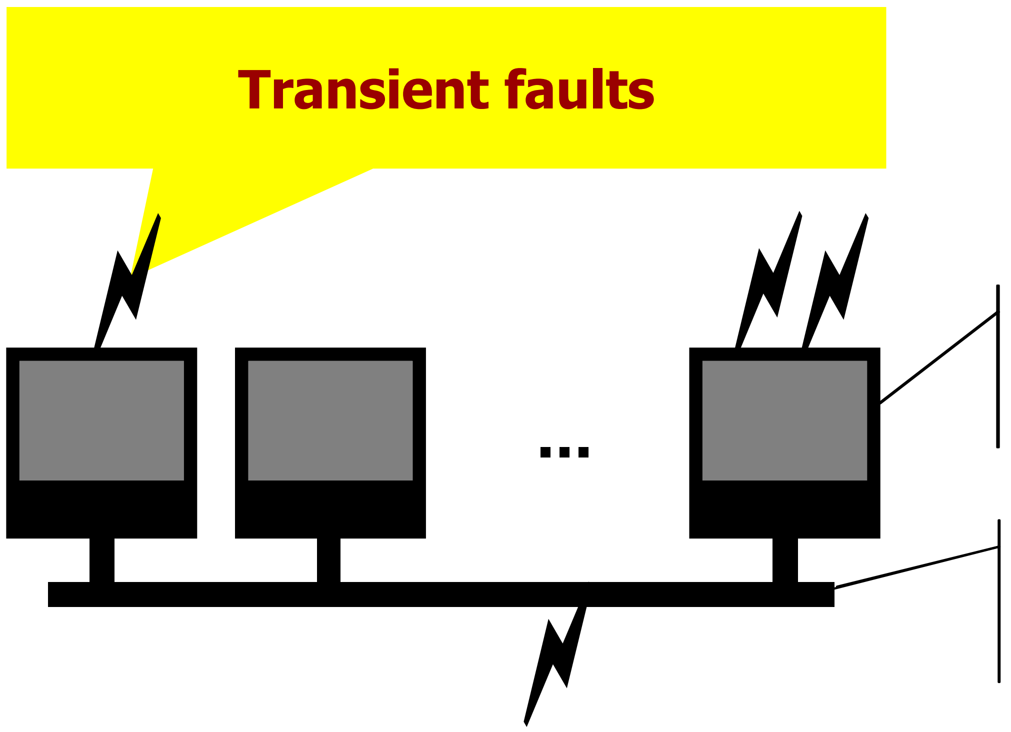
**vs.**

- **Off-line non-preemptive**
  - Predictable

## Outline

- Motivation
- ➔ System architecture and fault-model
  - Fault-tolerance techniques
- Problem formulation
  - Motivational examples
- Tabu-search optimization strategy
- Experimental results
- Contributions and Message

# Fault-Tolerant Time-Triggered Systems

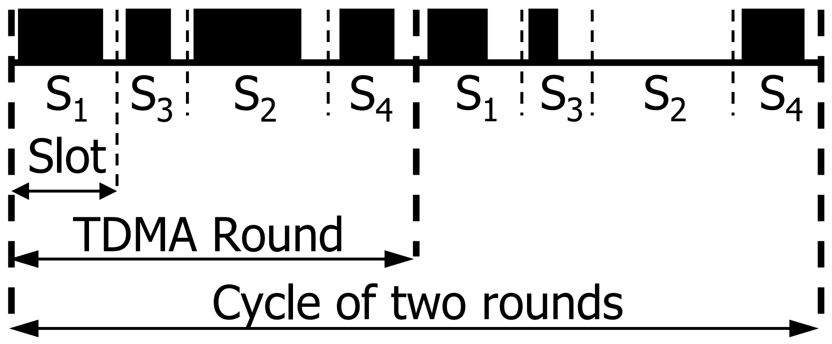


**Processes:**
Re-execution and replication

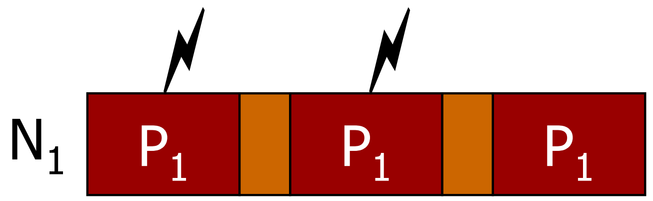
**Messages:**
Fault-tolerant protocol

Time Triggered Protocol (**TTP**)

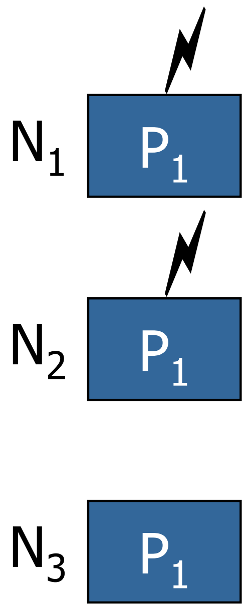
- Bus access scheme: time-division multiple-access (TDMA)
- Schedule table located in each TTP controller: message descriptor list (MEDL)



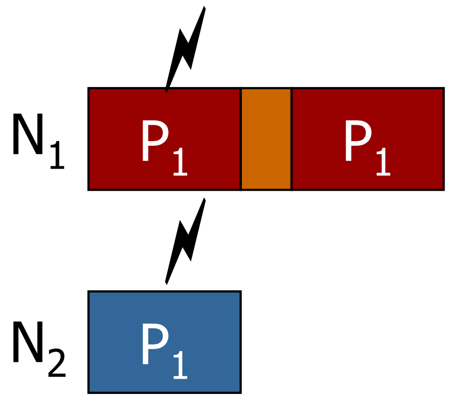
## Fault-Tolerant Techniques



Re-execution



Replication



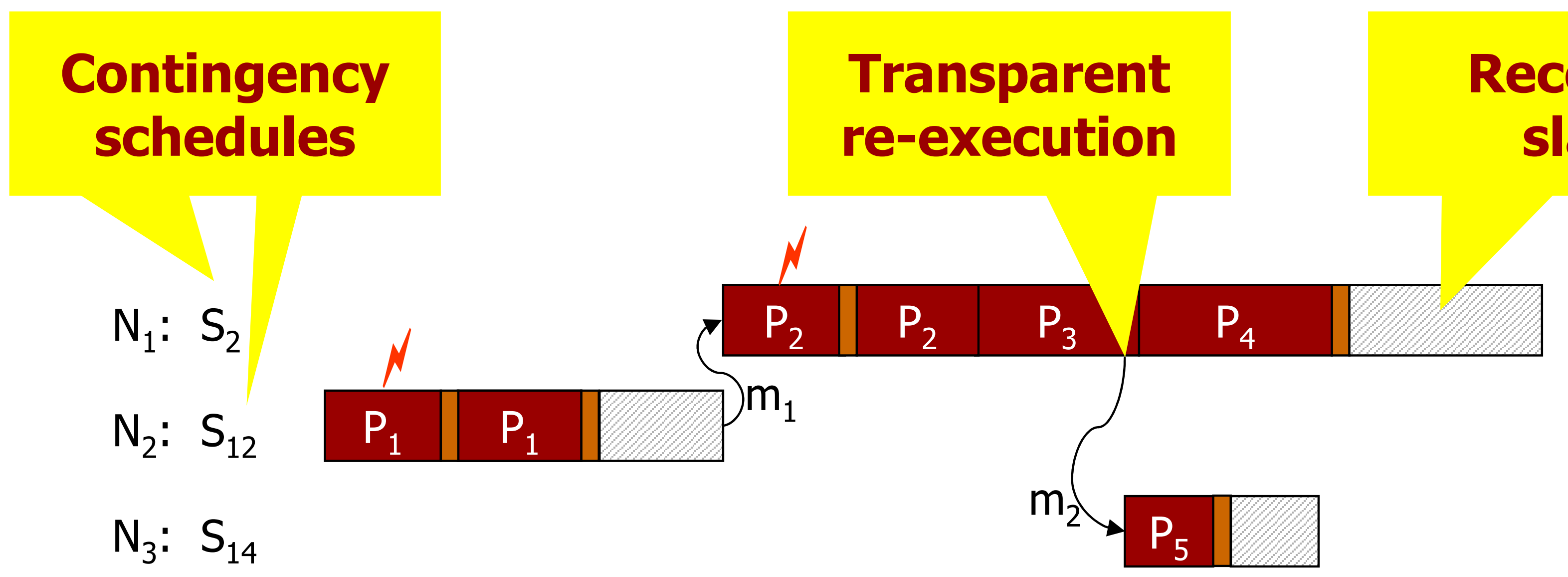
Re-executed replicas

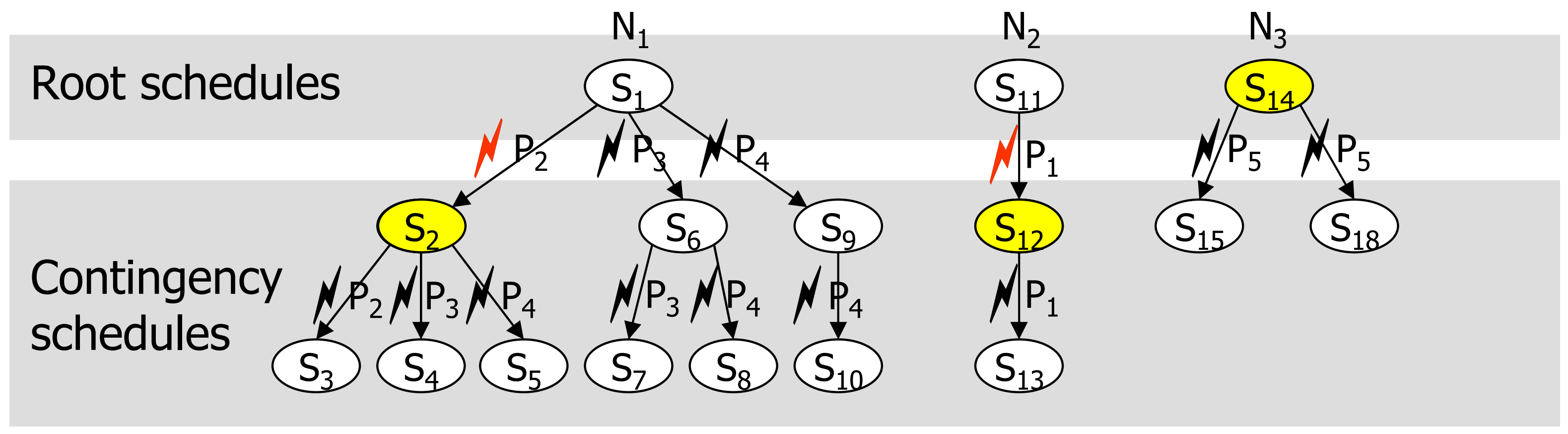
## Problem Formulation

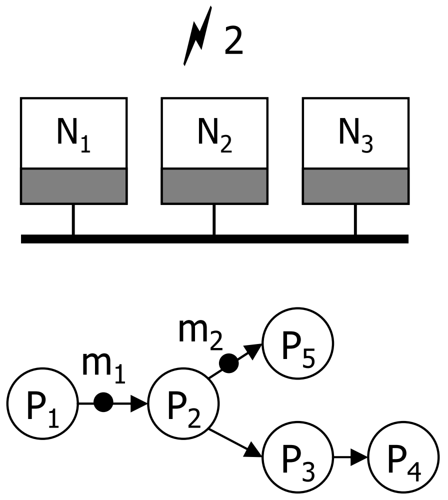
- Given
  - **Fault model**
    - Number of transient faults in the system period
  - System architecture
  - Application
    - WCETs, message sizes, periods, deadlines

- Determine
  - **Schedulable** and **fault-tolerant** design implementation
    - Fault-tolerance policy assignment
    - Mapping of processes and messages
    - Schedule tables for processes and messages

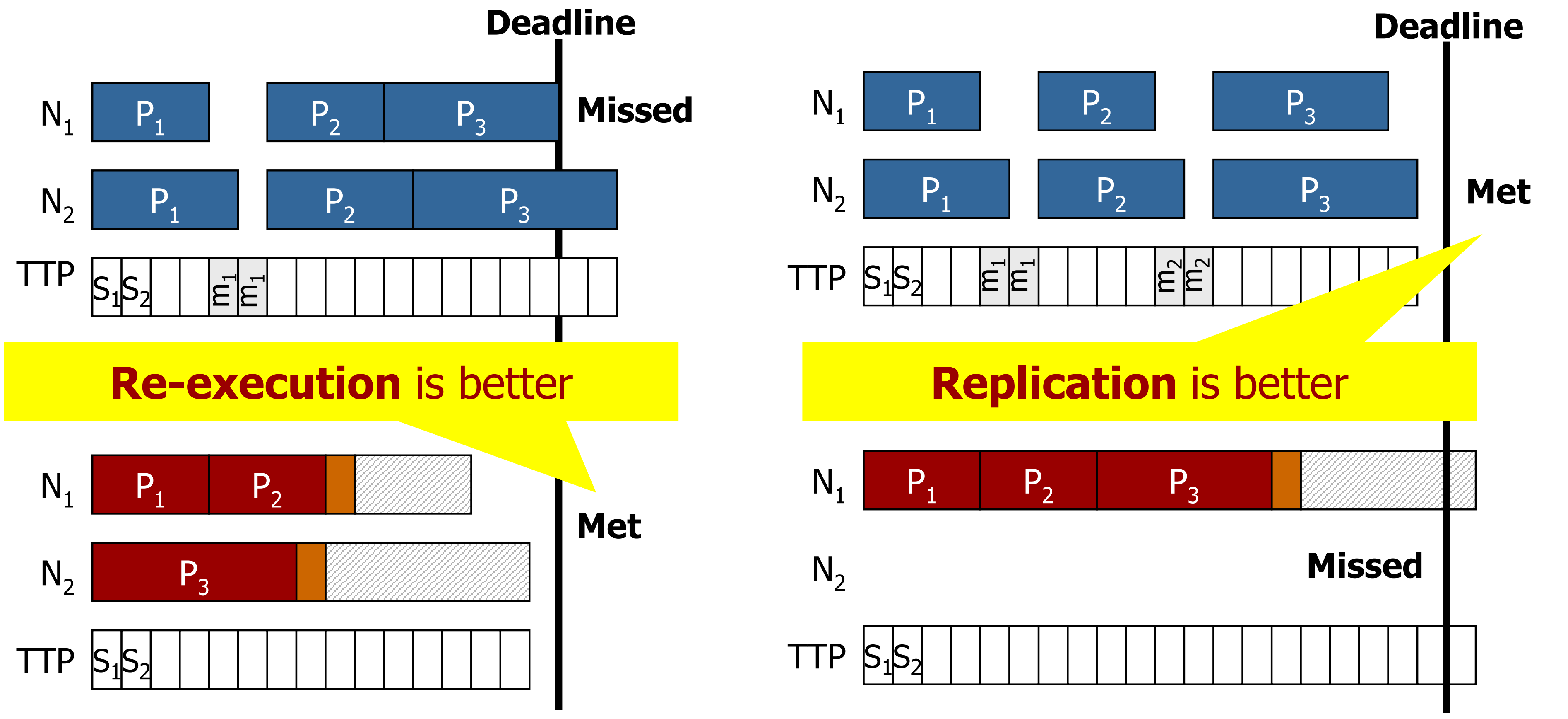
# Static Scheduling [Kandasamy et al. 03]

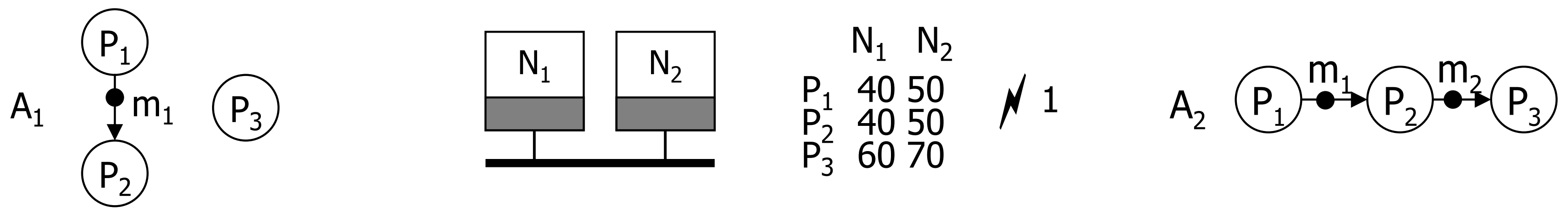






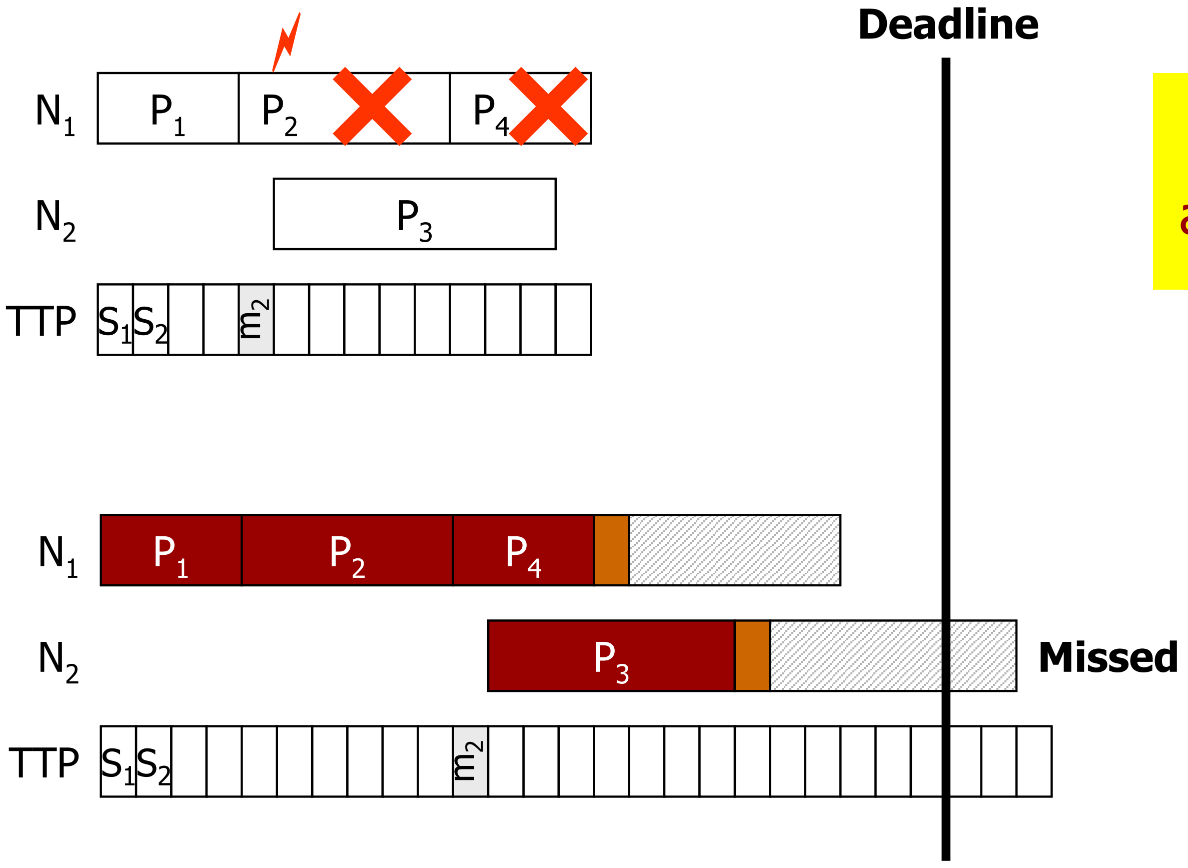
# Re-execution vs. Replication



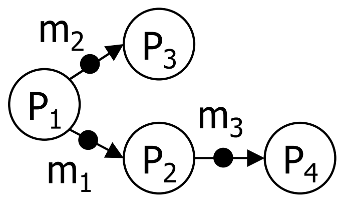


|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 40 | 50 |
| $P_3$ | 60 | 70 |

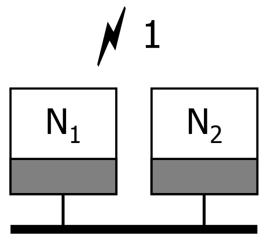
# Fault-Tolerant Policy Assignment



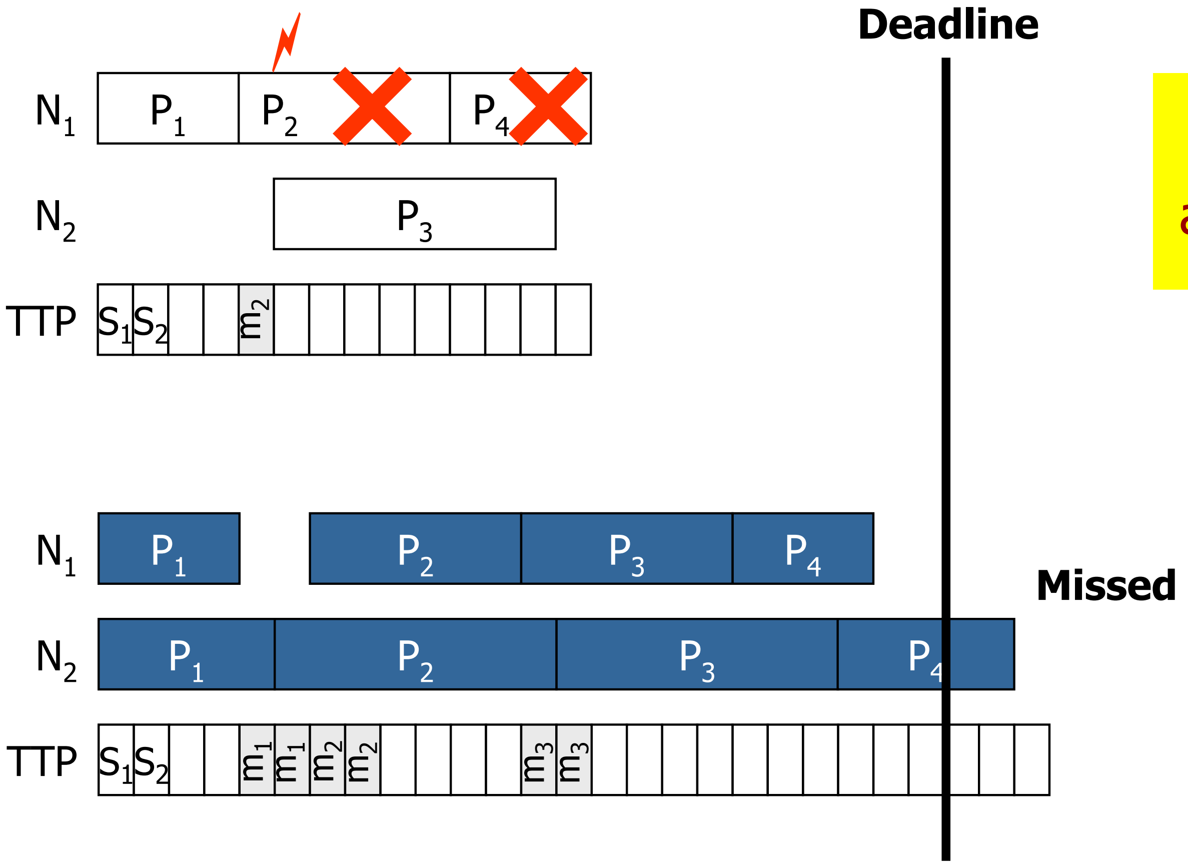
No fault-tolerance: application **crashes**



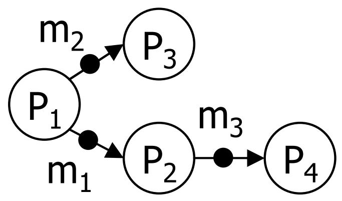
|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 80 |
| $P_3$ | 60 | 80 |
| $P_4$ | 40 | 50 |



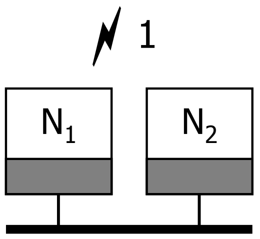
# Fault-Tolerant Policy Assignment



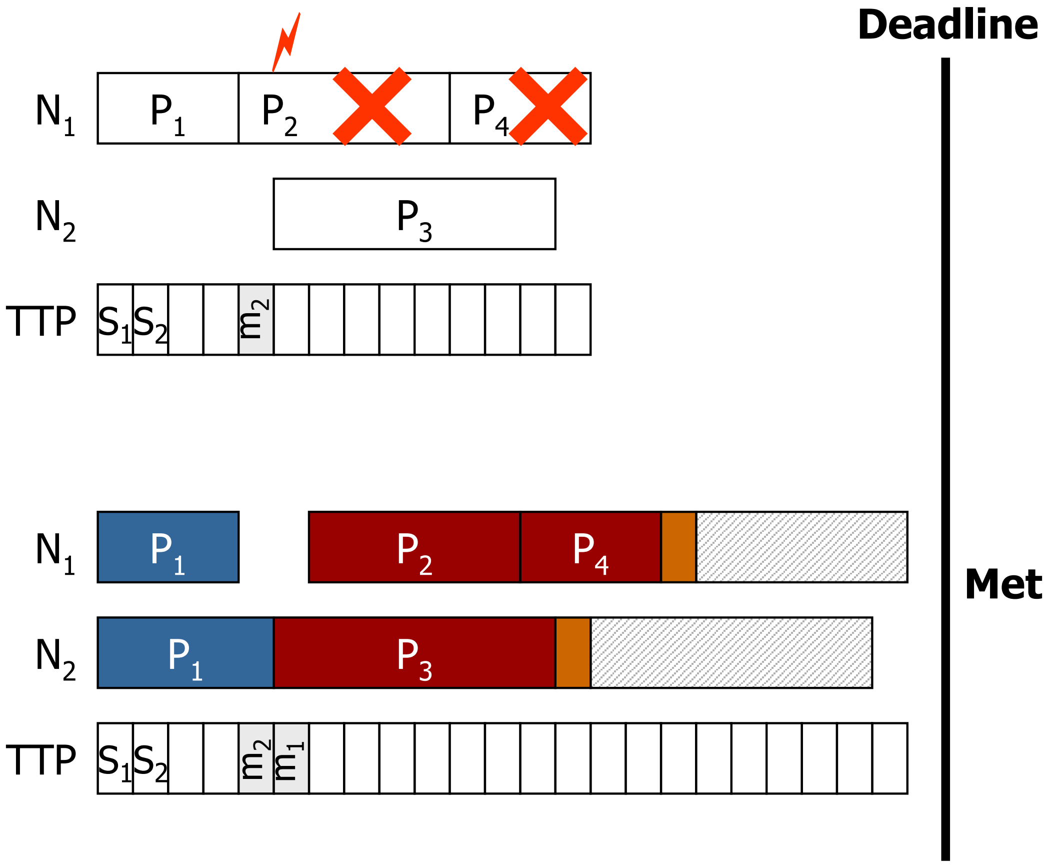
No fault-tolerance: application **crashes**



|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 80 |
| $P_3$ | 60 | 80 |
| $P_4$ | 40 | 50 |

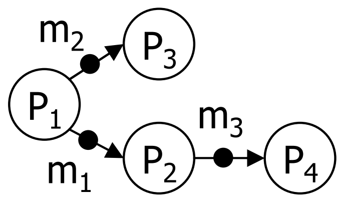


# Fault-Tolerant Policy Assignment

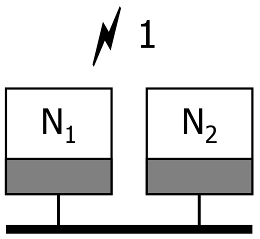


No fault-tolerance: application **crashes**

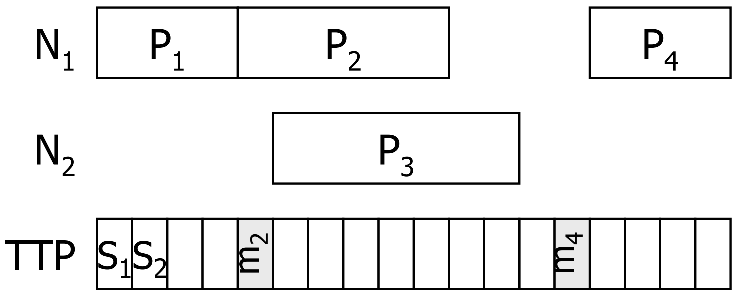
**Optimization** of fault-tolerance policy assignment



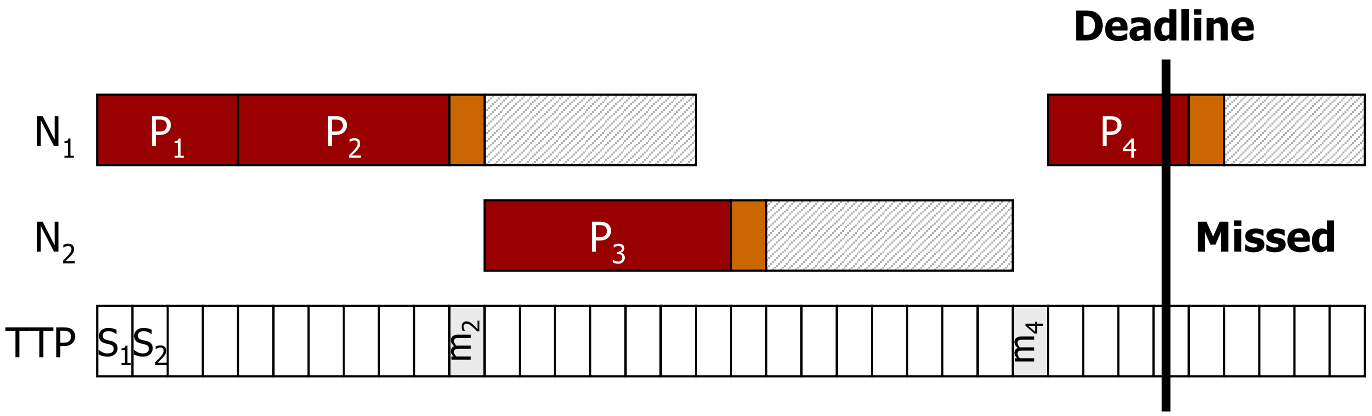
|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 80 |
| $P_3$ | 60 | 80 |
| $P_4$ | 40 | 50 |

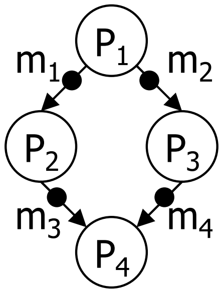


# Mapping and Fault-Tolerance

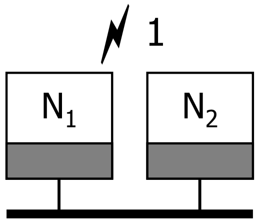


Best mapping without considering fault-tolerance

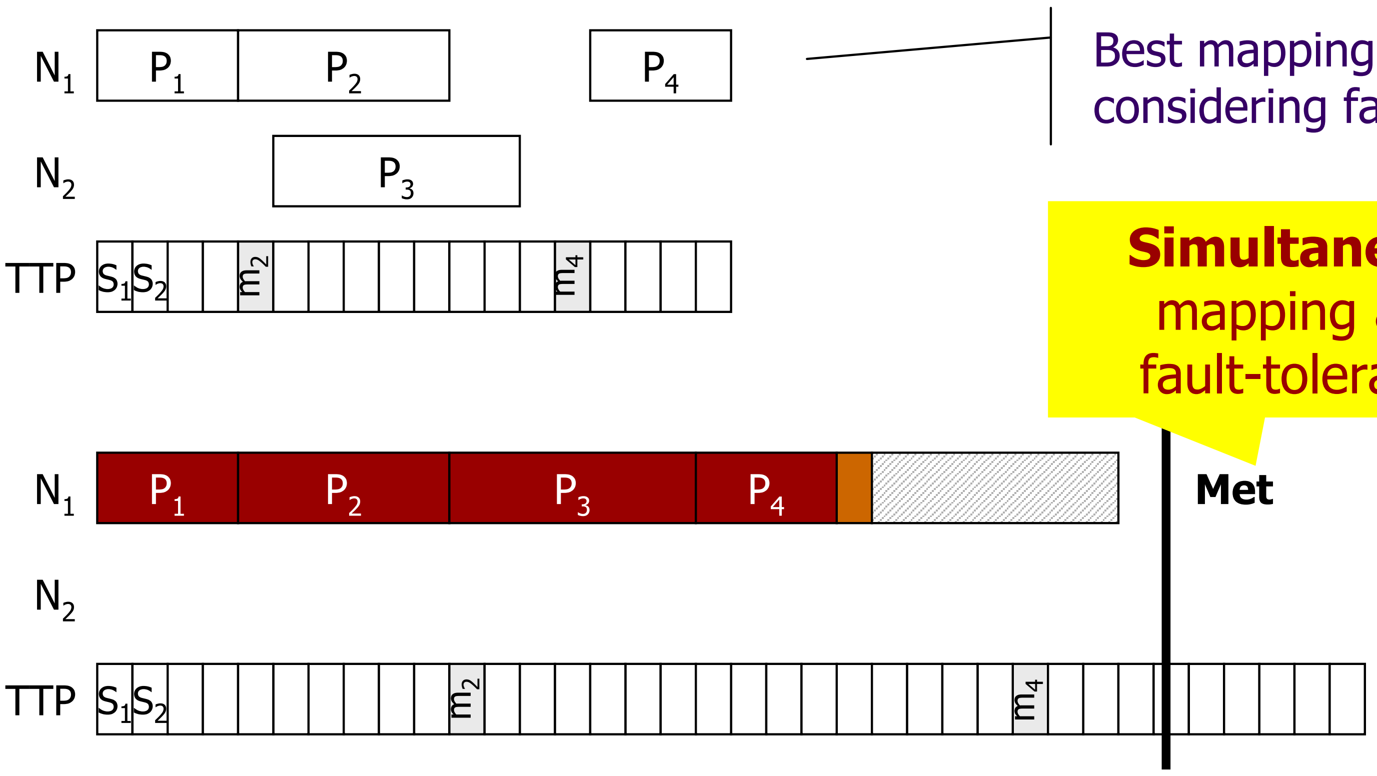


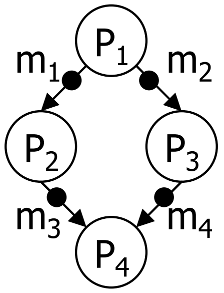


| | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | X |
| $P_2$ | 60 | 70 |
| $P_3$ | 60 | 70 |
| $P_4$ | 40 | X |

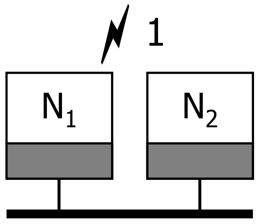


# Mapping and Fault-Tolerance





|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | X |
| $P_2$ | 60 | 70 |
| $P_3$ | 60 | 70 |
| $P_4$ | 40 | X |



## Optimization Strategy

- Design optimization:
  - Fault-tolerance policy assignment
  - Mapping of processes and messages

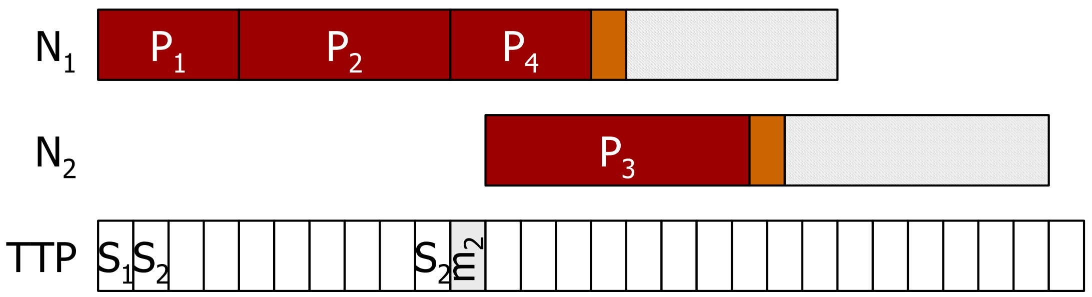
  $\Big\}$ **Tabu-search**

  - Root schedules

  $\Big\}$ **List scheduling**

- Three tabu-search optimization algorithms:
  1. Mapping and Fault-Tolerance Policy assignment (**MRX**)
     - Re-execution, replication or both
  2. Mapping and only Re-Execution (**MX**)
  3. Mapping and only Replication (**MR**)

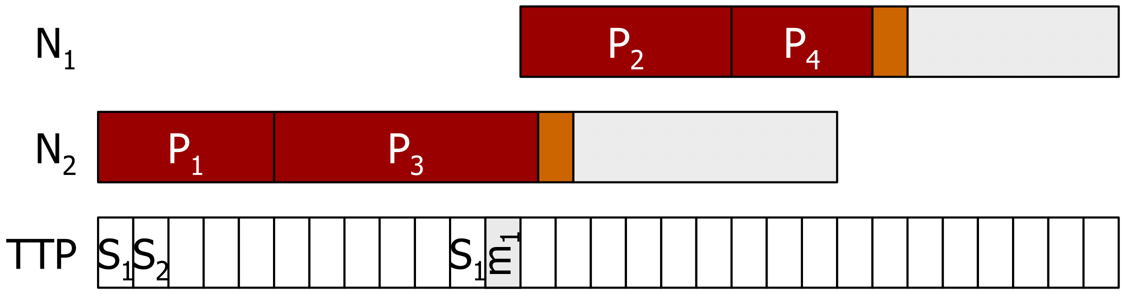
# MRX Tabu-Search Example



| | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

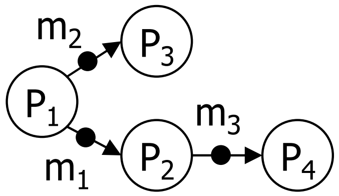
**Current** solution

**Design transformations**

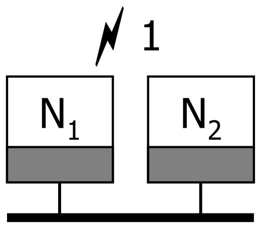


| | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

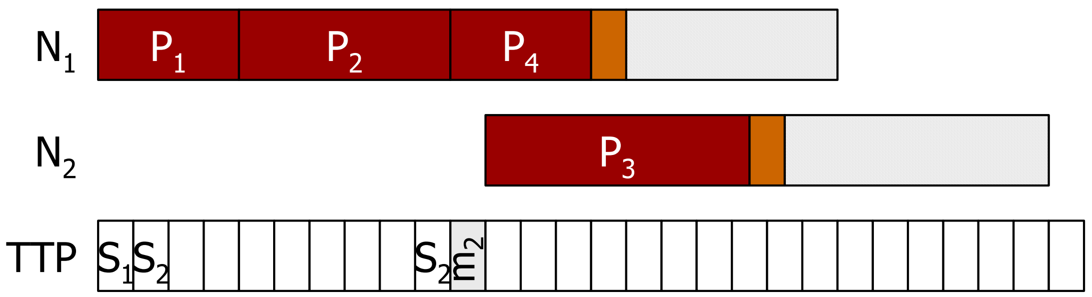
**Tabu** move & **worse** than best-so-far



| | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 75 |
| $P_3$ | 60 | 75 |
| $P_4$ | 40 | 50 |



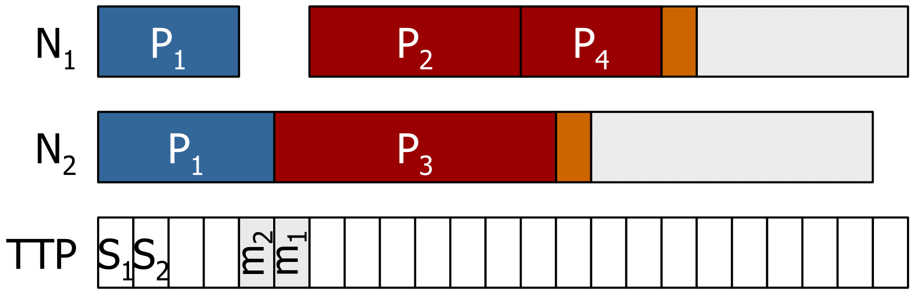
# MRX Tabu-Search Example



| | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

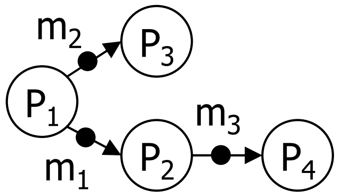
**Current** solution

**Design transformations**

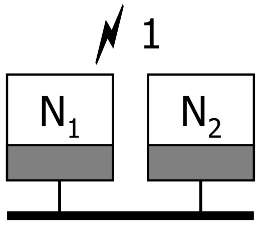


| | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 2 | 1 | 0 | 0 |
| Wait | 0 | 0 | 2 | 1 |

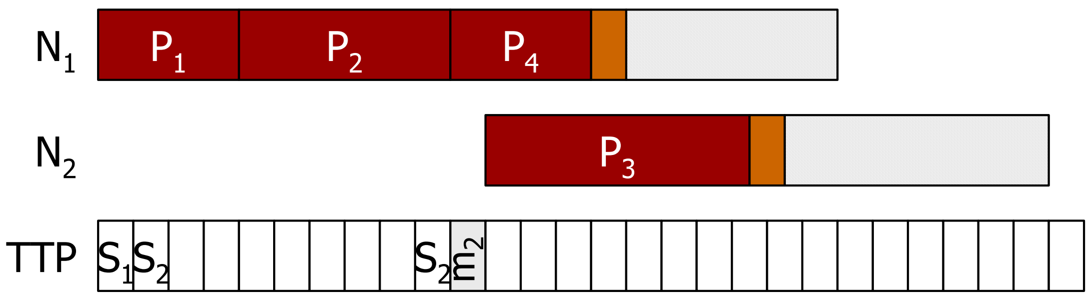
**Tabu** move & **better** than best-so-far



| | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 75 |
| $P_3$ | 60 | 75 |
| $P_4$ | 40 | 50 |



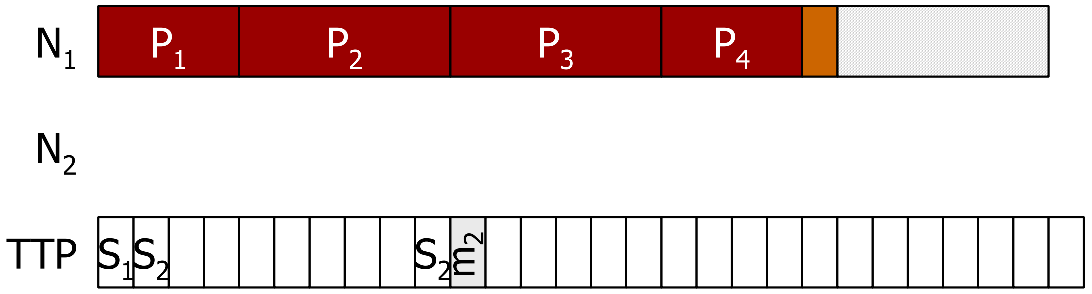
# MRX Tabu-Search Example



|  | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

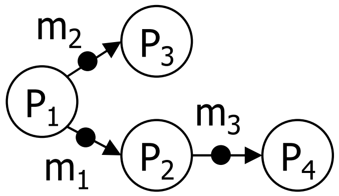
**Current** solution

**Design transformations**

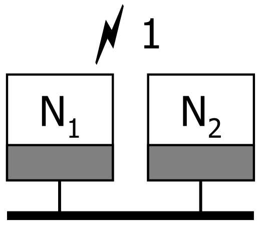


|  | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

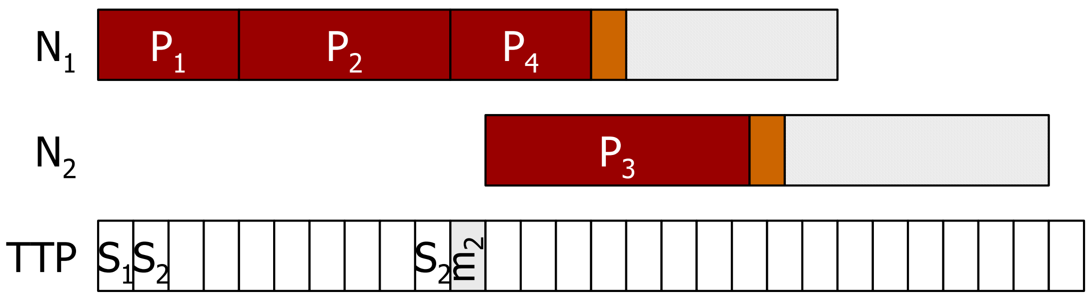
**Non-tabu** & **worse** than best-so-far



|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 75 |
| $P_3$ | 60 | 75 |
| $P_4$ | 40 | 50 |



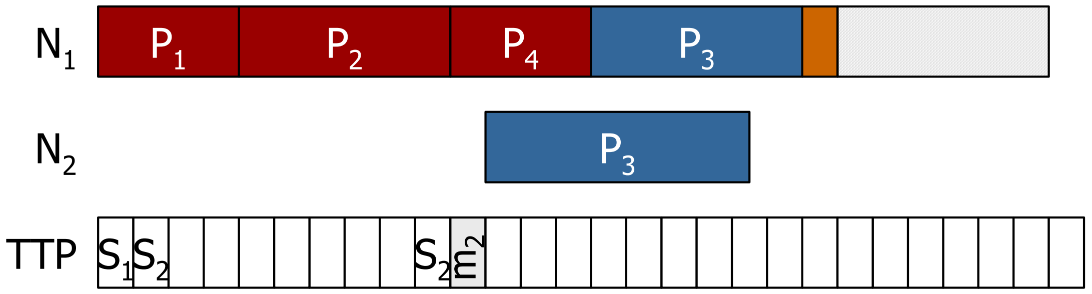
# MRX Tabu-Search Example



|  | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

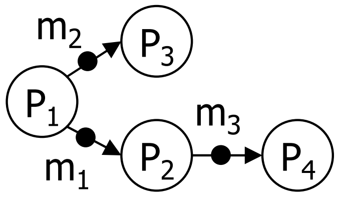
**Current** solution

**Design transformations**

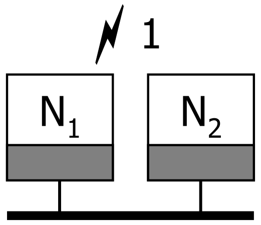


|  | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Tabu | 1 | 2 | 0 | 0 |
| Wait | 1 | 0 | 1 | 1 |

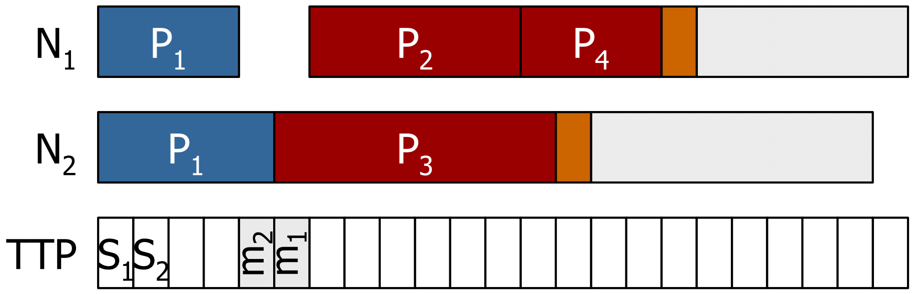
**Non-tabu** & **worse** than best-so-far



|  | $N_1$ | $N_2$ |
|---|---|---|
| $P_1$ | 40 | 50 |
| $P_2$ | 60 | 75 |
| $P_3$ | 60 | 75 |
| $P_4$ | 40 | 50 |

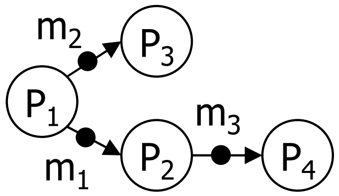


## MRX Tabu-Search Example

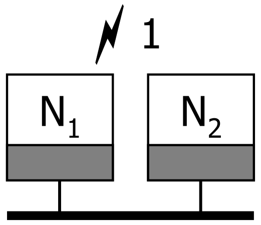


|      | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|------|-------|-------|-------|-------|
| Tabu | 2     | 1     | 0     | 0     |
| Wait | 0     | 0     | 2     | 1     |

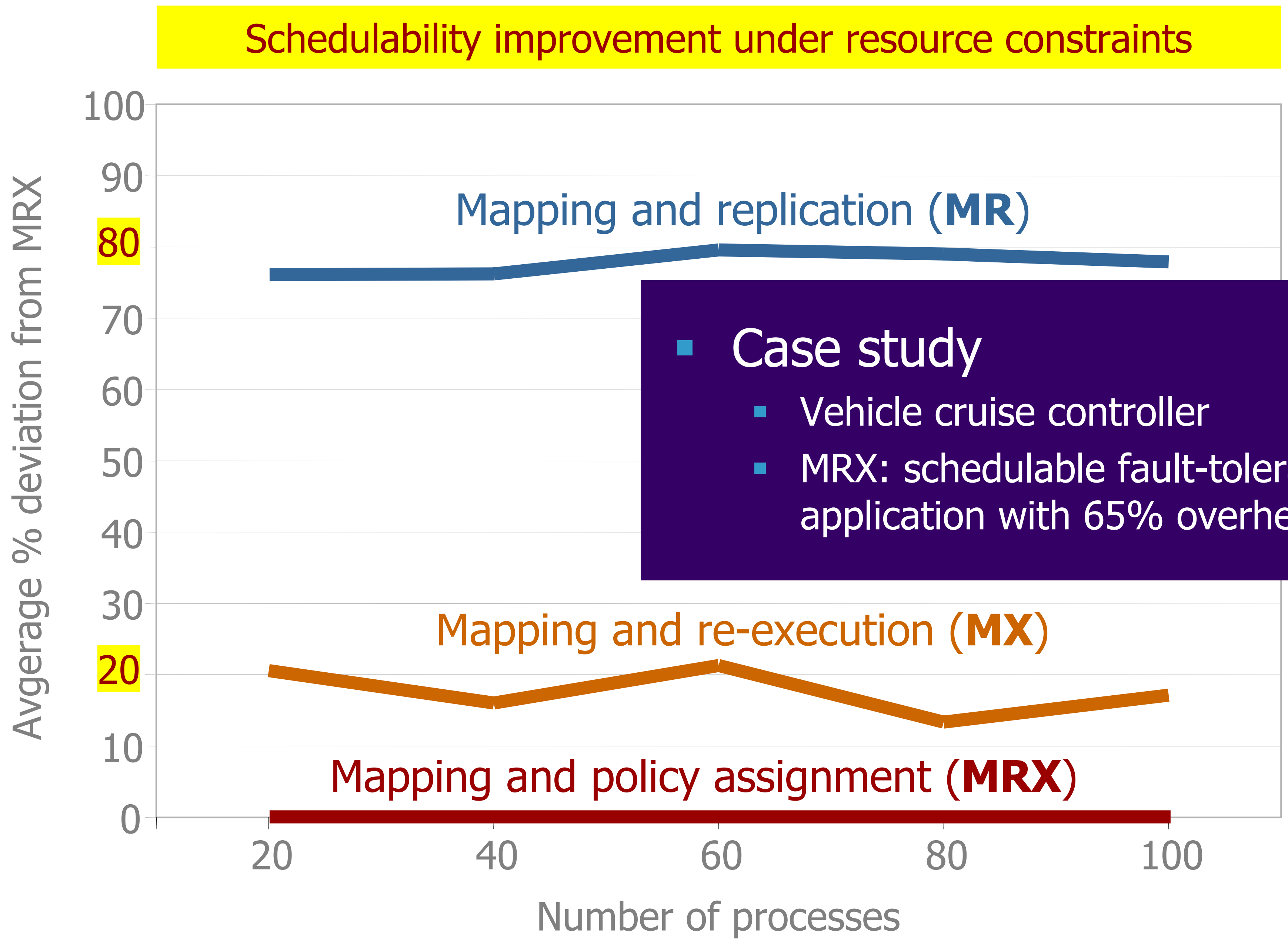
**Current** solution



|       | $N_1$ | $N_2$ |
|-------|-------|-------|
| $P_1$ | 40    | 50    |
| $P_2$ | 60    | 75    |
| $P_3$ | 60    | 75    |
| $P_4$ | 40    | 50    |



## Experimental Results



- Case study
  - Vehicle cruise controller
  - MRX: schedulable fault-tolerant application with 65% overhead

## Contributions and Message

- Contributions
  - Combined re-execution and replication
  - Optimization algorithms for fault-tolerance policy assignment
  - Efficient contingency schedule generation

**Optimization** of fault-tolerance policy assignment needed for cost-effective fault tolerance