Scalability Assessment of Reconfigurable Manufacturing Systems (RMS) under New Product Integration

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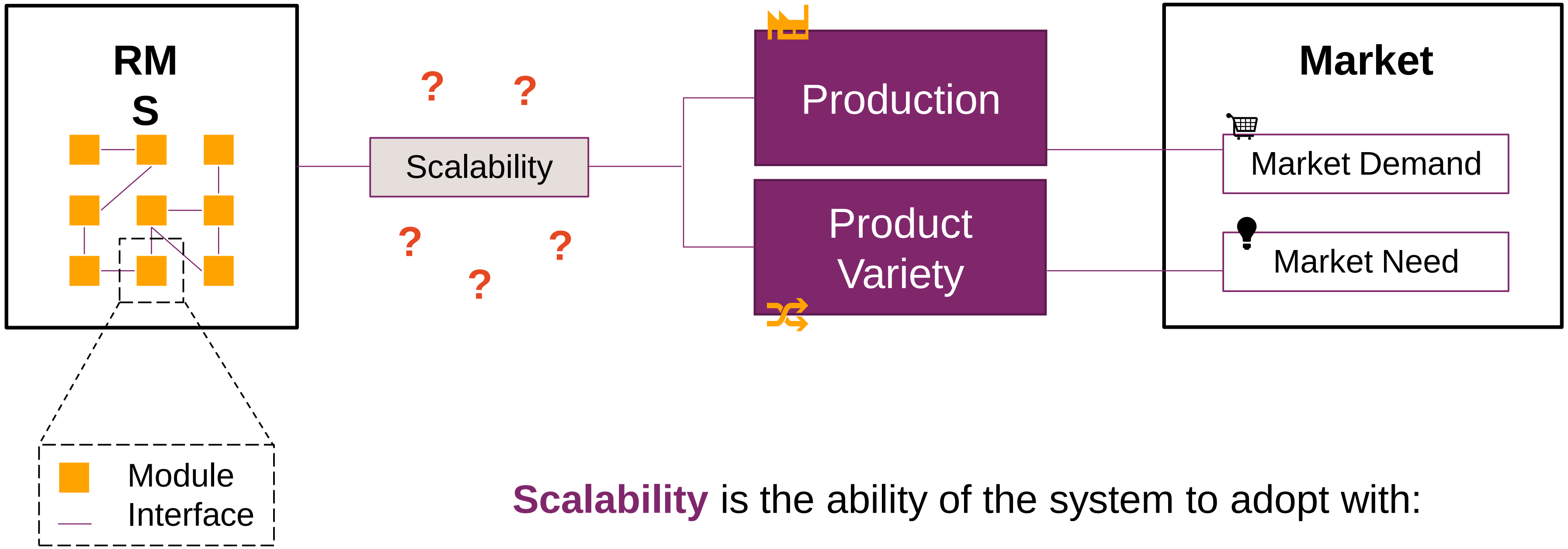
Industrial Motivation



Scalability is the ability of the system to adopt with:

- change in demand
- or new products arrival
- with limited effort and cost.

Literature Review

Author (Year)	Literature Area				Summary
	RMS Characteristic	Reconfiguration Potential	Optimization based RMS	Scalability Assessment	
Deif & ElMaraghy (2006)	✓		✓		Open RMS architecture
Koren et al. (2016)	✓		✓	✓	Scalability definition through capacity increments
Farid (2017)	✓	✓			Quantifies reconfiguration freedom and flexibility
Yelles-Chaouche et al. (2021)	✓		✓		Reviews RMS optimization and research gaps
Cerqueus & Delorme (2023)		✓		✓	Calculate scalability by computing the hypervolume of the Pareto-optimal set of reachable configuration
Andersen et al. (2024)	✓				Systematic methodology for changeable RMS
Rezaee & Moghaddam (2025)			✓		RMS configuration design considering capacity scalability
Chaikovskaia et al. (2026)	✓		✓		Optimizes convertibility versus investment cost
This work	✓	✓	✓	✓	**Scalability assessment based on the structural modification effort required for new product integration**

Research Gap & Contribution

Existing studies mainly address:

- RMS characteristics
- Initial RMS configuration and planning
- Reconfigurability potential

Gap:

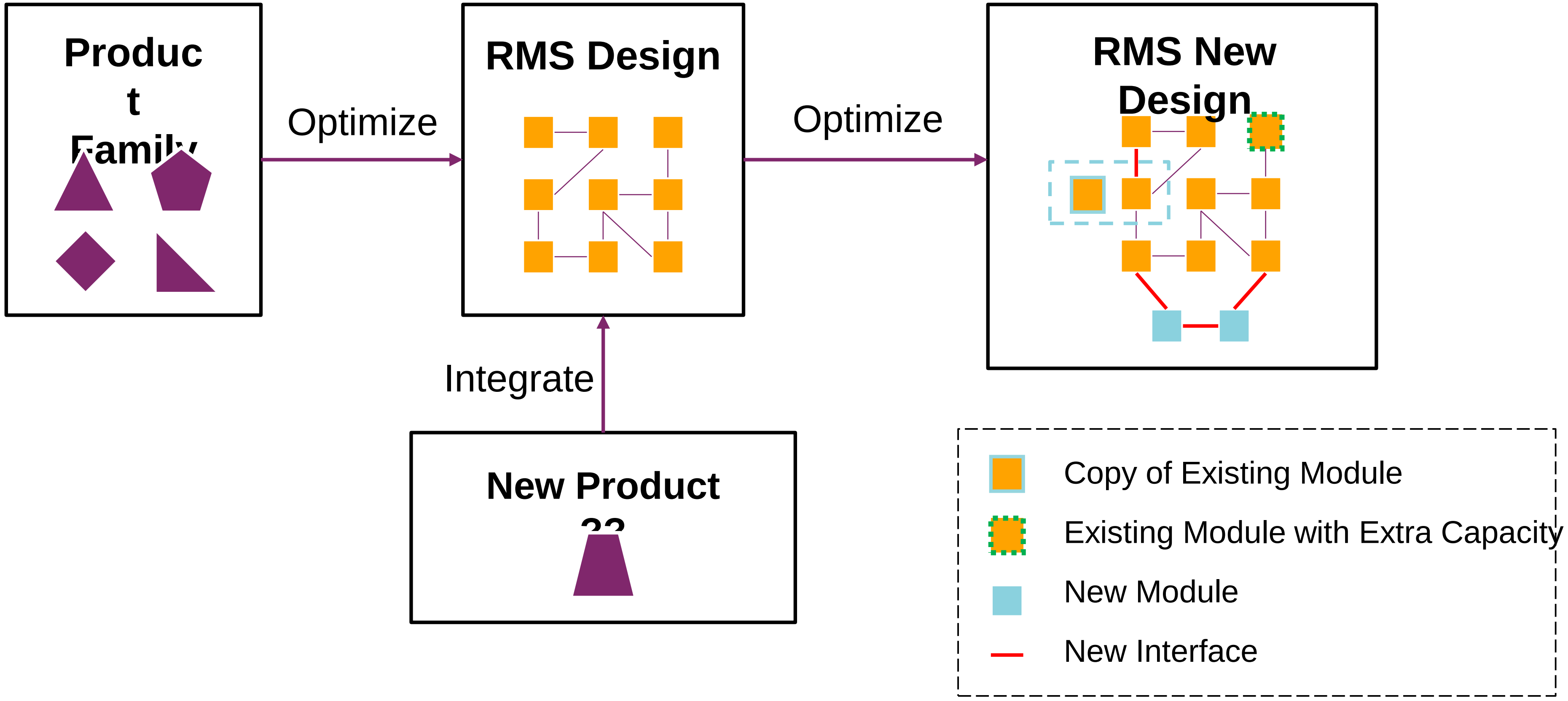
The structural modification effort required to integrate a new product into an already optimized RMS

Contribution:

This work proposes a scalability assessment based on:

- New module installation
- Module replication
- New interface creation
- Capacity extension

Research Problem



Methodological Framework

Design of RMS for Product Family

First stage

Input Data:

- Product family $p \in P$ and demand level
- Operations O_p
- Precedence relations $E_p \subseteq O_p \times O_p$
- Modules $m \in M$ and processing capabilities
- Potentional Interfaces $I_{m,n}$

Optimization:

Equation (1)

Output:

- Optimal RMS configuration and layout
- Installed modules $M^{inst} \subset M$
- Installed interfaces $I^*_{m,n}$
- Production plans for the product family

New Product Integration

Second stage

Input Data:

- Data of new product
- Output of first stage
- Computed residual capacity of Modules:

$$CapRes_m = Cap_m - \sum Processing\ time\ on\ modulde\ m$$

Optimization:

Equation (2)

Output:

- Updated RMS configuration
- Required system modifications (module installation, interface addition, capacity expansion)
- Production plan and module assignments for the new product

Scalability Assesment

Evaluation Metrics:

- Utilization of modules and residual capacities
- Number of structural modifications required
- Additional capacity and interface requirements
- Total system reconfiguration cost
- Flexibility of the system for future product introductions

Stage 1 – Design of RMS for Product family

Input Data:

- Product family $p \in P$ and demand level D_p
- Operations O_p
- Precedence relations $E_p \subseteq O_p \times O_p$
- Modules $m \in M$ and processing capabilities
- Capacities Cap_m
- Potential Interfaces $I_{m,n}$

Decisions:

- Which modules and interfaces are effectively used in the RMS configuration
- Which module performs each operation
- Which production plans (routes) and sequences are used for each product
- How production quantities are distributed among different plans

Output:

- Optimal RMS configuration and layout
- Installed modules $M^{inst} \subset M$
- Installed interfaces $I^*_{m,n}$
- Production plans for the product family

Stage 1 – Design of RMS for Product family

Mathematical model

MILP Model

Objective Function:

$$max \sum_{p \in P} \sum_{r \in R} q_{p,r}$$

$q_{p,r} \in Z$: Quantity of product *p* produced using plan *r*.

Main Decision Variables:

$x_{p,r,o,m} \in \{0,1\}$	Assignment variable
$S_{p,r,i,j} \in \{0,1\}$	Sequencing variable (path decision)
$q_{p,r} \in Z$	Quantity of product p produced using plan r

Main Constraints:

- Assignment Constraints
- Resource Constraints
- Technological Constraints
- Production Constraints
- Routing Constraints

Stage 2 – New Product Integration

Input Data:

- Data of new product (operations, precedences, demand)
- Output of first stage
    - Optimal RMS configuration and layout
    - Computed residual capacity of Modules:

$$CapRes_m = Cap_m - \sum Processing\ time\ on\ modulde\ m$$

- Reconfiguration data

Decisions:

- Which modification will be applied on the RMS configuration
- Which module performs each operation for the new product
- Which sequence is used for the new product

Output:

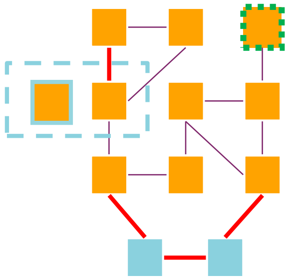
- Updated RMS configuration
- Required system modifications (module installation, interface addition, capacity expansion)
- Production plan and module assignments for the new product

Stage 2 – New Product Integration

Mathematical model

Objective Function:

$$min\ \underbrace{c^{mod}\sum_{m\in M} y_m}_{\text{New Module}} + \underbrace{c^{copy}\sum_{m\in M^{inst}} k_m}_{\text{Module Replication}} + \underbrace{c^{I}\sum_{m,n\in M, I*_{m,n}=0} \delta_{m,n}}_{\text{New Interface}} + \underbrace{c^{cap}\sum_{m\in M} e_m}_{\text{Capacity Extension}}$$



Parameters		Decision Variable	
C^{mod}	Cost to newly install a module	$y_m \in \{0,1\}$	If module *m* is installed in Stage 2, 1; otherwise, 0.
C^{copy}	Cost to add one additional copy of a module	$k_m \in \{0,1\}$	If add one extra identical copy of module *m*, 1; otherwise, 0.
C^{I}	Cost to add one new directed interface	$\delta_{m,n} \in \{0,1\}$	If add directed interface between module *m* and *n*, 1; otherwise, 0.
C^{cap}	Cost per unit of extra capacity added	$e_m \geq 0$	Amount of extra capacity added to module *m*.

Stage 2 – New Product Integration

Mathematical model

Constraints:

Reconfiguration Constraints		Logic
Structural feasibility	*Add*	• Existing modules (Stage 1) remain active; • New modules, copies, interfaces, or extra capacity can be added only when allowed.
Capacity feasibility	*Update*	The processing time required by the new product must not exceed: • residual capacity + added capacity + copied module capacity.
Interface feasibility	*Update*	If two consecutive operations are assigned to two modules: • the interface between them must already exist or be added.

Scalability Assessment

Capacity Utilization & Scalability Potential

Module Utilization ratio [Kumru (2011)]

$$Utilization_m = \frac{Load_m}{Cap_m}$$

Residual capacity ratio (Module level)

$$ResidualRatio_m = \frac{CapRes_m}{Cap_m}$$

1 → Very scalable
0 → Less scalable

Residual capacity ratio (System level)

$$ResidualRatio_{system} = \frac{\sum_m CapRes_m}{\sum_m Cap_m}$$

Kumru, M. (2011). Determining the capacity and its level of utilization in make-to-order manufacturing: A simple deterministic model for single-machine multiple-product case. *Journal of Manufacturing Systems*, *30*(2), 63-69. https://doi.org/10.1016/j.jmsy.2011.03.006.

Scalability Assessment

Scalability Definition for this work

Scalability is defined as the capability of an already designed RMS to integrate a new product while respect its initial configuration and requiring only limited structural and capacity modifications.

~1	More scalable	System handle the new product easily.
~0	Less scalable	Adding the product is almost equivalent to redesigning the system

Reconfiguration Effort Index

$$REI = w_m \frac{N_{newModule}}{N_{newModule}^{max}} + w_c \frac{N_{Copy}}{N_{Copy}^{max}} + w_i \frac{N_{newInterface}}{N_{newInterface}^{max}} + w_e \frac{\sum_m e_m}{E^m}$$

$$w_m + w_c + w_i + w_e = 1$$

Scalability Index

$$Scalability = 1 - REI$$

Scalability Assessment

Expansion Efficiency

Total Reconfiguration Cost

$$Cost_{reconfiguration} = Cost_{modules} + Cost_{copies} + Cost_{interfaces} + Cost_{capacities}$$
$$= Objective\ of\ stage\ 2$$

Expansion cost per extra unit

$$Cost\ per\ Extra\ Unit = \frac{Cost_{reconfiguration}}{D_{new\ product}}$$

Reconfiguration Cost Ratio

$$RCR = 1 - \frac{Cost_{reconfiguration}}{Budget}$$

Scalability Assessment

Analysis

SI	RCR	Status
High	Positive	Scalable and affordable
High	Negative	Scalable but expensive
Low	Positive	Affordable but structurally less scalable
Low	Negative	Not scalable and not affordable

Instance

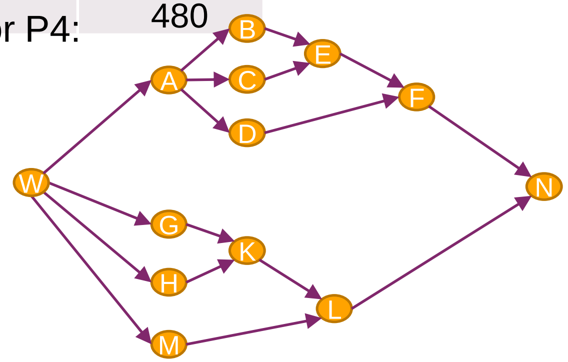
Products	Operation		Demand
P1	5	L, PR, SC, IN, PK	180
P2	5	L, AD, CU, IN, PK	120
P3	6	L, PR, GR, SC, IN, PK	100
P4	13	W, A, B, C, D, E, F, G, H, K, L, M, N	80
			150

Module	Operations	Capacity
M1	L, GR	480
M2	PR, SC, W, A, B, G, H, AS	480
M3	PR, SC, C, D, G, H, M, AS	480
M4	PR, GR, AD, CU, B	480
M5	IN, E, K, L	480
M6	PK, F, N	480

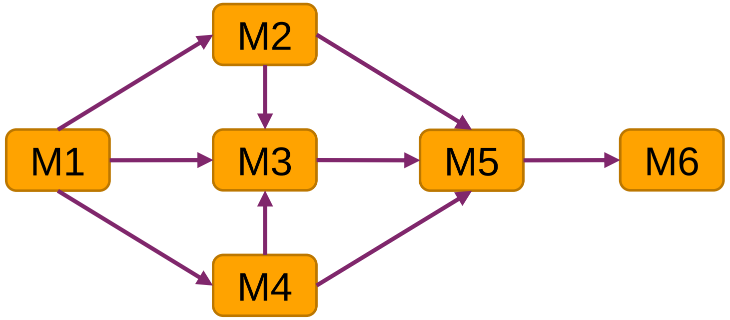
Cost component	Value
Add unused module	100
Add one module copy	80
Add one new interface	20
Add one unit of extra	0.7

Parameter	Value
Maximum plans per product	5
Minimum units per used plan	10
Capacity increase limit	90

Operations Precedences for P4:

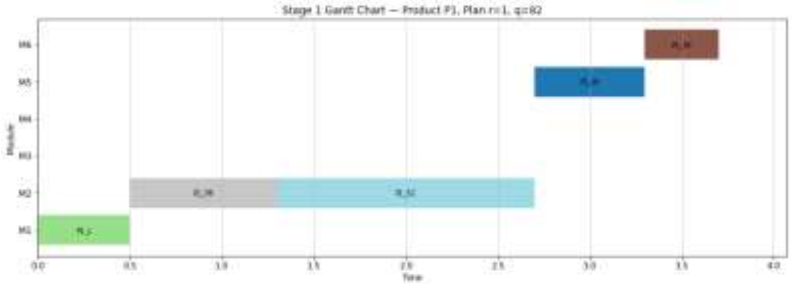


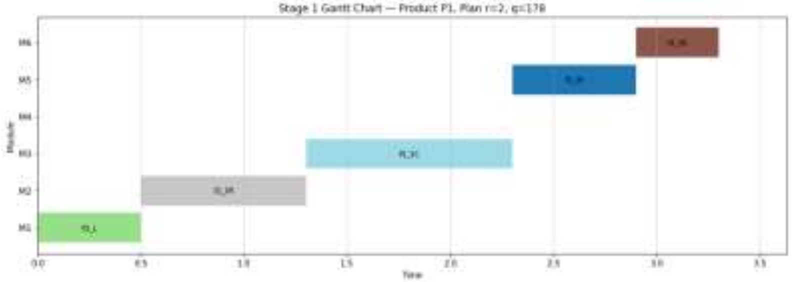
Potential RMS Design:



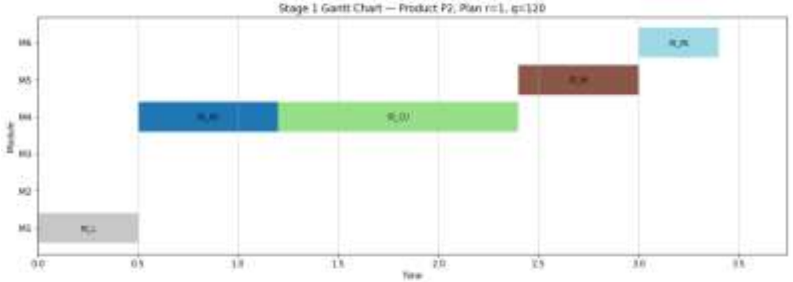
Results – Stage 1

P1

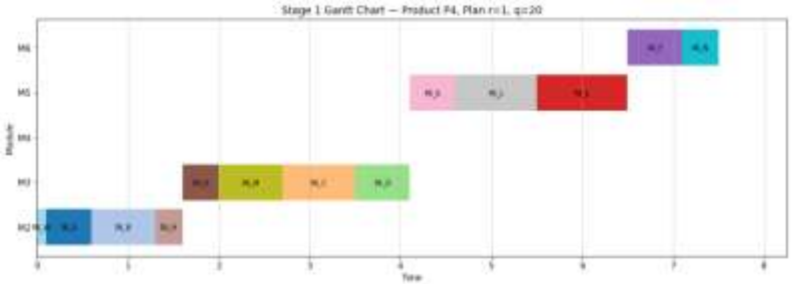


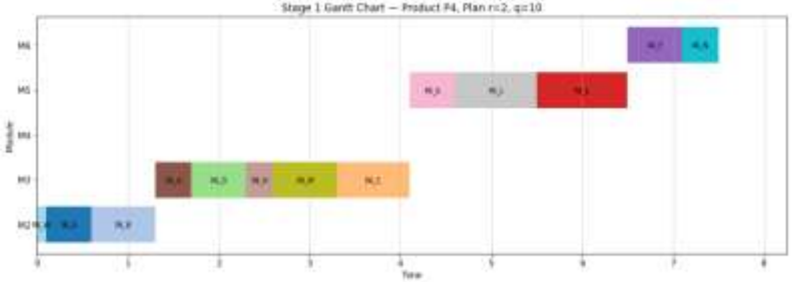


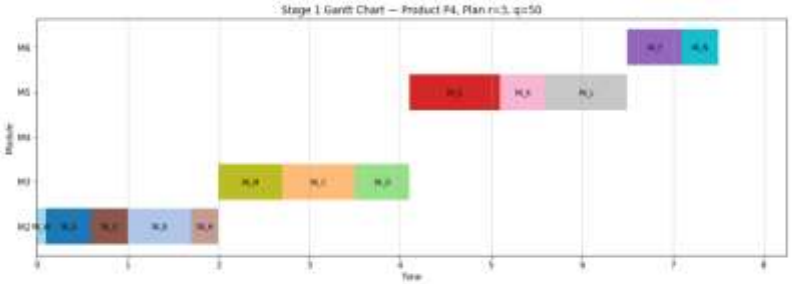
P2



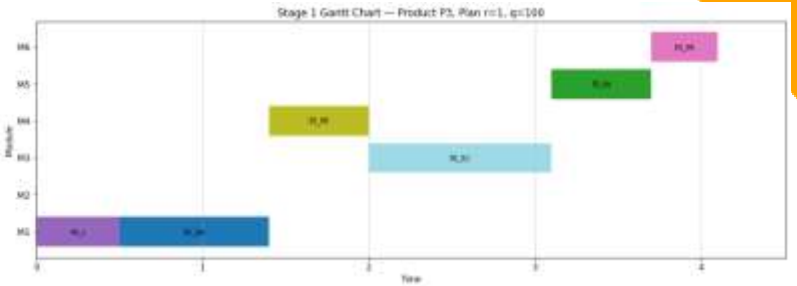
P4





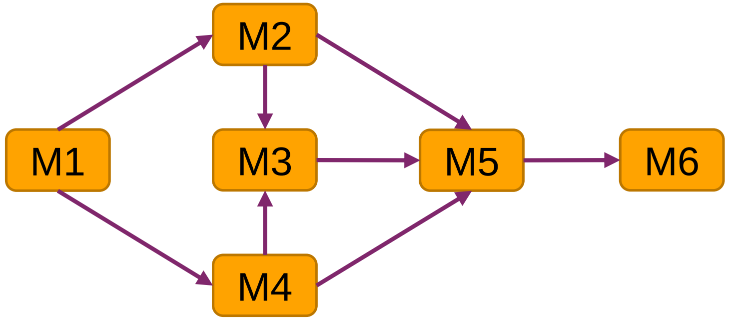


P3



	D	Q(1)	r1	r2	r3
P1	180	260	82	178	
P2	120	120	120		
P3	100	100	100		
P4	80	80	20	10	50
Total		**560**			

Optimal RMS Design:

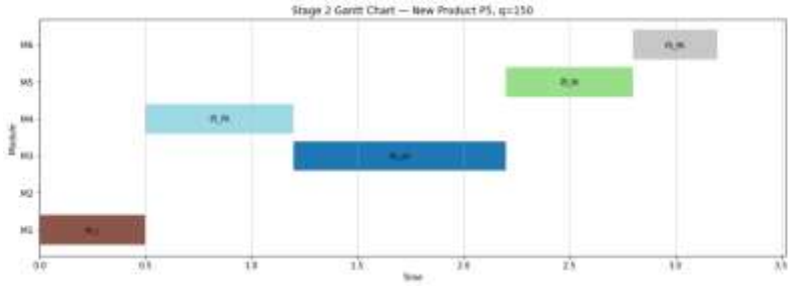


Results – Stage 2

Module	Capacity	Load	Residual	Utilization	Residual Ratio
M1	480	330	150	68.75%	31.25%
M2	480	467.8	12.2	97.46%	2.54%
M3	480	471	9	98.13%	1.88%
M4	480	288	192	60%	40%
M5	480	480	0	100%	0%
M6	480	272	208	56.67%	43.33%

System Residual Ratio = 19.83%

P5



$$Cost_{reconfiguration} = Objective\ of\ stage\ 2 = 160$$

Copy of Existing Module		M3, M5
Module with Extra Capacity		-
New Module		-
New Interface		-

$$REI = w_m \frac{N_{newModule}}{N^{max}_{newModule}} + w_c \frac{N_{Copy}}{N^{max}_{Copy}} + w_i \frac{N_{newInterface}}{N^{max}_{newInterface}} + w_e \frac{\sum_m e_m}{E^m}$$

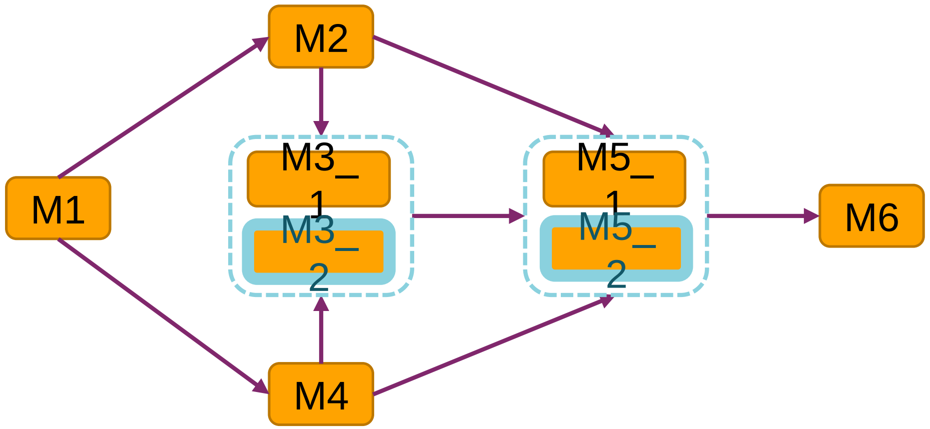
$$= 0.4 \times 0 + 0.3 \times \frac{2}{3} + 0.2 \times 0 + 0.1 \times 0 = 0.2$$

$$Scalability = 1 - REI = 1 - 0.2 = 0.8$$

$$Cost\ per\ Extra\ Unit = \frac{Cost_{reconfiguration}}{D_{new\ product}} = \frac{160}{150} = 1.06$$

$$RCR = 1 - \frac{Cost_{reconfiguration}}{Budget} = 1 - \frac{160}{200} = 0.2$$

New RMS Configuration:



Conclusion

Key Contribution

- Proposed a two-stage optimization framework for RMS scalability assessment under new product integration.
- Developed a scalability evaluation approach.

Future Work

- Validation on larger industrial case studies.
- Considering travel time and cost between modules.
- Development of module reusability.
- Sustainability assessment.

Thank you for your attention ☺

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