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An integrated multi-horizon approach for long-term reconfiguration and mid-term sequencing in global production networks

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A B S T R A C T

Rapid adaptation to volatile demand is a critical challenge for production systems in global production networks. While reconfigurable manufacturing systems enable structural adjustments of capabilities and capacities, reconfiguration activities temporarily reduce production feasibility because capabilities can be unavailable during dismantling, transportation, and installation. This paper presents an integrated multi-horizon planning approach that jointly considers long-term reconfiguration decisions and mid-term order allocation, sequencing, and replanning. Mixed-integer linear optimization models explicitly capture reconfiguration with respective dismantling, transportation, and installation processes. Computational results show that reallocating existing capabilities reduces long-term costs, while sequencing and mid-term replanning are essential to avoid backorders and improve responsiveness.

1. Introduction

Global production networks (GPNs) connect geographically dispersed production systems through financial, material, and information flows [1] and are increasingly exposed to volatile, uncertain, complex, and ambiguous conditions [2]. Unpredictable market developments, rising customer expectations, shorter product life cycles [3], and disruptive events [4,5] challenge the efficient and reliable operation of GPNs. To remain competitive, production systems must be adapted rapidly and cost-efficiently [3].

Within a predefined flexibility corridor, such adaptations can be achieved without physical changes to the production system. Once this corridor is exceeded, reconfigurability enables structural adjustments through the addition, removal, or modification of machine modules [6]. Reconfigurable manufacturing systems (RMS) provide this adaptability, thereby offering advantages over dedicated manufacturing lines (DML) with fixed structures [7,8]. Despite these benefits, reconfigurability is often underutilized in practice due to high upfront investments and uncertain future returns, while later system modifications can cause substantial additional costs [9]. In many industrial applications, particularly in the automotive supplier industry, DML are still predominantly used today. However, RMS are increasingly used to cope with rising product variety and demand volatility. Beyond investment considerations, a key challenge is that reconfiguration activities temporarily reduce available capacity and functionality. While installation times are typically short [8], transportation may require several days or weeks, during which the reconfigured capability is temporarily unavailable, as no line is equipped with the specific capability. If not explicitly considered, this leads to backorders or inventory buildup.

In GPNs, production strategy, network footprint, and network management decisions define the core tasks [1]. Incorporating reconfigurability in long-term planning can reduce investments. At the same time, operational feasibility must be ensured in the mid-term by accounting for downtime and temporary capability unavailability. In addition, the benefits of reconfigurability can be realized through adaptive replanning under evolving customer demand. However, these planning levels are often addressed separately. To address this gap, an integrated multi-horizon optimization approach for reconfiguration planning in GPNs is proposed. The contribution is the integration of long-term network configuration, mid-term sequencing under temporary capability unavailability, and adaptive replanning under evolving demand. Unlike existing approaches, the proposed integration ensures that long-term decisions remain operationally feasible and can be consistently adapted across planning horizons. This integration enables consistent decision-making across planning horizons and supports the effective utilization of RMS.

The remainder of this paper is structured as follows. Section 2 reviews related work. Section 3 presents the proposed multi-model optimization approach and Section 4 demonstrates its application using industrial use cases. Finally, Section 5 discusses the results and concludes the paper.

2. State of the art

The literature is evaluated with respect to order allocation across a GPN, capability transfers between RMS, and the integration of reconfiguration decisions across different planning horizons. Existing approaches differ significantly in their planning scope, modeling focus, and level of integration [10].

Early studies predominantly address reconfigurability at the machine or line level. [11] consider modular machine reconfiguration within a single production line, where components are added or removed to adjust capacity. While such approaches capture local flexibility, they neglect interactions between production sites and the reallocation of capabilities across a network. More recent contributions extend the analysis to the network level. [12] allow the relocation of modular production units between sites to adapt capacity at

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the network level. Reconfigurability in their model remains capacity-based rather than capability-based. Other approaches consider the reassignment of production lines to product variants or the coordination of ad-hoc reconfigurations [13,14]. [15] focus on capacity adjustments and restrict reconfiguration to the acquisition of new capabilities. While the aforementioned studies primarily focus on long-term network configuration planning, other studies address reconfigurability only in mid-term planning. [16] combines lot-sizing and sequencing decisions, yet does not explicitly model reconfiguration sequences or temporary capability unavailability. Other approaches incorporate reconfiguration aspects into mid-term planning by determining which machine modules should be activated in each period to minimize production and reconfiguration costs [17,18]. These approaches remain limited to machine-level adjustments and do not capture reconfiguration sequences or capability transfers between production systems. More recent work considers order allocation and reconfiguration sequencing in GPNs, but focuses on setup decisions rather than capability transfers [19].

In summary, existing literature either addresses reconfigurability in long-term network configuration or focuses on mid-term operational planning. However, these decision levels are typically treated separately, without explicitly ensuring feasibility under temporary capability unavailability or consistency across planning horizons. In particular, the interaction between long-term configuration decisions to quantify the benefits of RMS, mid-term sequencing as well as order allocation across GPN, and adaptive replanning remains insufficiently addressed. This gap motivates the integrated multi-horizon approach proposed in this paper.

3. Multi-horizon planning approach

Fig. 1 illustrates the proposed integrated multi-horizon planning approach for GPNs with RMS. The approach consists of three interconnected mixed-integer linear optimization models (MILP) addressing long-term network configuration, mid-term operational planning, and mid- term adaptive replanning of reconfiguration decisions. The key contribution lies in the integration and coordination of these models. It assumes the availability of RMS with transferable capabilities, deterministic input parameters, and predefined planning horizons, and focuses on the final assembly production stage.

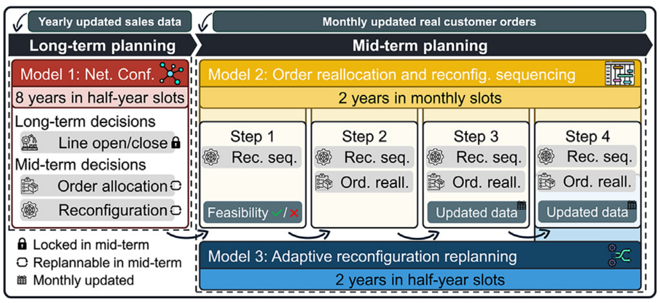

Fig. 1. Integrated multi-horizon planning approach illustrating the three optimization models, their respective planning horizons, and the decisions addressed at each step in GPNs with RMS.

Model 1 determines a long-term network configuration, including capability allocation and investment decisions. The opening, closing or relocation of production lines remains fixed in the mid-term planning horizon, while the reconfiguration of capabilities is permitted. As these long-term decisions must be realized in the mid-term, Model 2 ensures operational feasibility by jointly determining order reallocations and detailed reconfiguration sequences while explicitly accounting for temporary capability unavailability. At the same time, the flexibility enabled by RMS requires adaptive planning, which is addressed by Model 3 through replanning of reconfiguration decisions in response to updated demand information, without altering the long-term network configuration. Inventory and backorder quantities are bounded, with penalty costs discouraging excessive use. Model 2 therefore acts as a sequencing-based feasibility layer that verifies whether the decisions from Model 1 and Model 3 can be executed under temporary capability unavailability. If no feasible solution can be identified, the backorder constraint can be relaxed to identify critical orders and support iterative adjustment. Together, the three models integrate long-term investment and reconfiguration planning with detailed sequencing and mid-term adaptability, ensuring feasible and responsive operation of RMS in GPNs. Dividing decisions across three models makes complexity manageable.

3.1. Long-term network configuration planning (Model 1)

Model 1 determines a cost-optimal long-term network configuration for the GPN. The model defines long-term decisions regarding the line activity, investment decisions such as new line construction and high-level planning for the allocation and reallocation of production capabilities. These decisions establish the structural framework within which mid-term, detailed planning is performed. Model 1 is formulated as a MILP minimizing the total expected cost c of the GPN (Eq. (1)).

$$\min c^{total} = c^{variable} + c^{overutil} + c^{underutil} + c^{fixed} + c^{feature\ acquisition} + c^{feature\ reallocation} + c^{feature\ or\ line\ disposal} + c^{releases} + c^{logistic} + c^{line\ moving} + c^{new\ line\ construction} \quad (1)$$

A key constraint (Eq. (2)) ensures the temporal consistency of capability availability on production lines. A capability $f \in F$ exists on line $l \in L$ in period $t \in T$ ($u^{existing}_{l,f,t}$) if it was present in the previous period and not reallocated to another line $m \in L'$ ($u^{moving}_{l,m,f,t}$), or if it is newly acquired ($u^{receiving}_{l,f,t}$) or reallocated from another line $k \in L$ to the line ($u^{moving}_{k,l,f,t}$). L' extends L by a non-active line representing the possibility to scrap capabilities.

$$u^{existing}_{l,f,t} = u^{existing}_{l,f,t-1} + u^{receiving}_{l,f,t} + \sum_{k \epsilon L} u^{moving}_{k,l,f,t} - \sum_{m \epsilon L'} u^{moving}_{l,m,f,t}, \ \forall \ l \epsilon L,\ f \epsilon F, t \epsilon T \quad (2)$$

Additional constraints ensure demand fulfillment and include capacity limits capturing both production and reconfiguration times, activation rules for production lines, construction and ramp-up times, spatial limitations, capability dependencies and exclusivity, and customer release requirements. These constraints were adapted and extended based on [15].

3.2. Order reallocation and reconfiguration sequencing (Model 2)

Model 2 determines cost-optimal order reallocations and reconfiguration sequences. The model extends the approach proposed in [19]. Its objective is to ensure feasible and efficient network management by balancing production, inventory, and backorders while explicitly accounting for temporary capability unavailability during reconfiguration processes. Since the network configuration cannot be altered within this model, feasibility is ensured through early production and inventory buildup as well as delayed fulfillment via backorders. To capture detailed sequencing decisions, the planning horizon is structured hierarchically. Macro periods $t \in T$ represent long-term planning intervals, identical to Model 1. Each macro period is subdivided into meso periods $m \in M$, for which updated demand information is available. The lengths of t and m are determined by the demand resolution at the respective planning horizon. Each meso period is further divided into micro periods $z \in Z$ with variable lengths, enabling the explicit sequencing of production and reconfiguration activities. The objective function of Model 2 (Eq. (3)) minimizes total operational costs. In contrast to Model 1, inventory and backorder costs are explicitly included, as Model 2 captures temporary capability unavailability caused by reconfiguration activities at the mid-term level.

$$\min c^{total} = c^{variable} + c^{overutil} + c^{underutil} + c^{inventory} + c^{backorder} + c^{feature\ acquisition} + c^{feature\ reallocation} + c^{logistic} + c^{update\ release} \quad (3)$$

Demand fulfillment for order $o \in O$ in meso period $m \in M$ is ensured through the following balance (Eq. (4)).

$$\eta_{o,m} = \sum_{l \epsilon L} \sum_{z \epsilon Z} q_{o,l,z} + I_{o,m-1} - I_{o,m} - B_{o,m-1} + B_{o,m}, \ \forall \ o \epsilon O,\ m \epsilon M \quad (4)$$

The quantity demanded $\eta_{o,m}$ should be satisfied by production $q_{o,l,z}$ on any production line $l \in L$ or inventory from the previous period $I_{o,m-1}$. Furthermore, it is possible to fulfill backorders from the previous period $B_{o,m-1}$, build up inventory $I_{o,m}$, and generate new backorders $B_{o,m}$, while respecting limits on inventory and backorder quantities.

Production is restricted to active lines with sufficient capacity and the required capabilities. Reconfiguration constraints ensure that capabilities can only be installed after dismantling and transportation have been completed. Installation and dismantling processes reduce capacity and are not restricted to a single micro period, allowing the representation of varying process durations. This requires that, once a reconfiguration activity has started, its execution must continue without interruption across consecutive micro periods until completion. Furthermore, in each micro period, a production line can either be used for production, for reconfiguration, or remain idle. Customer release constraints ensure that production is only permitted when the corresponding releases are available and that reconfigured lines receive updated releases before production resumes.

3.3. *Adaptive reconfiguration replanning (Model 3)*

Model 3 enables the adaptive replanning of previously determined reconfigurations to use the benefits of RMS. It focuses exclusively on revising mid-term decisions such as order allocation, capability reallocation, and the timing of reconfiguration activities in response to updated demand information or operational deviations. The MILP solved in Model 3 is structurally equivalent to Model 1 and deliberately independent of the sequencing formulation of Model 2. While Model 2 addresses detailed sequencing, inventory, and backorders, Model 3 revisits mid-term configuration decisions using the long-term formulation, keeping line opening, closing, and moving fixed, and allowing only capability reconfiguration. Thus, Model 3 is restricted to the network structure defined by Model 1, while allowing adjustments of capability allocation, order allocation, and reconfiguration timing within this structure.

All feasibility constraints related to demand fulfillment, capacity limits, capability availability, construction and ramp-up times, spatial restrictions, capability dependencies, and customer release requirements are enforced analogously to Model 1. By allowing mid-term decisions to be replanned without altering long-term network configuration decisions, Model 3 ensures that the flexibility provided by RMS can be effectively utilized under dynamic demand conditions.

4. Results

The proposed approach is validated using two industrial-scale use cases and experiments from an automotive supplier (Table 1).

Table 1
Use cases calculated with and without reconfiguration.

	Use case 1	Use case 2
Product group	Pumps	Breaking systems
Production lines	15	26
Possible capabilities	18	18
Sites	4	10
Calculated experiments	8	4

The use cases represent high-volume, mass-produced products with a high degree of vertical integration across multiple value-adding stages in the GPN. The presented analysis focuses exclusively on the final assembly stage. Long-term planning at the use case company is based on forecasted customer orders over an 8-year horizon (yearly updated), while mid-term planning relies on real customer order data over a 2-year horizon (monthly updated).

4.1. *Long-term network configuration benefits*

Taking reconfiguration into account for the long-term network configuration planning significantly reduces necessary investment and expected operational costs with cost reductions between 4 and 14% observed across all experiments in both use cases. This indicates that the additional flexibility provided by RMS is beneficial and can be effectively exploited by the proposed MILP. Table 2 represents this effect for one experiment from use case 2, where total costs decrease by 9.82% compared to a reference solution in which no reconfiguration is permitted. Cost reductions are primarily driven by lower variable and logistic costs as well as reduced fixed costs resulting from fewer active production lines. Moreover, fewer capabilities need to

Table 2
Cost comparison for Model 1 with and without reconfiguration.

Costs	Model 1 without reconfiguration	Model 1 with reconfiguration	Δ%
Underutilization costs	≈ €14,083,000	≈ €7,817,000	−44.49%
Overutilization costs	≈ €2,481,000	≈ €3,717,000	49.82%
Release costs	≈ €1,750,000	≈ €1,850,000	5.71%
Logistic costs	≈ €228,073,000	≈ €210,268,000	−7.81%
Feature acquisition costs	≈ €4,796,000	≈ €2,000,000	−58.30%
Variable costs	≈ €108,866,000	≈ €98,442,000	−9.57%
Fixed costs	≈ €16,835,000	≈ €14,603,000	−13.26%
Feature reallocation costs	-	≈ €1,019,000	-
Feature disposal costs	≈ €1,090,000	≈ €1,150,000	5.50%
Total costs	≈ €377,973,000	≈ €340,866,000	−9.82%

be acquired, as they can be provided through the reallocation of existing capabilities. Although additional reallocation costs are incurred, these are more than compensated by the reduction in investment and operating costs.

For use case 1, a baseline representing manual planning with fixed order allocations is used for comparison. In this baseline, the optimization model is restricted to evaluating costs under fixed order assignments. Allowing reconfiguration within this baseline reduces total costs by 7.71%. When both reconfiguration and flexible order allocation are enabled, total costs decrease further by 12.24% compared to the baseline with reconfiguration. These results highlight the additional value of optimization-based reconfiguration and order allocation decisions compared to fixed manual planning assumptions. This baseline serves to isolate the effects of reconfiguration and order allocation decisions.

4.2. *Impact of sequencing and order reallocation (Step 1–2)*

Step 1 demonstrates that order allocations derived from long-term planning may become infeasible when detailed reconfiguration sequencing and temporary capability unavailability are considered in the mid-term. This shows that neglecting reconfiguration timing leads to infeasible production plans, even if long-term decisions appear cost-optimal, emphasizing the importance of integrating sequencing decisions into network planning.

In Step 2, order reallocation is permitted and optimized jointly with reconfiguration sequencing in Model 2 (Fig. 1). As shown in Table 3, total costs increase slightly compared to the long-term plan, indicating that production cannot always be assigned to the most cost-efficient lines once sequencing constraints are considered.

Table 3
Cost comparison for Step 2.

Costs	Rough planning Model 1	Detailed planning Model 2 (Step 2)	Δ%
Underutilization costs	≈ €1,634,000	≈ €1,622,000	−0.73%
Overutilization costs	≈ €2,297,000	≈ €2,262,000	−1,52%
Logistic costs	≈ €95,013,000	≈ €97,324,000	2.43%
Variable costs	≈ €49,280,000	≈ €48,609,000	−1,36%
Feature reallocation costs	≈ €806,000	≈ €761,000	−5.58%
Feature acquisition costs	≈ €2,000,000	≈ €2,000,000	0.00%

However, operational feasibility is fully restored, which can be verified in Fig. 2, where the sequence of dismantling, transportation, and installation is consistently maintained. Temporary infeasibilities are resolved through inventory buildup or, where unavoidable, through delayed production via backorders.

The following example highlights that the described flexibility becomes unavoidable in the absence of required capabilities. Capability F13 is moved from L07 to L04 and becomes available in meso period 1. During meso period 0, no active line is equipped with F13,

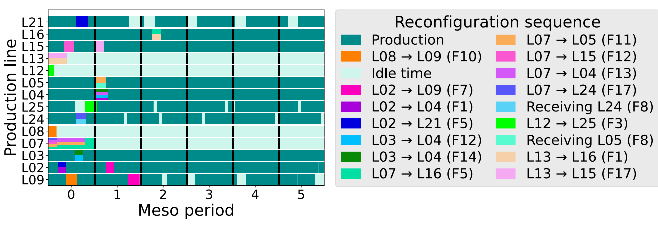

Fig. 2. Reconfiguration sequence (Step 2).

making inventory buildup impossible, and demand in meso period 1 can only be fulfilled through delayed production in meso period 2. A similar effect can be observed for capability F5, whose temporary unavailability during reconfiguration is compensated by early production and inventory buildup. Due to the aggregation of forecasted orders and capacities at the half-year level, utilization rates remain largely constant within each macro period and change primarily at reconfiguration points.

4.3. Impact of updated demand information (Step 3)

In Step 3, forecasted orders are updated with real customer order data. Due to significantly lower demand volumes, utilization rates decrease across production lines (Fig. 3), revealing substantial overcapacity under the previously planned configuration. Fig. 4 shows that several reconfiguration actions planned in the long-term model lose relevance once real demand information becomes available. Some reconfigurations are omitted entirely, while others are revised with respect to timing. These results show that a significant share of long-term reconfiguration decisions become obsolete once real demand information becomes available, underlining the necessity of adaptive replanning.

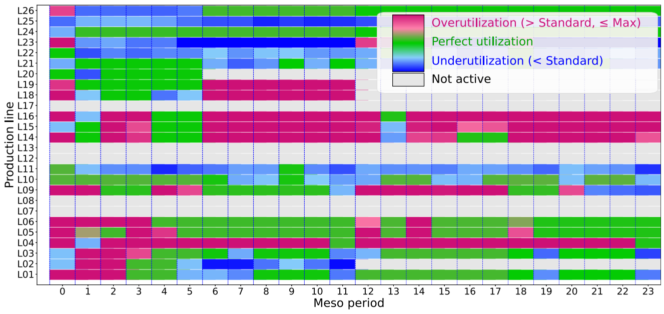

Fig. 3. Production line utilization rates (Step 3).

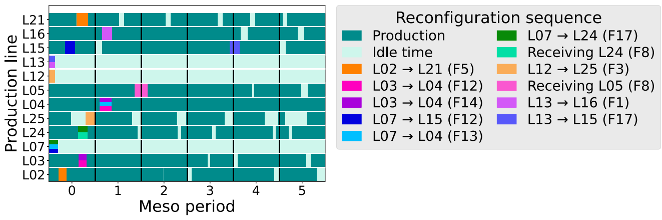

Fig. 4. Reconfiguration sequence (Step 3).

4.4. Benefits of adaptive replanning (Step 4)

Step 4 first applies Model 3 to replan mid-term decisions over a 2-year horizon. As a result, the number of capability reallocations is further reduced and reconfiguration decisions are better aligned with actual demand requirements. Revised decisions differ with respect to source and target lines, affected capabilities, and execution periods. Other reconfigurations are omitted entirely.

The replanned configuration is transferred to Model 2, where all reconfigurations are sequenced without further revision. Compared to Step 3, total backorder quantities are significantly reduced, while other costs remain largely comparable (Table 4). In particular, backorder costs decrease, confirming that adaptive replanning improves feasibility while reducing unnecessary reconfiguration activities.

4.5. Summary of results

Overall, the results demonstrate that (i) integrating reconfigurability into and using RMS in long-term network configuration planning significantly reduces investment and operating costs, (ii) detailed mid-term sequencing and order reallocation are required to ensure feasibility under temporary capability unavailability, and (iii) adaptive replanning allows the flexibility of RMS to be effectively exploited under evolving demand conditions by reducing unnecessary reconfigurations and backorders. The results should be interpreted as case-specific evidence derived from the considered industrial use cases and the corresponding data settings.

Table 4
Cost Comparison Step 3 and Step 4 for Model 2.

Costs	Step 3	Step 4 – Replanning	Δ%
Underutilization costs	≈ €3,477,000	≈ €3,175,000	−8.69%
Overutilization costs	≈ €1,585,000	≈ €1,558,000	−1.70%
Logistic costs	≈ €92,884,000	≈ €92,341,000	−0.54%
Variable costs	≈ €45,488,000	≈ €45,867,000	0.83%
Feature reallocation costs	≈ €491,000	≈ €596,000	21.38%
Feature acquisition costs	≈ €2,000,000	≈ €2,000,000	0.00%
Inventory costs	≈ €361,000	≈ €359,000	−0.55%
Backorder costs	≈ €8,481,000	≈ €2,477,000	−70.79%
Update release costs	≈ €2,660,000	≈ €3,560,000	33.83%
Total Costs	≈ €157,426,000	≈ €151,934,000	−3.49%

5. Conclusion

The results demonstrate that the benefits of RMS can only be realized when reconfiguration decisions are consistently integrated across planning horizons. In particular, long-term optimal configurations may become infeasible when reconfiguration timing is neglected, while adaptive mid-term replanning is essential to effectively utilize the available flexibility and avoid unnecessary reconfigurations and backorders. Beyond economic benefits, the reuse of existing production system components also contributes to a more resource-efficient transformation of GPNs. Nevertheless, the proposed approach is subject to limitations. The current models assume deterministic input parameters, including deterministic reconfiguration durations. Extending the approach towards a stochastic formulation that incorporates uncertainty represents a direction for future research. In addition, the planning horizons and the other model parameters are predefined. Therefore, future research may investigate their impact through sensitivity analysis, as the choice of these factors influence the stability of investment decisions. Furthermore, a more automated execution of the models by a daydreaming engine would be beneficial [20]. Overall, the proposed approach provides a structured and quantitative basis for integrating reconfigurability into production network planning and supports the evaluation and justification of RMS in GPNs.

CRediT authorship contribution statement

Michael Martin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Vanessa Altmann:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.cirp.2026.04.025.

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