Optimization Model-Driven Adaptation in Interconnected Manufacturing Networks

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Abstract: *In an ever-evolving market landscape, companies often excel at spotting opportunities within their existing product range but struggle to identify opportunities for new product lines. This gap underscores that traditional approaches, often siloed and focused on singular manufacturing systems, fall short in exploiting the full spectrum of capabilities that an interconnected, ecosystem-wide perspective offers. This research proposes to bridge this gap by extending the adaptability analysis from isolated systems to an interconnected network framework by manufacturing potential collaborative efforts. The study introduces an optimization model designed to accurately give adaptation recommendations based on shared capabilities. It capitalizes on our results of an ontology-based matchmaking process to effectively map identified manufacturing service providers candidates. The model encapsulates a decision-making process in an enterprise's location and operation allocation network, aiming to map out the identified candidates, explore feasible task allocations, and ultimately select an optimal configuration that meets the manufacturing requirements. An illustrative case involves a stroller manufacturer branching into folding bicycle production. This scenario serves as a validation of the model, showcasing its ability to enhance company adaptability and resilience. Through interconnected production networks, the model helps seizing new production opportunities and accurately estimate co-production costs.*

Keywords: *Interconnected Production Networks, Optimization Model, Physical Internet, Resilience, Adaptability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☒ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☐ In-Person presentation*

1 Introduction

Over the past few years, the paradigm of traditional manufacturing planning has increasingly shifted towards optimizing collaborative efforts at the inter-enterprise level, a strategic pivot in response to the challenges and competitiveness demands of emerging markets(Andres et al., 2021). Historical examples like the collaboration during World War II among companies such as Ford, Douglas, and Convair, as well as the partnership between GM and Philips for the HOPE ventilator project during the COVID-19 pandemic, showcase the effectiveness of this evolution. Similarly, Ford’s initiative with the Mustang Mach-E electric SUV demonstrates the same collaborative spirit driven by strategic market expansion, not just the need for crisis management.

However, the rapid changes in market demands and advancements in production technologies have made it increasingly difficult for a single enterprise to effectively respond on its own(Hu et al., 2020). Today, a collaborative network of partners, leveraging shared capabilities and resources, is crucial to mitigate the environmental and social impacts of operational expansion. This approach aligns with Virtual Enterprise concept (Polyantchikov et al., 2017), where the outsourcing of manufacturing tasks goes beyond transactional exchanges and into strategic interconnected production networks. Collaborative manufacturing partner selection for a product in a collaborative environment is a complex decision-making problem that requires comprehensive consideration of multiple attributes of candidate partners(Moghaddam and Nof, 2018). Yet, current research often overlooks crucial factors such as the degree of alignment between a partner's manufacturing capabilities and the overall financial consideration(Li et al., 2021). This gap highlights the need for an integrated approach, leading to a fundamental research question: *How can enterprises strategically select partner candidates to optimize the configuration of a Virtual Enterprise and effectively capitalize on new production opportunities?*

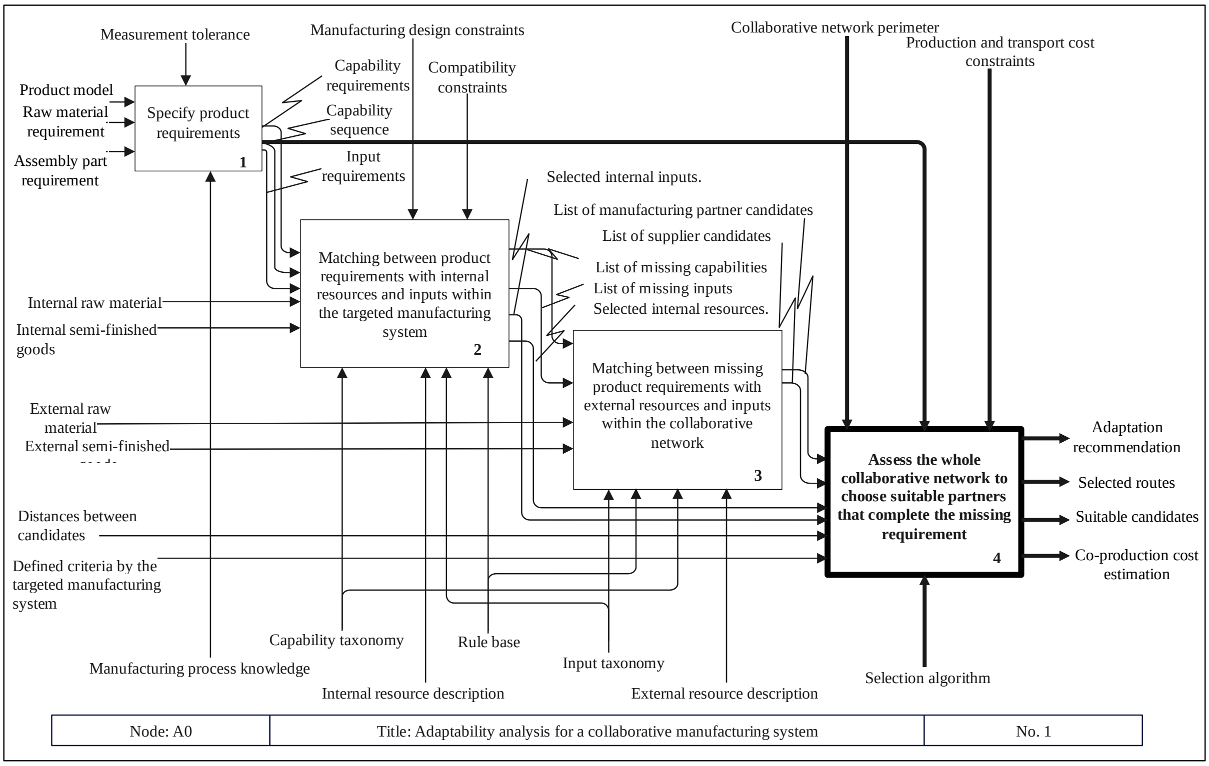

Figure 1: Adaptability analysis framework for a new production opportunity in an interconnected collaborative manufacturing network(Ferhat et al., 2023).

Building on our previous work, we have developed a framework for adaptability analysis within collaborative manufacturing systems, as depicted in Figure 1. This framework consists of two main objectives: initially, identifying potential partners through a matchmaking sub-process that aligns resources with operational requirements; subsequently, the selection of suitable candidates from this pool, which forms the crux of this research (sub-process 4 in bold on figure 1). The core challenge addressed in this paper is the Partner Selection Problem (PSP), focused on selecting optimal partners within a a production network. Addressing our research question, this process ensures that strategic alignment and financial considerations are at the forefront of partner selection decisions, aiming to optimize both operational efficiency and production network resilience.

This paper introduces an illustrative case study involving a leading folding stroller manufacturer that plans to expand into folding bicycle production using the Partner Selection Problem (PSP). This example primarily demonstrates the practical application of our optimization model, which estimates the co-production costs—including manufacturing and transportation expenses. Such insights are critical for leaders in making informed decisions about new manufacturing opportunities and underscore the significance of cooperative innovation in interconnected markets.

The paper first explores the theoretical background, followed by a discussion of our contribution, including the PSP implementation. It then moves into the context of an illustrative case study, examining the implications of our findings. The final section draws conclusions and suggests directions for future research, offering a comprehensive look at both the theoretical and practical aspects of partner selection in modern manufacturing environments.

2 Theoretical background

2.1 Production network

Over the past two decades, considerable scientific research and numerous projects have focused on production and manufacturing networks (Mladineo et al., 2018). These studies, highlighted by researchers such as (Müller, 2006) and projects like those by (Markaki et al., 2013) have employed various terminologies to describe types of production networks. These include "global production networks" (Jaehne et al., 2009), reconfigurable collaborations" (Schuh et al., 2008), "dynamic manufacturing networks" (Markaki et al., 2013), "virtual enterprises" (Camarinha-Matos et al., 2009) and “universal manufacturing systems”(Kusiak, 2022). Virtual enterprises are particularly notable as dynamic, opportunity-driven networks established to seize specific business opportunities within a limited timeframe.

A significant challenge in managing these networks is partner incompatibility, which often leads to the failure of collaborative projects (Dacin and Hitt, 1997). It is crucial for organizations, regardless of size, industry, or location, to select partners that not only align with their objectives but also bring the necessary skills and strategic orientations that complement their own operations(Emden et al., 2006). This needs to form a production network with suitable partners brings us to a critical inquiry:

R.Q: How can enterprises strategically select partner candidates to optimize the configuration of a Virtual Enterprise and effectively capitalize on new production opportunities?

2.2 Partner Selection Problem

Effective partner selection is critical to successfully capitalize on market opportunities. Known as the Partner Selection Problem (PSP), this issue arises when the production process requires integration of various technological operations that different enterprises within the network can perform. Addressing the PSP involves assessing potential partners' capability to meet production demands efficiently.(Huang et al., 2018; *Production Networks meet Industry 4.0*, 2020; Tao et al., 2012; Wu and Su, 2005).

Partner selection problem in production networks has been a recurring issue in various studies. (Han Zhao et al., 2006)proposed a method of rough production planning based on case-based reasoning to address partner selection and task assignment in extended enterprises. (Wu and

Barnes, 2011) discussed partner selection and production-distribution planning in defective supply chain network systems, showing that the proposed approach outperformed existing methods. (Veza et al., 2015) highlighted the importance of evaluating enterprise performance to solve the partner selection problem in production networks. (Mladineo et al., 2017)introduced the HUMANT algorithm to solve partner selection problems in Cyber-Physical Production Networks. (Polyantchikov et al., 2017)focused on sustainable partner network solutions for virtual enterprise formation. (Guo et al., 2019) proposed a Distributed Approximation Approach to solve the sustainable supply chain network design problem by dividing it into partner selection and transportation planning sub-problems. Overall, these studies emphasize the significance of effective partner selection methods in optimizing production network. These studies underscore the importance of developing robust partner selection methodologies to optimize production networks effectively and efficiently. Researchers concur that decomposing the complex problem of partner selection into manageable sub-problems allows for more focused and effective solutions (Wu and Barnes, 2018).

3 Contribution

3.1 Problem Description

In this study, we propose an Integer Linear Programming (ILP) model to address the (PSP) within a production network. The model aims to minimize total production costs, encompassing both manufacturing expenses for each operation and transportation expenses between enterprises by proposing a new Virtual Enterprise configuration. It facilitates strategic enterprise selection and precise determination of operation and transport quantities that align with the product's nomenclature and manufacturing process. Our approach builds on a foundational ontology-based framework and enhances decision-making by integrating enterprise selection with optimal path determination within the network. This dual focus enables a comprehensive allocation of tasks across selected enterprises, accounting for both their unique production capabilities and the logistical intricacies of the production sequence.

In Figure 3, the diagram represents a product that requires five distinct operations for its manufacturing process. These operations are mapped out across a network consisting of three pre-identified manufacturing systems, each capable of performing some of the required operations. Our objective is to determine the optimal configuration of a new VE, effectively aligning each required operation with the most suitable manufacturing system. Through this approach, we aim to enhance the coordination within the production network, selecting the best partners and their corresponding operations to streamline the manufacturing of the product.

Despite numerous studies on partner selection within production networks, there remains a significant gap in dynamically adapting these strategies for Virtual Enterprises, particularly in environments characterized by rapid market fluctuations and swift technological progress. This study aims to bridge this gap by devising a responsive partner selection methodology tailored for Virtual Enterprises, enhancing their agility and effectiveness in capitalizing on emerging opportunities, as directly addressed by our research question.

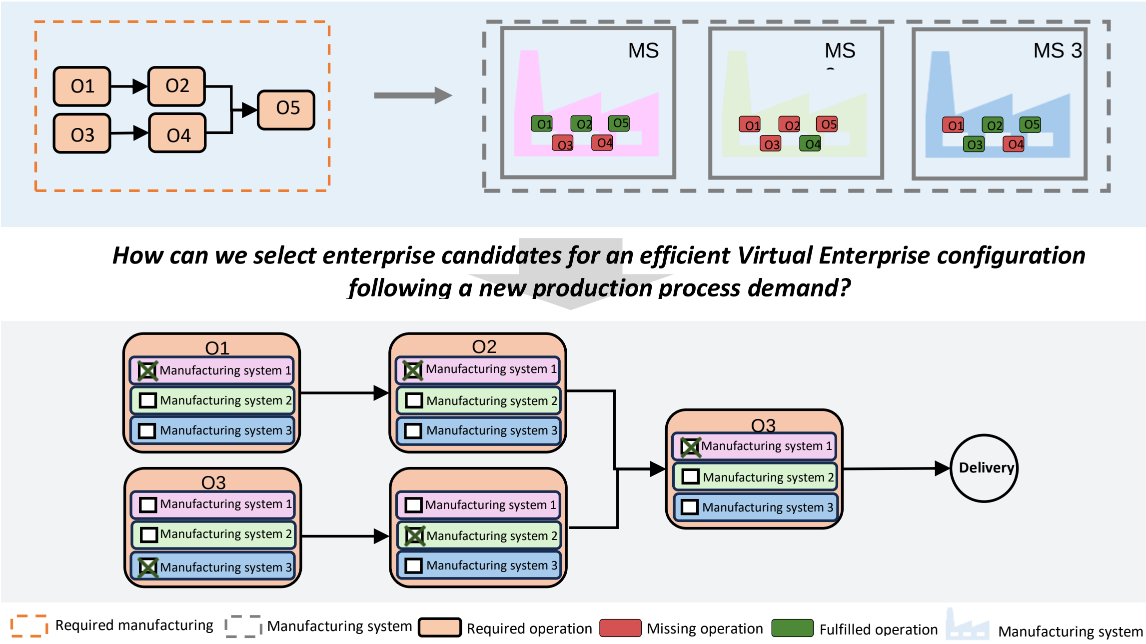

Figure 3: Partner selection problem application within a production network for a new production process.

3.2 Model Assumptions

Manufacturing enterprises can share their capabilities within the network to fulfil a new production demand, but it is crucial to select optimal agents (enterprise) for each activity (operation) to achieve the new production requirement with a reasonable manufacturing and transport cost. To navigate this challenge, we establish the following assumptions:

Hypothesis 1 (H1): Exclusive Operation execution

We suppose that each required operation is executed exclusively by a single enterprise, precluding the co-production of any part of a product by multiple enterprises.

Hypothesis 2 (H2): Single Output Provision

We posit that each operation undertaken by any enterprise resource results in a single output.

Hypothesis 3 (H3): Leadership and Opportunity Offer

This hypothesis posits that a leading enterprise within the network spearheads new production opportunities, making pivotal decisions based on global production costs and partner bids. This leader assesses partner proposals against cost-efficiency and strategic fit, ultimately determining the network's engagement in a co-production partnership.

3.3 Objective function

$$min \sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{I} C_i^j \,.\, Y_{ik}^j \; + \sum_{i}^{I}\sum_{k}^{K}\sum_{j}^{I} t_{ik} \,.\, Y_{ik}^j$$

This objective function aims to minimize the total co-production cost for a demand D. The cost includes the manufacturing cost for each resource of each enterprise selected and the transportation cost inter-enterprises.

3.4 Variables

- $\boldsymbol{Y_{ik}^{j}}$: Quantity produced by enterprise i for operation j, which then serves as the input for enterprise k to carry out the subsequent operation.

3.5 Parameters

- C_i^j : Manufacturing cost of operation j by company i.
- t_{ik} : Transport cost between company i and company k.
- $a^{jj'}$: Operation sequence indicating if operation j must precede operation j'.
- *D:* Final product Demand.
- n^j: Base unit demand for operation j (nomenclature description).
- Cp_i^j: Production capacity of enterprise I for operation j.
- I: Set of enterprises, indexed by i.
- J: Set of operations, indexed by j.

3.6 Constraints

Constraint 1: "Demand fulfilment"

Ensure that the total production for each operation matches the demand.

$$\forall j \in J : \sum_{i}^{I} \sum_{k}^{I} \boldsymbol{Y_{ik}^{j}} = \boldsymbol{D} * n^j$$

Constraint 2: "Sequence of operations"

Enforce the sequence of operations according to $a^{jj'}$.

$$\forall j, j' \in J : such\ that\ a^{jj'} = 1, then\ \forall k \in I : \sum_{i}^{I} \boldsymbol{Y_{ik}^{j}} \geq \sum_{l}^{I} \boldsymbol{Y_{kl}^{j'}}$$

Constraint 3: "Exclusive Operation Allocation"

Ensure that each operation j is procured by only one enterprise i with its required demand.

$$\forall j \in J, \forall i, k \in I : \boldsymbol{Y_{ik}^{j}} = \boldsymbol{D} * n^j$$

Constraint 4: "Enterprise Operational Capacities"

Production quantities must not exceed the production capacities of each enterprise.

$$\forall j \in J, \forall i \in I : \sum_{k}^{I} \boldsymbol{Y_{ik}^{j}} \leq Cp_i^j$$

4 Illustrative case

4.1 Context

In our illustrative case, we examine the strategic expansion of a leading folding stroller enterprise into a new production opportunity: folding bicycles. The manufacturing process for folding bicycles, as detailed in Figure 4, encompasses five distinct operations outlined in the nomenclature located in the upper left of the figure. This process constructs the bicycle using the following components: a frame, a pair of wheels, a front set, a saddle, and a transmission instrument. Central to this study is an analysis focused on the semi-products—those that have undergone specific operations—denoted by numbers 11, 12, 13, and 14, leading to the final product marked as 15. It is these intermediate forms, the semi-products, that hold particular significance in our research, providing critical insight into the efficiency and effectiveness of the production network.

As depicted in the right side of figure 4, the market expansion of the stroller enterprise to a folding bicycle production is supported by a pre-established network of seven enterprises, identified from a larger candidate pool through an ontology-based matchmaking process refined from our initial knowledge graph.

The goal is to select an optimal subset of partners and pathways within this network that minimizes co-production costs. Each selected enterprise contributes distinct resources required for the operations, with unique manufacturing costs and transportation expenses influenced by their geographical distances. The initial production target is set at 50 folding bicycles. By calculating the total production cost, which includes both manufacturing and transportation expenses, we provide the enterprise leader with a co-production cost analysis. This analysis is crucial for making informed decisions about this new production opportunity.

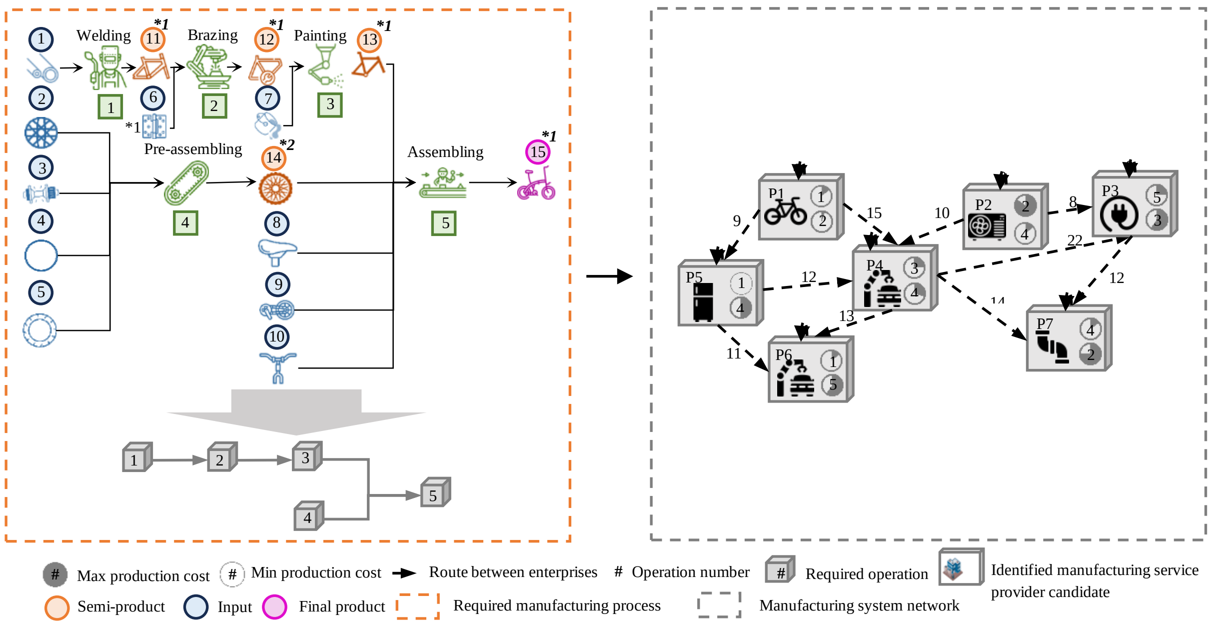

Figure 4: Folding bicycle production requirement for a production network.

4.2 Results

The optimization model has been solved using (IBM ILOG Cplex Optimization Studio). It provides an approach to evaluate stroller company's expansion into the folding bicycle market.

It does so by integrating diverse operational and logistical variables to establish a cost structure. Specifically, the model predicts that adopting this new manufacturing strategy would result in a production cost of 1800 euros for the required demand of 50 folding bicycles. This estimation is foundational for the company, guiding investment decisions and setting a benchmark for financial sustainability in this new market foray (see figure 5).

As illustrated in figure 5, the model proposed anew VE configuration.Enterprise P1 is the starting point, handling Operations 1 with the production of 50 welded frames (semi-product 11) for the folding bicycle. It also executes Operation 2, procuring 50 outputs of brazed folding frames (semi-product 12). The continuation of the manufacturing process sees the semi-finished product 12, with a transport quantity of 50, moving to Enterprise P4P4's handles simultaneously the parallel execution of Operations 3 and 4, producing 50 painted folding bicycle frames (semi-product 13) and 100 wheels (semi-product 14), respectively. Both semi-products 13 and 14 are transported to the next enterprise with a transport quantity of 150 to be assembled within the last enterprise 6. Enterprise P6 is depicted as the final assembly point for Operation 5, where all components come together to complete the folding bicycles (see table 1).

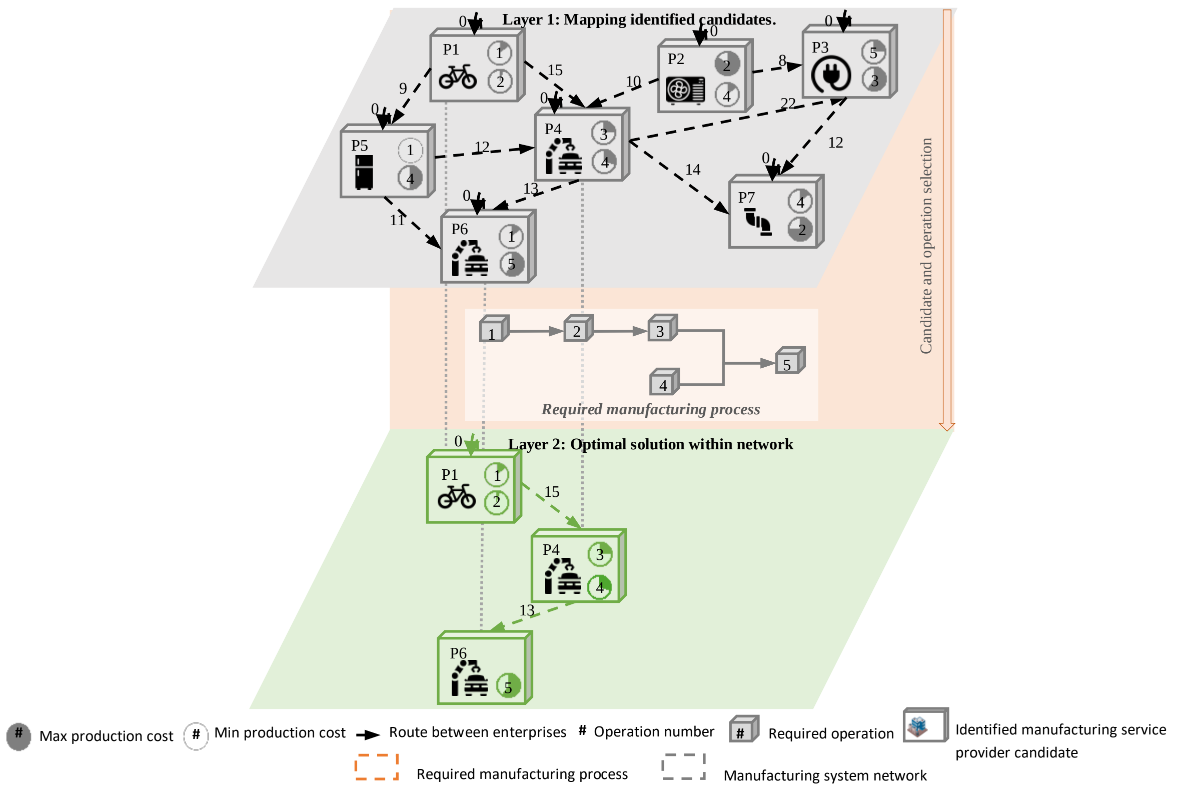

Figure 5: New Virtual Enterprise configuration of the production network for the folding bicycle production opportunity.

The estimated co-production cost and the detailed production path underscore the model's utility in identifying and mapping out the most cost-effective and operationally efficient pathway for the new production opportunity. The leading enterprise of folding strollers can use this detailed financial analysis and the optimized network configuration to make informed decisions about the economic viability and strategic direction of expanding into the folding bicycle market.

Table 1: Operation-enterprise production quantity allocation.

Depart enterprise	*Affiliated operation*	*Following enterprise*	*Production quantity*
1	1	1	50
1	2	4	50
4	3	6	50
4	4	6	100
6	5	6	50

5 Conclusion and perspectives

In the landscape of modern manufacturing, enterprises are frequently compelled to seek partnerships within a production network when new production opportunities arise. This necessity is often driven by limitations in capacity, capability, or financial resources. The critical challenge in such scenarios is to select the most suitable partners who can collaboratively form a new Virtual Enterprise, one that meets the specific criteria set forth by the decision-maker. Addressing this challenge, our research introduced an optimization model tailored to the Partner Selection Problem (PSP). This model is adept at estimating co-production costs, encompassing both manufacturing and transportation expenses, to provide enterprises with the comprehensive financial insights necessary for strategic planning and decision-making. Specifically, our illustrative case demonstrates the model’s practical application, as it maps out the production of 50 folding bicycles, selecting partners and pathways to optimize co-production costs, and ensuring an efficient allocation of production quantities. This model not only aids in evaluating the feasibility and viability of the stroller company’s expansion into folding bicycles but also serves as a benchmark for production cost comparison in similar industrial applications.

To enhance this proposed PSP model, we recommend these following perspectives:

- Encompassing dynamic variables such as production timelines and batch sizes can be added to expend the model to a job-shop scheduling problem for an operational application.
- Further explore reconfiguration implications, particularly the financial impact associated with modifying production lines, including layouts and machinery, to accommodate new manufacturing ventures.
- Expand the model's capabilities to allow multiple enterprises within the network to undertake an operation procurement. This will provide a more flexible and comprehensive approach to operation allocation across the production network.

These recommended expansions are not solely theoretical; they call for empirical validation and testing. Future experiments could involve applying the model in varied industrial environments to assess its robustness, adaptability, and scalability. Moreover, case studies involving real-time production settings could validate the model's effectiveness in dynamic scenarios, providing deeper insights.

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