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Dynamic Containerized Modular Capacity Planning and Resource Allocation in Hyperconnected Supply Chain Ecosystems

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Introduction

Challenges in traditional construction industry

According to the Environmental Protection Agency (EPA), traditional building methods generate around 56 million tons of debris every year.



91% of industrial businesses are **currently being impacted by resource scarcity**

The scarcest resources are:

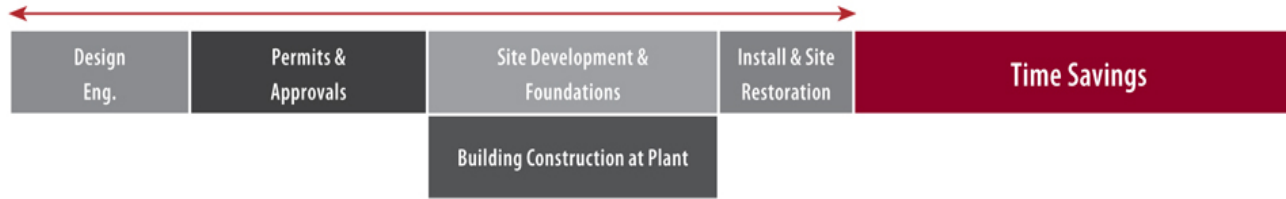
- 1 Raw materials** (affected for 37%) 
- 2 Energy** (affected for 34%) 
- 3 Labor** (affected for 32%) 

This resource scarcity has led to increased costs for 37 percent of businesses, as well as supply chain disruption for 27 percent and slowdowns in production capacity for 25 percent.

Introduction

Modular construction

Modular Construction Schedule



Site Built Construction Schedule



A controlled environment allows building modules quickly, precisely, and safely.



Large multi-story buildings can be stacked in less than two weeks in some cases.



GREENER

Reuse & Less Material Waste
Less Air Pollution & Energy Use



FASTER

Elimination of Weather Delays
Reduced Construction Schedule



SMARTER

Better Quality Controls
Less Risk of Injuries

Introduction

New challenges – modular building transportation



Distance restrictions

- Due to **road size and load restrictions**, it usually isn't feasible to ship modules far.
- The **costs and transportation difficulties** greatly increase as the shipping distance of modular buildings increases.

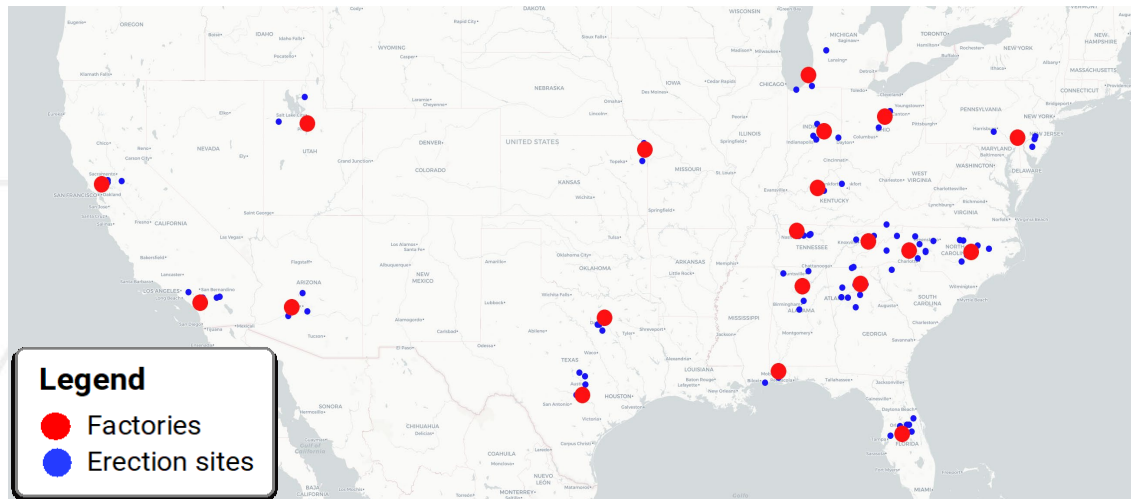


Illustration of fragmental distributed erection sites and target nearby factories

The need for nearby factories to minimize transportation costs is problematic due to

- (1) **fragmental** project locations
- (2) **high expenses** of building numerous factories
- (3) **the short-term nature** of modular building projects

Introduction

PI & Our solution

Physical Internet (PI) proposed by Montreuil aims to shape supply chains towards sustainability. In this work, we are inspired by the following core concepts of PI:

- **Modularity**
- **Containerization**
- **Open resource sharing**

Our solution:

- 1) Instead of establishing numerous long-term factories at each project locations (i.e., erection sites), the construction company **leases nearby factory buildings for short-term use**, typically a few months.
- 2) Each factory consists of multiple **movable production units**. When a factory closes, these production units can be easily moved to another factory location and seamlessly put into production.

Schematic Diagram for Modularity and Containerization

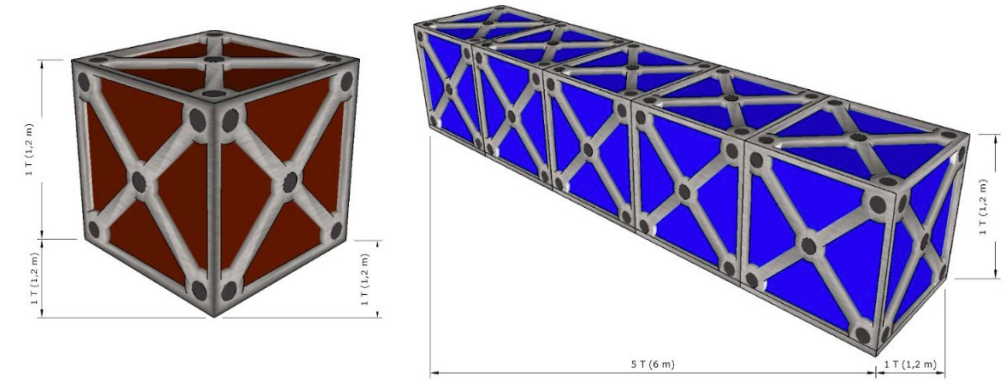
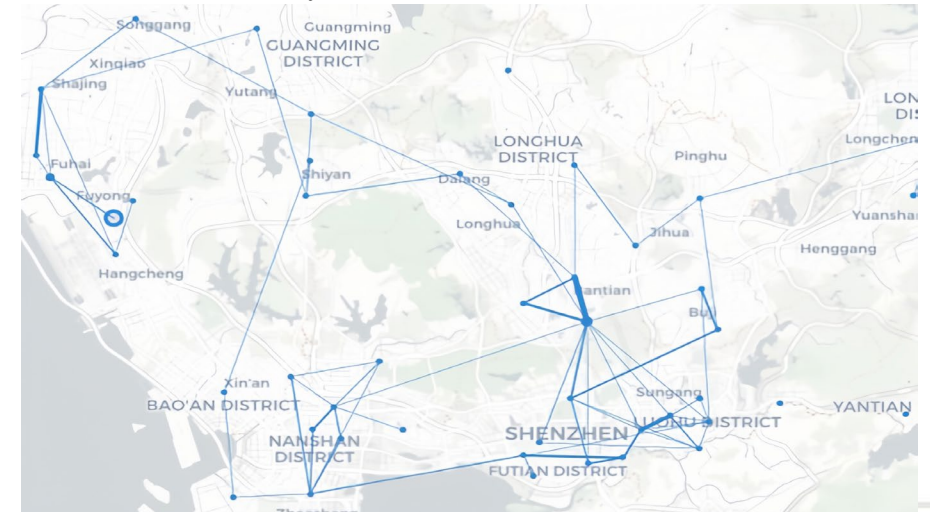


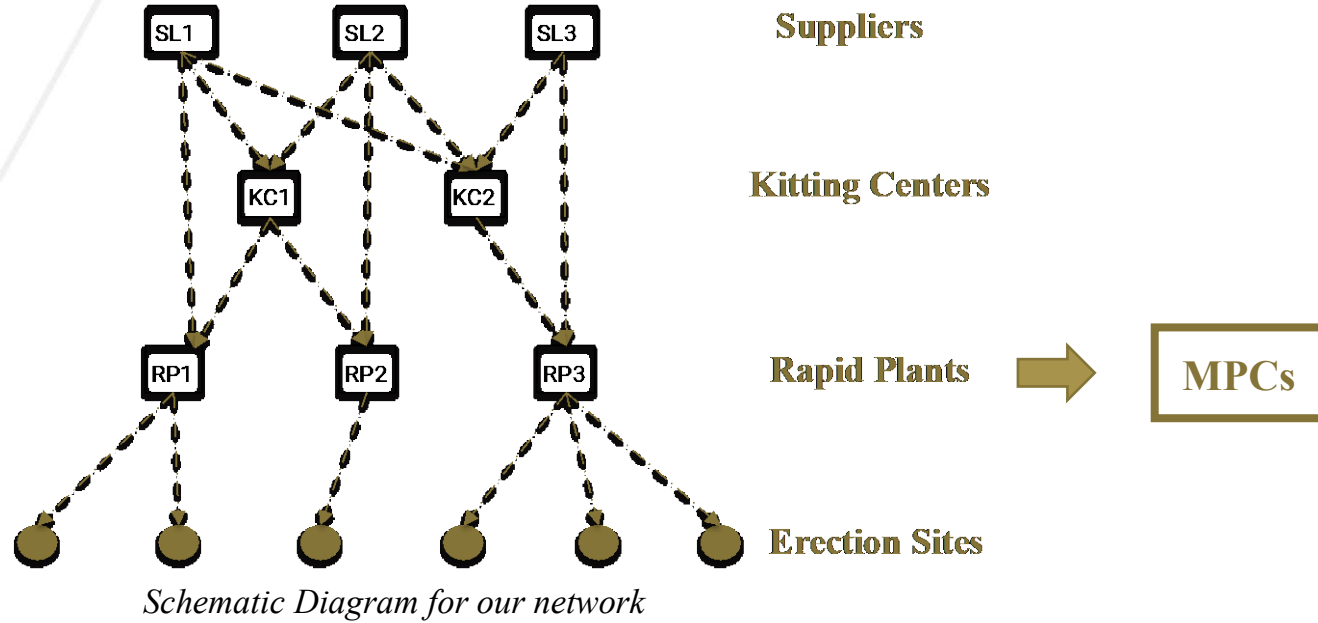
Illustration of resource relocation between hubs



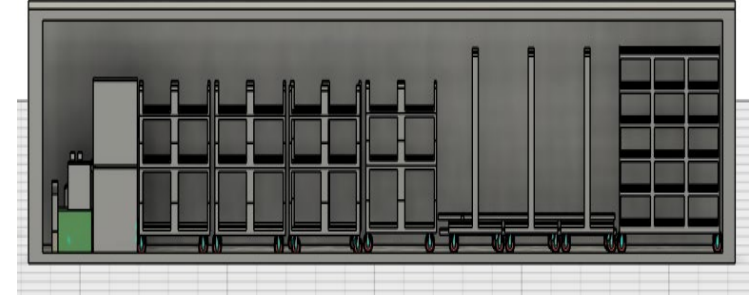
Note: cumulative plot for resource movements

Introduction

Mobile production containers (MPCs)



Schematic Diagram for MPCs



Container delivery options



Potential Benefits

- Mobility and transportability
- Quick deployment and set-up
- Standardization
- Flexibility in facility expansion
- Cost-efficiency
- Easy management

Literature Review

Physical Internet and resource sharing

- **Montreuil, B. (2011):** *Toward a Physical Internet: meeting the global logistics sustainability grand challenge. Logistics Research, 3, 71-87.*
- **Crainic, T.G., Klibi, W. and Montreuil, B. (2023):** *Hyperconnected city logistics: a conceptual framework. In Handbook on City Logistics and Urban Freight (pp. 398-421).*

Dynamic capacity planning

- **Yao, X., Almatooq, N., Askin, R.G. and Gruber, G. (2022):** *Capacity planning and production scheduling integration: improving operational efficiency via detailed modelling. International Journal of Production Research, 60(24), pp.7239-7261.*
- **Liu, X., Li, J., Dahan, M., & Montreuil, B. (2024):** *Multi-Period Stochastic Logistic Hub Capacity Planning for Relay Transportation. In Proceedings of IISE Annual Conference.*

Dynamic resource deployment

- **Faugère, L., Klibi, W., White III, C., & Montreuil, B. (2022):** *Dynamic pooled capacity deployment for urban parcel logistics. European Journal of Operational Research, 303(2), 650-667.*
- **Xu, Y., Liu, Y., & Montreuil, B. (2022):** *Dynamic Workforce Scheduling and Relocation in Hyperconnected Parcel Logistic Hubs. In Proceedings of IISE Annual Conference, 2022.*

Rolling horizon planning

- **Yuan, P., Han, W., Su, X., Liu, J. and Song, J. (2018):** *A dynamic scheduling method for carrier aircraft support operation under uncertain conditions based on rolling horizon strategy. Applied Sciences, 8(9), p.1546.*
- **Sahin, F., Narayanan, A., & Robinson, E. P. (2013):** *Rolling horizon planning in supply chains: review, implications and directions for future research. International Journal of Production Research, 51(18).*

Problem Description

- Inspired by PI innovative concepts, this work focuses on **facility network capacity planning** and **resource deployments with MPCs**.
- Our target is to maximize the overall profit of the supply chain ecosystem by utilizing facility resources efficiently and building consistent weekly production schedules under **stochastic demands**.
- In the case study, we utilize the **real data** from a large company that partnered with our research team.

Strategic Stage - Capacity Planning



1. Market deployment planning
2. Facility network & capacity planning
3. Project-facility assignment

Tactical Stage – Resource Deployment



1. MPC rental scheduling
2. Facility production planning
3. Module inventory planning

Problem Description

Capacity Planning

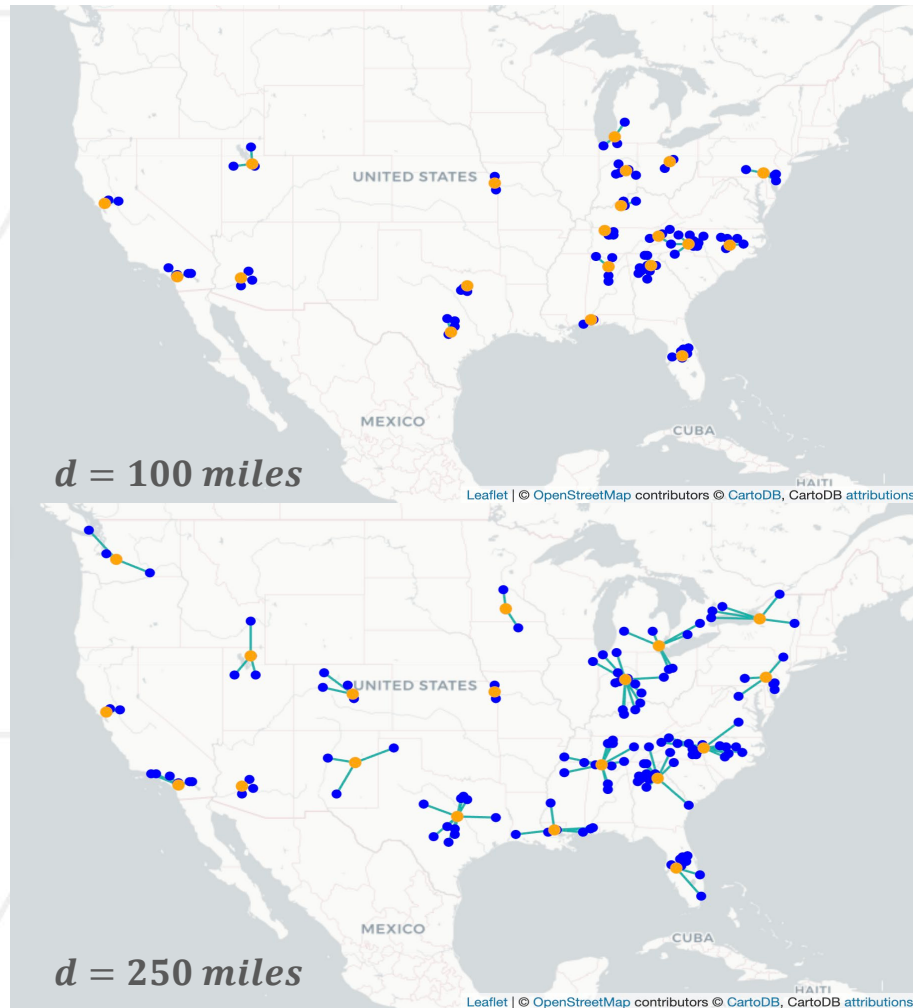


Illustration of project-facility assignment with various distance limits

Key decision areas:

1. Market deployment planning

- Decide whether accept or reject a project
- Evaluate different growth strategies (e.g., expansion from a region vs. chasing demand across the country)
- Test different target markets / target market shares

2. Dynamic facility network & capacity planning

- Decide facility locations from a given potential location set
- Multi-period facility network design (e.g., open, close, reopen)
- Monthly network capacity expansion / reduction based on the changing demand

3. Project-facility assignment

- Test various distance limits for project-facility assignment (i.e., from facility locations to erection sites)

Objective:

To maximize profits as the total revenue from accepted projects minus various costs, including (1) new facility commissioning costs, (2) open facility rental costs, (3) capacity adjustment costs, and (4) transportation costs from facilities to erection sites.

Problem Description

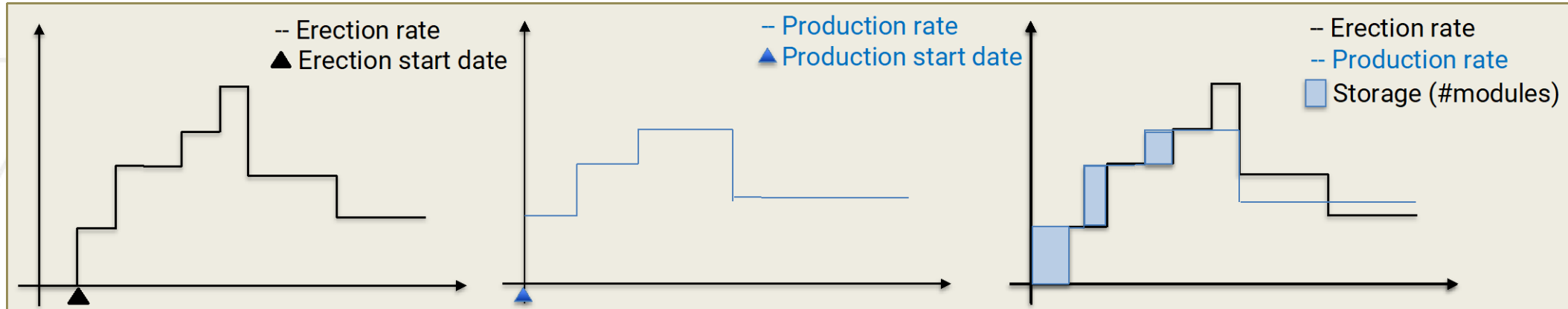
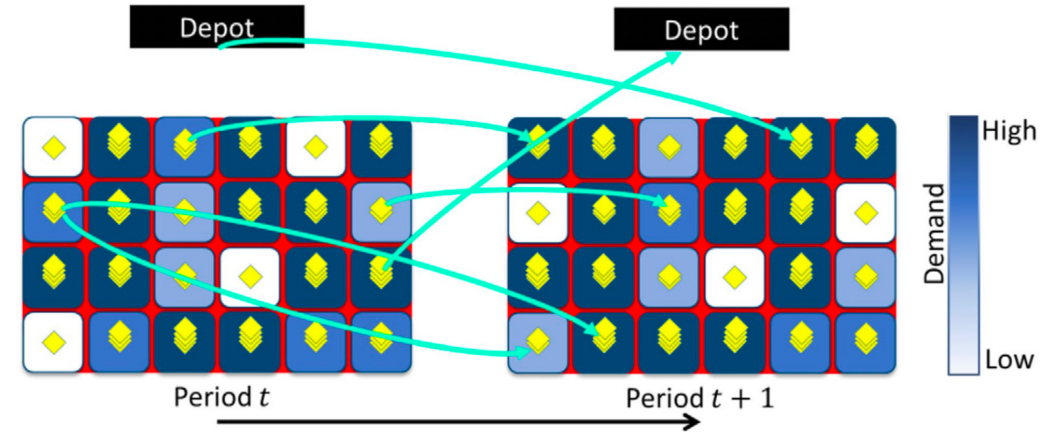
Resource Deployment

Key decision areas:

- The **allocation** of MPCs in Shipping Containers to project activities and the **scheduling** of those activities in time together with reacting to disruptions.
- The **relocation** and the **transportation** for shipping MPCs

Objective:

To minimize total costs, encompassing (1) module storage costs, (2) production lateness costs, (3) MPC transportation costs, (4) MPC rental commissioning and decommissioning costs.



Methodology

Interactions between two stages

Strategic Planning

Stage 1: Capacity Planning

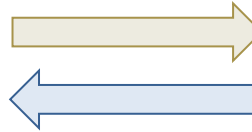
*Total planning horizon: 1 - 5 years
Length of each period: 1 month*

Inputs

- Potential facility locations
- Real demand & demand forecast
- Target market share
- Target regions

Inputs & feedback from stage 1 to 2

- Facility locations & status
- Facility-project assignments
- MPC approximate number & initial locations



Inputs & feedback from stage 2 to 1

- Facility unfinished modules
- MPC number & current locations

Tactical Planning

Stage 2: Resource Deployment

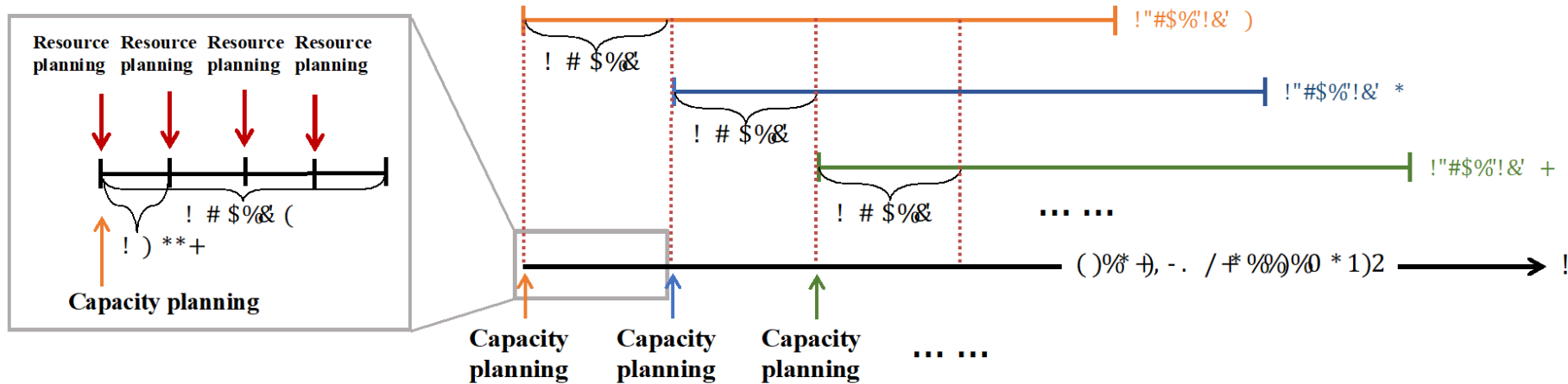
*Total planning horizon: 6 - 18 months
Length of each period: 1 week*

Inputs

- Project timeline
- Production schedules
- Spatial-temporal demand correlation
- Container transportation cost

Methodology

Rolling horizons



Faced with dynamic changes of demand, integrated capacity and resource planning is proposed to improve operational efficiency and flexibility utilizing a rolling horizon approach with updated inputs.

ROLLING HORIZON PROCEDURE

```
/* Iterative process between capacity planning and resource deployments for dynamic
changes */
```

$$t = 0;$$
WHILE $t < \text{END}$ **THEN****IF** $t \bmod S^l = 0$ **THEN**

```
/* Capacity planning*/
```

Run **CAP**(t, T^l);

UPDATE Opened facilities and assigned projects;

UPDATE Approximate number of MPCs;

IF $t \bmod S^s = 0$ **THEN**

```
/* Resource deployment */
```

Run **RES** (t, T^s);

UPDATE Produced number of modules for each open facility;

UPDATE MPC allocations and relocations;

IF $t \bmod 28 = 0$ THEN

UPDATE Unfinished or produced-in-advance modules with

assigned projects;

UPDATE Number of leased or returned MPCs at facilities;

$$t = t + 1;$$

RETURN Joint capacity and resource plans

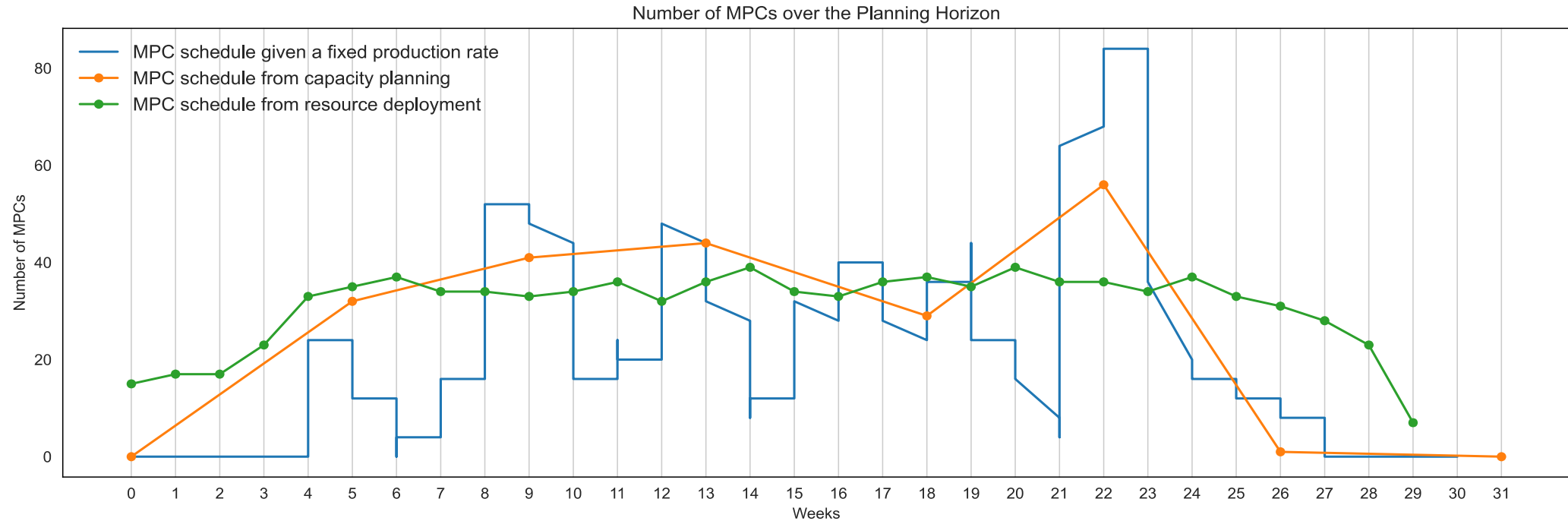
CAP(t, T^l): modules (or agents) for capacity planning at time t and with planning horizon T^l

RES(t, T^s): modules (or agents) for resource deployments at time t and with planning horizon T^s

S^l and S^s : the frequency for running capacity planning and resource deployments models, respectively.

Experimental results

The required number of MPCs over time

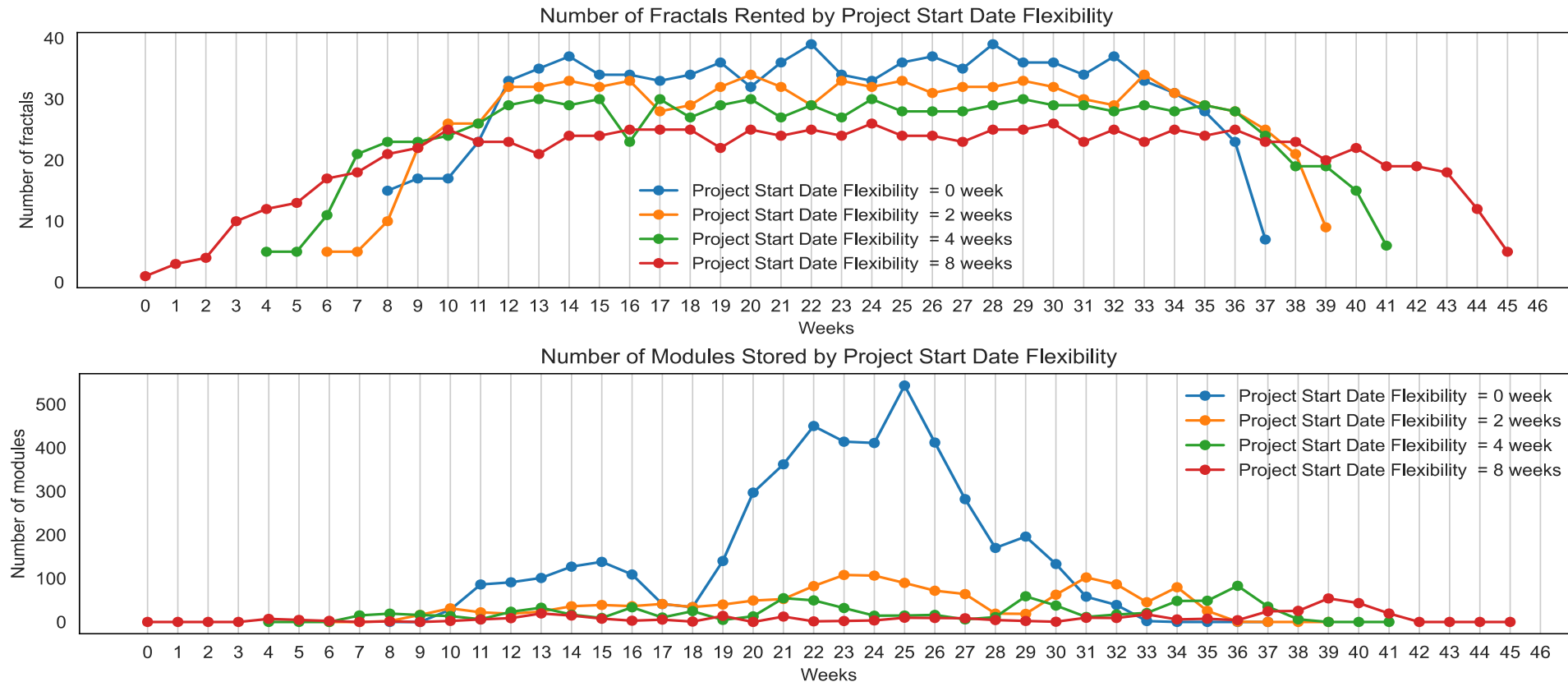


Main takeaways:

- Employing the relocation method can lead to further enhancements in resource utilization
- Our model effectively smooths the workload with a more consistent production schedule

Experimental results

Number of MPCs / Storage with various project erection start date flexibility



Main takeaways:

- Flexible start dates reduce MPC peak demand
- Flexible start dates reduce the need for excessive module storage space

Conclusion



- Inspired by PI, we proposed a two-stage framework using rolling horizon procedure for capacity planning and resource deployment in hyperconnected supply chain ecosystems.



- By iteratively solving this two-stage model, it enables to capture the stochastic demand and facilitate quick adjustments on emerging factors (e.g., production disruptions).



- The results show that it is computational feasible to use this loop structure to solve capacity planning and resource deployment problem. In addition, performing resource relocation and relaxing project start date can improve resource utilization.



- For future research,
 - evaluate this framework with **weekly demand forecast data** and various **disruption scenarios**
 - **stochastic programming approach** on strategic planning stage considering uncertain conditions
 - distributed production planning and scheduling among **multi-layer production networks**

Thank you!

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