Strategic Network Design for Hyperconnected Mobile Supply Chains

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Abstract: *In today's competitive world, businesses must offer high-quality products that can be delivered fast and cheaply. Three main strategies have been identified to solve this challenge: fast delivery, deploying inventory near to customers, and distributed production near to customers. Using Physical Internet concepts of resource sharing and flow consolidation leveraging modularization, standardization, interfaces, and protocols, Marcotte and Montreuil were the first to introduce the concept of Hyperconnected Mobile Production to contribute to the distributed production near-to-customers strategy. But their work only considered single tier supply chain. In this paper, we introduce Hyperconnected Mobile Supply Chains, a hyperconnected multi-party open hub network with plug-and-play modular mobile production units for the multi-layers involved across the supply chain system. We propose a decision-making framework for the strategic network design of hyperconnected mobile supply chains, for selecting the location, size, and number of facilities for open-hub network, leveraging capacity pooling and plug-and-play modular mobile production unit.*

Keywords: *Physical Internet, Strategic Network Design, Hyperconnected Network, Mobile Production, Modular capacity, Sustainability*

***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

In recent years, the concept of containerized production, i.e. encapsulated production lines capable of producing a product in its entirety, has gained momentum. Notably, the F3 Factory project, a major European public-private sector initiative for the chemical industry, was launched in 2009 to investigate the potential impact of containerized production in the chemical industry. The results published in 2014 highlighted considerable benefits, including a reduction in capital expenditure by 40%, operational expenditure by 20%, energy consumption by 30%, required footprint by 50%, the number of equipment required by more than 60%, and a decrease in product’s time to market, while increasing production yield and capacity by more than 20% (EU Commission Cordis’s website). This first major research led companies like Bayer to develop containerized production units, as shown in Figure 1.

Figure 1: Containerized production unit in operation (left) during loading/unloading (right)

Source: Kessler.S, 2015

Containerized production and mobile supply chains broadly address the lack of flexibility, adaptability, and robustness of traditional supply chains. As described by Jabbarzadeh et al. (2016) traditional supply chains often rely on a small number of fixed production sites producing a wide range of products that will be delivered to the customer through a distribution network. While this centralized vision allows for economies of scale and better management of production sites, it has the drawback of poor flexibility, adaptability, and robustness (Shahmoradi-Moghadam and Schönberger, 2021). Another crucial motivation for mobile supply chains is sustainability. With global demand increasing, companies traditionally preferred production in economically advantageous locations to maximize profit. However, societal pressures for more sustainable production and processes are pushing for a shift toward more environmentally responsible and closer-to-market production.

An aspect yet to be addressed in the current perception of mobile supply chain is resources and information sharing across multiple tiers. To the best of our knowledge, literature is scarce regarding multi-tier mobile supply chains.

The rest of this paper is constructed as follows: we begin with a literature review to depict the state-of-the art regarding mobile supply chains. We then introduce the concept of a hyperconnected mobile supply chain and propose a strategic network design formulation aimed at minimizing total cost and environmental footprint. Finally, we demonstrate the cost reduction of the proposed model in a case study in the realm of modular construction.

2 Literature Review

As described by Jabbarzadeh et al. (2016), traditional supply chains are centralized: a small number of fixed production sites produce a variety of products that will be delivered to the customer through a distribution network. While allowing economy of scale and efficient management of production sites, this centralized concept suffers from low flexibility, adaptability, and robustness. (Shahmoradi-Moghadam and Schönberger, 2021). To address these limitations, the concept of Distributed Manufacturing Systems (DMS) has emerged (Matt et al., 2015).

Mobile Supply Chains (MSC) is an evolution of DMS, aiming to overcome the lack of flexibility, adaptability, and robustness of traditional fixed supply chains. Shahmoradi-Moghadam and Schönberger (2021) described MSC as focusing on producing as close as possible to markets to enhance service levels and fast-deployment of production units into vast geographical regions. This mobile concept also allows for better management demand fluctuations, facilitates mass customization, and reduces asset investment and logistics costs. A popular application of Mobile Supply Chains is Modular Manufacturing. Because the container contains everything that is required for production, companies are capable of better responding to variations in demand, reducing financial risks, and increasing profits (Baldea et al., 2017).

However, most of the literature related to Mobile Supply Chains and Mobile Manufacturing focuses on Vehicle Routing Problems with predetermined networks (Shahmoradi-Moghadam, H. and Schönberger, J., 2021; Halper et al., 2011), single-tier network design (Jena et al., 2015) and does not leverage the concept of an open network (Dotoli et al., 2005)

Marcotte and Montreuil (2016) were the first to introduce the concept of Hyperconnected Mobile Production. This concept, emerging from the convergence of eight production threads, leverages a network of open certified production facilities interconnected by a hyperconnected transportation for fulfillment and shipping, businesses will have real-time access to all relevant data about their hyperconnected mobile production modules, including information on the next location of the module or the next production program. Consequently, they are capable of dynamically expanding and contracting their production capacity in regions, enhancing flexibility and responsiveness within the supply chain. For such type of production, Fergani et al. (2020) developed a tactical network design using a multi-objective optimization model that minimizes costs and environmental impact of the network for this Single-Tier problem, using a predetermined network of open fabs was predetermined.

3 The concept of hyperconnected mobile supply chains (HMSC)

In traditional supply chains, every tier is mostly centralized in a few locations. Stakeholders from each tier ship from their own facility(ies) or leverage a 3PL network. While this strategy allows each player to leverage economies of scale and better handle processes, it also implies low flexibility, agility and, in the worst case, possibly results in substantial transportation costs if demand points are far from the location.

As previously discussed, mobile supply chains (MSC) already aim to address such issues. However, to the best of our knowledge, most applications of MSC and hyperconnected mobile production have focused on single-tier supply chains (Marcotte and Montreuil, 2016; Fergani et al., 2020) or in support of existing supply chain systems and networks (Shahmoradi-Moghadam and Schönberger, 2021).

Nonetheless, real-world supply chains are complex, interconnected multi-tier systems, in which pairwise relationships exist between the production steps of each tier. To tackle those issues, we propose the concept of hyperconnected mobile supply chains. It can be understood as a multi-party open hub network where each actor can deploy its hyperconnected plug-and-play modular mobile production units. Leveraging the Physical Internet concepts of hyperconnected transportation, open network, resource sharing, and hyperconnected production, hyperconnected mobile supply chains are designed to ensure flexible, agile, and robust operations, facilitating optimal information sharing between each tier and ultimately benefiting both customers and supply chains.

Compared to integrated supply chains - where each stakeholder has its own supply chain - or collaborative supply chains - where stakeholders try to establish strategic alliances - in hyperconnected mobile supply chains, alliances between stakeholders are not required to share resources or information, as the open network is composed by certified open facilities that can host any containerized production module and be used by any current or new certified actor.

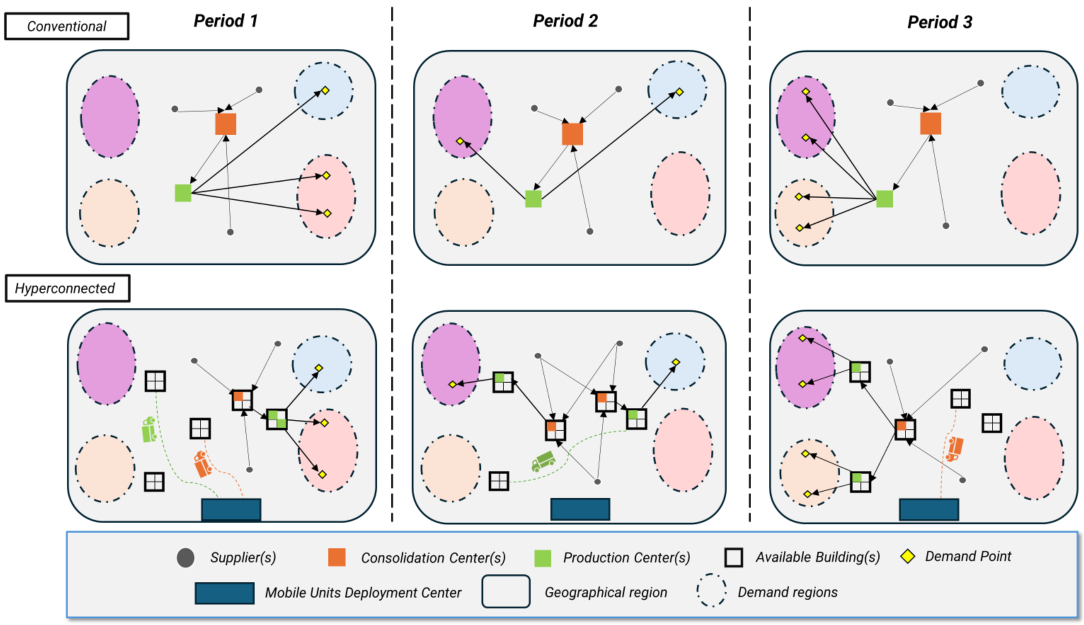

Figure 2 : Comparison between Conventional and Hyperconnected Mobile Supply Chains

Indeed, in a conventional supply chain, a unique (or multiple) fixed facility(ies) for each tier will serve the demand of the different geographical areas. In a hyperconnected mobile supply chain, whenever a demand point appears, if there is already production capacity available nearby, the demand will be assigned to the corresponding facility. If not, then production capacity will be deployed by each tier near the demand point. Such dynamic deployment is feasible thanks to the hyperconnectivity of the mobile production module, which implies that each stakeholder has access to an accurate demand forecast to plan a robust deployment and guarantee a sufficient service level. As illustrated in Figure 2, hyperconnected mobile supply chains aim at reducing delivery distances and enhance ability to capture demand, as capacity can be distributed across the network of open hubs. Thus, finding the optimal pool of open hubs is critical to guarantee the efficiency of the proposed supply chain.

4 Problem description and Methodology

4.1 Problem description

We consider a context where there is a deterministic demand for a given number of products m at period t in a market α. To satisfy this demand, we aim to leverage the hyperconnected multi-tier mobile supply chains network structure, with in our case four tiers. The first tier will consist of all demand points. The second tier will be the hyperconnected production facility network, referred to as tier-1 production, responsible for producing products based on the demand from the first tier and utilizing shipments from the third tier. The third tier will be the hyperconnected consolidation facility network, referred to as tier-2 production, responsible for receiving components from suppliers and consolidating shipments toward the second tier. The fourth and final tier will be the suppliers' network.

In such a multi-tier network, our aim is to determine at the strategic level, for each period t (from the set of periods T), a set of facilities to open from the set of potential facilities L, for how many time periods, as well as their corresponding size and capacity. The last two decisions will be made by assigning the two types of production capacity, tier-1 and tier-2 respectively, to facilities. Another decision will be the volume of products that will be shipped to downstream tiers and the quantity that is asked to upstream tiers.

This set of decisions is made considering that all the demand for a market α for product m during period t is satisfied while respecting capacity constraints at each facility (i.e. the square footage used by the assigned production capacity doesn't exceed the size of the facility). Note that for each tier, the outbound quantity of products needs to satisfy the requirements of the downstream tier.

In our context, we identified two objective functions: minimizing the total cost (operating, opening, and transportation costs) and the environmental footprint of the network.

4.1.1 Economic cost Objective F_1

The first objective function is related to the total cost induced by the network, including the operation cost for a facility of tier 1 and 2 operating at a capacity c during a period t, the opening cost of opening a facility for production of tier 1 or 2 at time t until time t', the transportation cost of product from a facility of tier 1 to market, the transportation cost of products from a facility of tier-2 to a facility of tier 1 and the transportation cost of components from suppliers to tier-2 facility.

4.1.2 GHGs emission Objective F_2

The second objective function is about the GHCs emissions. We considered the emissions of GHGs associated with the tier-1 and tier-2 production at capacity c, the GHCs emissions linked with the transportation of product between a facility with tier-2 production capacity to tier-1 facility, and the GHCs emissions associated with the transportation of product from a facility with tier-1 production to market. As we want to consider GHC emission related to transportation at a strategic level, we considered the average distance between the chosen facility and the market, not optimizing the routing.

The mathematical formulation of our model can be found in Appendix 1.

5 Preliminary results and discussions

To illustrate our concept, we leverage data collected in the context of a research project with a global construction company interested in innovation in the field of Modular Construction. Hyperconnected Mobile Supply Chains is a concept of interest in such a field. Indeed, it implies that modules are produced in factories before being delivered to erection sites, i.e. demand points. Given the strategic level of our decision, we choose a period of one month (t) with a planning horizon of one year.

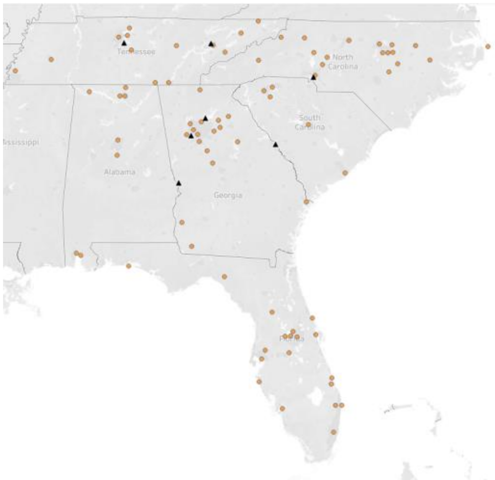

Figure 3 : Set of demand points (orange) and suppliers (black)

For this case study, we considered two scenarios: Traditional Distributed and HMSC. In the former, our network is composed of two tier-1 facilities fulfilled by one tier-2 facility, linked to the closest supplier. All demand points will be served by the closest of the two tier-1 facilities. For the latter scenario, we identified a pool of 142 potential facilities where tier-1 and/or tier-2 production capacities can be deployed near the demand points.

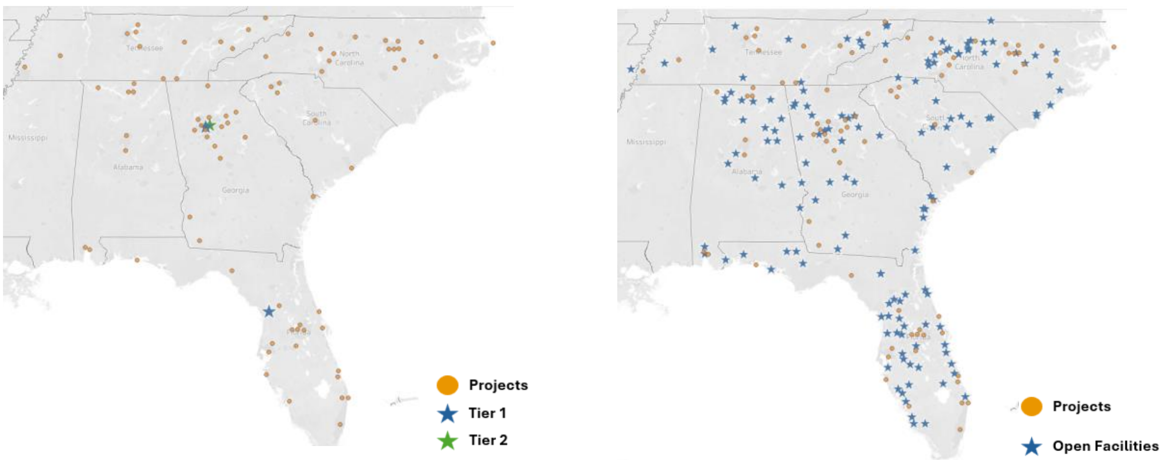

Figure 4: Set of locations for Traditional Distributed (left) and HMSC (right)

In a first attempt, we solved the problem only considering the economic cost objective F_1.

All calculations were performed on an AMD Ryzen 5 5600H (3.3 GHz) with 16GB RAM. The mathematical model was solved by using GUROBI 11.0.0, with an optimality gap set to 3%.

Compared to the base case of Traditional Distributed, we found that HMSC used a maximum of 32 smaller-sized facilities and induced a smaller average traveled distance for each tier of the supply chains, as illustrated in Table 1. This can be explained by the flexibility in terms of locations and capacity levels of HMSC. Indeed, this concept enables the use of multiple smaller -sized facilities closer to demand points, and the dynamic deployment of capacity when needed. The capabilities of the network reflects on the average distance traveled and deployed capacity for each tier.

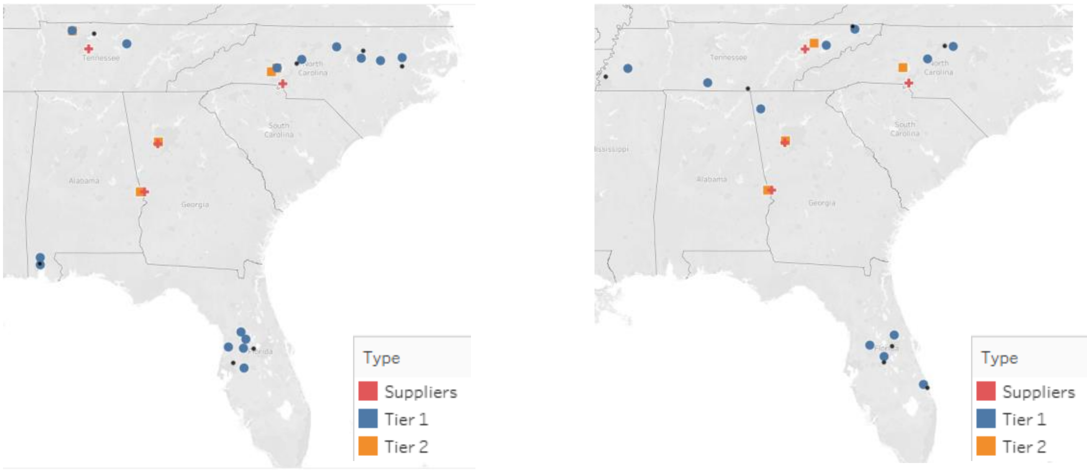

Figure 5: HMSC in Period 8 (left) and Period 9 (right) with projects (black)

Table 1: Summary of Base case vs HMSC computations

	Scenario		Improvement
	Base	HMSC	
Avg. Distance Travelled Tier 1 (miles)	172	51.2	70,2%
Avg. Distance Travelled Tier 2 (miles)	244.8	155.6	36,4%
Avg. Distance Travelled Suppliers (miles)	47,8	19,2	59,9%
Average Deployed Capacity Tier 1 (unit/day)	27	2,3	91,2%
Average Deployed Capacity Tier 2 (unit/day)	21	6,5	69%

6 Conclusion

This paper introduces the concept of hyperconnected mobile supply chains, leveraging the full potential of the Physical Internet within the framework of multi-tier supply chains. We have laid the groundwork by developing an initial bi-objective mixed integer programming

formulation for the strategic network design of a hyperconnected mobile supply chain, considering both financial cost and environmental impact.
While our preliminary study only considered the economic objective, it was an important first step in demonstrating that the concept of hyperconnected mobile supply chains, leveraging an open network and distributed logistics, has a powerful impact on the flexibility, agility, and cost of multi-tier supply chains. Our future research involves evaluating the output from the proposed model using tactical planning models, studying potential interactions and feedback between the two levels, and developing the bi-objective version of the model.

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Appendix 1

Indices:

- α: Market
- m : Module
- l : Location
- t : Period
- i : Tier in network, $i \in [\![1,2]\!]$
- p : Type of truck

Mathematical Sets:

- D_{mt} : Set of demand of module m in market α at period t
- M : Set of Products m
- R:Set of components required for kit k
- L : Set of Locations l
- C^i: Set of capacity for module of tier i, $i \in [\![1,2]\!]$
- T : Set of Periods
- S: Set of suppliers

Parameters:

- a_i : Area required for a production module of Tier i
- A_l: Available area at location l
- $C_{l,c}^{opex}$: Operating cost of capacity level c for facility l
- $C_{l,c}^{open\ tier\ i}$: Opening cost of capacity level c for Tier i at facility l
- $\bar{C}_{m,l,\alpha}$: Transportation cost to ship a module m from facility l to market α
- $\bar{C}_{k,l,l'}$: Transportation cost to ship a module kit k from facility l to facility l'
- $\bar{C}_{s,l}$: Cost of transporting a component between supplier s and facility l
- c_p^{truck}: Capacity of truck type p for transporting modules
- e_p: Carbon emissions for a truck type p used for module kits
- $E_{l,c}^{opex\ i}$: Carbon emissions for operating a module of Tier i at facility l
- $ds_{l,\alpha}$: Distance between location l and market α
- $ds_{l1,l2}$: Distance between facility $l1$ and facility $l2$
- $ds_{s,l}$: Distance between supplier s and facility l :
- $\lambda_{r,k}$: quantity of component r used for kit k
- $\theta_{k,m}$: quantity of kit k used for module m
- $d_{m,\alpha,t}$: Demand of module m in market α at period t
- ρ_i: Production capacity of a production module of Tier i
- $Z_{r,s,k}$: Quantity of component r supply from supplier s shipped for kit k
- w_c^i : Corresponding capacity level for module of tier i (range 2 to 16)

Decisions variables:

- $X_{l,c,t}^i$: binary variable equals to 1 if facility l has a capacity c for tier i at period t.
- $Y_{l,c,t,t'}^i$: binary variable equals to 1 if facility l is activated for tier i at max capacity c during period t to t'.
- $F_{m,l,\alpha,t}$: Quantity of module m shipped from facility l to serve market α at period t
- $V_{k,l,l',t}$: Quantity of kit k shipped from fracility l to serve facility l' at period t
- $Z_{r,s,l,t}$: Quantity of component r shipped from supplier s to facility l at period t
- $N_{l,\alpha,t}^1$: Number of trucks of Tier 1 leaving facility l for market α at period t
- $N_{l,l',t}^2$: Number of trucks of Tier 2 leaving facility l for facility l' at period t
- $N_{s,l,t}^{supplier}$: Number of trucks for components leaving supplier s for facility l at period t

Objective functions:

$$F_1 = \sum_T \sum_L \sum_C C_{l,c}^{opex} X_{l,c,t}^1 + \sum_T \sum_L \sum_C C_{l,c}^{opex} X_{l,c,t}^2 + \sum_{(t,t')\in T} \sum_L \sum_C C_{l,c}^{open\ type\ 1} Y_{l,c,t,t'}^1 + \sum_{(t,t')\in T} \sum_L \sum_C C_{l,c}^{open\ type\ 2} Y_{l,c,t,t'}^2 + \sum_T \sum_M \sum_L \sum_D \overline{C}_{m,l,\alpha} N_{l,t}^1 + \sum_T \sum_K \sum_L \overline{C}_{k,l,l'} N_{l,t}^2 + \sum_T \sum_S \sum_L \overline{C}_{s,l} N_{s,l,t}^{supplier}$$

$$F_2 = \sum_T \sum_L \sum_C E_{l,c}^{opex\ 1} X_{l,c,t}^1 + \sum_T \sum_L \sum_C E_{l,c}^{opex\ 2} X_{l,c,t}^2 + \sum_T \sum_D \sum_L \sum_M ds_{l,\alpha} * e_{type1}^{transport} * N_{l,t}^1 + \sum_T \sum_K \sum_L ds_{l,l'} * e_2 * N_{l,t}^2 + \sum_T \sum_S \sum_L ds_{s,l} * e_1 * N_{s,l,t}^{supplier}$$

Mathematical model:

$$Min\ F(x) = \left(F_1(x), F_2(x)\right)$$

s.t

$\sum_L V_{k,l,l',t} \geq \sum_\alpha \theta_{k,m} F_{m,\alpha,l',t}\ ; \forall\ l', m, k, t$ (1)

$\sum_S Z_{r,s,l,t} \geq \sum_K \sum_L \lambda_{r,k} V_{k,l,l',t}\ ; \forall r, l, t$ (2)

$\sum_l F_{m,\alpha,l,t} = d_{m,\alpha,t}; \forall m, \alpha, t$ (3)

$\left(\frac{w_c^2 X_{l,c,t}^2}{\rho_2} * a_2 + \frac{w_c^1 X_{l,c,t}^1}{\rho_1} * a_1\right) \leq A_l\ ; \forall\ l, t$ (4)

$N_{l,\alpha,t}^1 \geq \frac{\sum_m F_{m,\alpha,l,t}}{c_1^{truck}}\ ; \forall l, \alpha, t$ (5)

$N_{l,l',t}^2 \geq \frac{\sum_k V_{k,l,l',t}}{c_2^{truck}}\ ;\ \forall l, l', t$ (6)

$N_{s,l,t}^{supplier} \geq \frac{\sum_r Z_{r,s,l,t}}{c_2^{truck}}\ ;\ \forall s, l, t$ (7)

$\sum_K \sum_{l'} V_{k,l,l',t} \leq \sum_C \sum_K \sum_M \theta_{k,m} w_c^2 X_{l,c,t}^2\ ;\ \forall l, t$ (8)

$\sum_{m,\alpha} F_{m,\alpha,l,t} \leq \sum_C w_c^1 X_{l,c,t}^1\ ;\ \forall l, t$ (9)

$\sum_L \sum_C X_{l,c,t}^i \leq 1\ ; \forall t, i$ (10)

$X_{l,c,t}^i \leq \sum_{\tau=1}^t \sum_{\epsilon=t}^T Y_{l,c,\tau,\epsilon}^i;\ \forall l, c, t, i$ (11)

$\frac{c}{2} * a_1 * Y_{l,c,\tau,\epsilon}^i \leq A_l\ ; \forall l, i, c, \tau \in [1, t], \epsilon\ \in [t, \mathrm{T}]$ (12)

$\mathbb{X}, \mathbb{Y}\ \in \{0,1\}$ (13)

$N_{l,t}^i \in\ \mathbb{Z}_+\ ;\ \forall l, t, i$ (14)

$N_{s,l,t}^{supplier} \in\ \mathbb{Z}_+\ ;\ \forall s, l, t$ (15)

$V_{k,l,l',t} \in\ \mathbb{Z}_+\ ;\ \forall k, l, l', t$ (16)

$F_{m,l,\alpha,t} \in\ \mathbb{Z}_+\ ;\ \forall m, l, \alpha, t$ (17)

$Z_{r,s,l,t} \in\ \mathbb{Z}_+\ ;\ \forall r, s, l, t$ (18)

Constraints (1) and (2) ensure that tiers 1 and 2 receive enough products for production. Constraint (3) ensures that all the demand is satisfied. Constraint (4) ensures that the square footage of the assigned production capacity doesn't exceed the size of the facility. Constraints (5), (6) and (7) compute the number of trucks required between each tier. Constraints (8) and (9) ensure that we assign production only to open facilities. Constraints (10) ensure that each facility is open at one capacity level at each period. Constraints (11) ensure that a production capacity is assigned to a facility during a period only if the facility is open at this period. Constraints (12) ensure that the maximum capacity at which a facility is opened during a time interval doesn't exceed the size of the facility. Constraints (13) ensure that $\mathbb{X}, \mathbb{Y}$ are binary variables. Constraints (14) to (18) ensure that the other decision variables are integers.