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Simulation-based Assessment of Hyperconnected Mixing

Mixing centers differ from warehouses as they are not intended for deep extended storage but rather intended for short term flow storage. In that spirit, they are similar in intent to DCs that are used by retailers and distributors, yet they are rather used by manufacturers to consolidate products made in their multiple plants and/or stored in their warehouses so as to efficiently serve retail DCs, fulfillment centers, and/or outlets in their region.

We distinguish three types of mixing centers: dedicated, collaborative, and hyperconnected. Dedicated MCs are used by a single manufacturer. Collaborative MCs are used by a closed group of partnered manufacturers. Hyperconnected MCs (HMCs) are open on demand to any manufacturer. There are two extreme orientations for HMCs with myriads of variants: spot HMCs and steady HMCs. The spot HMC is focused on short term spot demand from manufacturers. For example, a manufacturer may deploy some products in a given HMC for a few weeks and then not use that HMC for months or years in the future. The steady HMC focuses on steadily serving manufacturers on a yearly or multi-year basis, seamlessly absorbing their seasonal, weekly and daily demand variations.

In this paper, we focus on a business aiming to implement a steady hyperconnected mixing center to service target clients that are manufacturers in consumer goods industry aiming to secure a steady facility from which to serve their customers (e.g. retail distribution/fulfillment centers, retail stores, e-drives) within a territory. In order to determine the new facility size, the business needs to assess its capacity requirements under different scenarios such as overall throughput and configurations of clients. Also, in order to assess and demonstrate its value added to prospective clients in its quest to grow its market share, it needs to estimate potential service capabilities that its clients will be in position of offering to their own clients, such as delivery frequency to targeted retailer DCs.

In this paper, we introduce a simulation-based methodology for performing potentiality assessments for steady HMCs. As shown in Figure 1, we explicitly contrast three alternatives operating schemes: manufacturers serving DCs of retailers (1) directly from their plants' warehouses, (2) from a dedicated MC, and (3) from a hyperconnected MC.

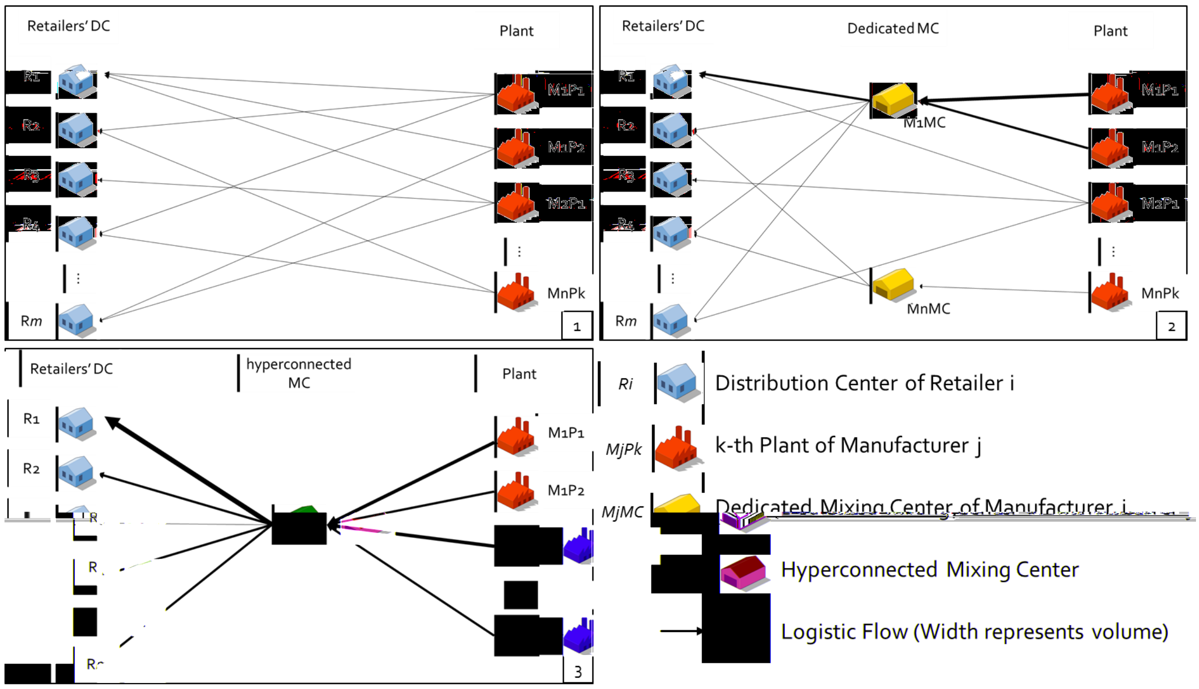

Figure 1: Contrasting Alternative Operating Schemes
No MC (1), Dedicated MCs (2), and Hyperconnected MC (3)

The paper is organized as follows. Section 2 provides a brief review of relevant literature. Section 3 describes the methodology. Sections 4 and 5 provide the description of an experimental case and simulation results for the sample case. Lastly, section 6 concludes by summarizing findings and suggesting future research avenues.

2 Literature Review

Sharing storage (warehousing, distribution) space and services between different firms who may or may not compete with each other has been proposed as a solution to improve logistics efficiency and sustainability. In general, three types of benefits are targeted: pooling inventory space, pooling throughput handling, and consolidating logistics flows. Pooling aims to smooth business-specific peaks and valleys as well as to reduce global safety stocks to deal with uncertainty induced risks. Flow consolidation aims to reduce transportation costs, energy consumption and greenhouse gas emissions, and to enable fast crossdocking operations (e.g. Balan, 2010).

Two types of sharing have been proposed in the literature: first collaborative then, more recently, hyperconnected storage (warehousing, distribution).

Collaborative storage is about sharing storage space and services among a group of partnering businesses. In collaborative storage, the storage facilities are not dedicated to each business, but rather dedicated to the group of partners. Franklin and Spinler (2011) address the efficiency and positive social and environmental impact of collaborative storage obtained through economies of scale and distributed investment. Pan et al. (2013) report on an optimization based study of the impact of collaborative (pooled) storage on the environmental performance of supply chains. Recently, Makaci et al. (2017) combine a literature review and interviews to outline the characteristics and advantages of collaborative warehousing. Reported advantages include decreased warehousing and transportation costs and increased shipping frequency. They also emphasize that collaborative warehousing partners often rely on a third-party logistics service provider (LSP), as the partners' core business may well not be in logistics. It is well known that manufacturers can improve their logistics efficiency and capabilities by utilizing 3PL services without making significant investments or internal innovation (Sinkovics and Roath, 2004). In collaborative warehousing, the 3PL expertise can resolve operation complexity issues and partner heterogeneity (Makaci et al., 2017). The role of a third-party LSP can be critical in hyperconnected MCs/DCs operations as well to handle the operational complexity and dynamics with increased diversity of products and the number of SKUs in the facility. The horizontal storage collaboration can also be extended to collaborative inventory management. For example, in the context of disaster relief supply chain, Toyasaki et al. (2016) show the impact of horizontal cooperation between humanitarian organizations on improving inventory management.

Core to the Physical Internet, hyperconnected storage is about openly sharing storage space and services, available on demand to any business (Montreuil, 2011; Montreuil et al., 2013). Storage service users are clients of storage service providers. Any business may be both a storage service client and provider, offering access to its storage space to clients in low internal-demand periods and relying on external storage services in peak periods. Other businesses may build and operate facilities devoted to offering on-demand hyperconnected storage services. While collaborative warehousing and distribution is about a stable network of facilities exclusive to a group of partners, hyperconnected warehousing and distribution is about a web of open facilities, allowing users high agility in dynamically adapting their deployment of products to evolving demand. With hyperconnected storage, clients may rely on a facility's services for dealing spot storage space demand surges, or engage in contracts for longer periods of time (weeks, months, seasons, years). Crainic and Montreuil (2016) embed hyperconnected distribution into their conceptual framework for hyperconnected city logistics, building on a thread of innovation and research on urban distribution/consolidation centers (e.g. Van Duin et al. 2010; Browne et al., 2011). Sohrabi et al. (2016a, 2016b) respectively contrast through an optimization-based investigation the economic and environmental performance of dedicated, collaborative and hyperconnected distribution, under distinct levels of delivery time offers to customers.

The hyperconnected mixing center studied in this paper provides steady hyperconnected storage service to its clients. Although many researchers such as Crainic and Montreuil (2016) and Sohrabi et al. (2016a, 2016b) addressed the potential benefits of hyperconnected storage, this paper aims at providing more rigorous insights on the operations and benefits of a hyperconnected MC. Also, this paper addresses the potential variations on the size of benefits of the HMC by the client sets which induce different throughput, number of SKUs, inventory variation and distinct delivery locations assuming the service contracts are based on longer period of time (e.g. years).

3 Methodology

We introduce hereafter a simulation-based methodology for assessing the required size for a hyperconnected MC operated by a logistics service provider (LSP) and the advantages to potential clients and for estimating the impact on the logistics operations of the players who are directly or indirectly affected by the service. The methodology is generically described, yet illustrations and descriptions focus on manufacturers serving retailers, be they brick-and-mortar, brick-and-click or pure-play e-commerce players.

The methodology can be synthesized as follows:

1. Define the set of key players as well as their operations and interrelationships;
2. Define the alternative operation scenarios to be contrasted;
3. Define the set of key performance indices (KPIs) for comparing the alternatives;
4. Define the simulation framework;
5. Define experimental scenarios;
6. Perform the experimentation and analysis.

Hereafter we address the first five steps in this methodology from a generic perspective, then we proceed with an empirical application of the methodology.

3.1 Defining the set of key players

The first step is to identify the set of key players. Depending on the context, there may be several types of such players. Here we focus on four types: manufacturers, retailers, carriers and a logistics service provider. Manufacturers are the potential clients of the hyperconnected MC. Retailers are the clients of the manufacturers, each manufacturer serving many retailers and each retailer being served by many manufacturers. Carriers ship products for manufacturers under contracts, from plants to the mixing center, the mixing center to retailers' distribution or fulfillment centers. The LSP aims to provide hyperconnected storage service to manufacturers from a new HMC in a target region.

There are a few typical contexts leading to a center-MC assessment study. First, a LSP leads the study. Second, a key manufacturer leads the study as such a center may provide a smart alternative to a dedicated center. Third, a group of manufacturers leads it, looking for a smart alternative to dedicated centers or a collaborative center. In the latter two contexts, a LSP may or not be with the manufacturer-s at the origin of the study, but one eventually gets engaged in the study. These alternative contexts affect the knowledge about the key player sets.

In context one, the LSP generally conducts a survey of manufacturers and retailers active in the targeted territory. When the LSP has experience in retail logistics, it usually has access to facts and data from its client manufacturers and retailers, and from its logistics operations. For these, the LSP may well have deep knowledge while for others its knowledge may be much thinner. In context two lead by a manufacturer, this player knows a lot about itself and its retail clients in the territory, yet may know much less about other manufacturers and non-served retailers. Context three is similar to context two, yet with a broader base of manufacturers from whom to gather facts and data.

This said, it is generally feasible to gather the entire set of retailers active in the territory, with the location, size and throughput of their distribution and fulfillment centers as well as stores when pertinent. Relative to the potential set of manufacturers, there exist databases listing those active in the territory, with the largest indeed being active in many territories around the world. These databases provide key statistic about the manufacturers. E-commerce data mining enables to track offered brands and products. This means that large sets of retailers and manufacturers may be identified, with varying degrees of available information.

Among the targeted information necessary to support simulation modeling, here is a typical non-exhaustive set:

- Overall revenue and throughput of manufacturers and retailers in the territory;
- Product portfolio of manufacturers, from their top categories down to their product families and models, notably with their dimensions and relative demand;
- Client-supplier relationships between manufacturers and retailers, including their mutual business volume and, ideally, logs of their transactions, orders and shipments as well as the policies regulating the reorder process in terms of quantity, frequency and delivery leadtime expectations;

Detailed information such as delivery frequency and minimal order quantity are important to gather. For example, under current dedicated operations, manufacturers ship independently, so often their delivery frequency to a retailer varies in function of demand size, with a aim to ship full truckloads as much as possible. Hence small retailers often face very low delivery frequency and are forced to order in long-lasting large quantities and to keep high safety stock. For most of them, increasing delivery frequency is desirable and is a negotiation target with manufacturers.

Knowledge about the carriers is also important. Carriers ship products for manufacturers under contracts, either in truckload (TL) mode or in less-than-truckload (LTL) mode. Based on the operating policy of a carrier or a contract, a carrier may deliver in a single-stop lane or a multi-stop lane. Also, a carrier may consolidate shipments from multiple manufacturers who are independently contracting with it to increase fill rate and reduce empty miles. Knowing this is key to understand and assess the overall costs, energy consumption and greenhouse gas emissions induced by the current situation. When assessing the introduction of a HMC, typical carrier contracts adapted to the pooled consolidation of multi-manufacturer goods in the MC have to be defined to allow fair comparison of alternatives.

Relative to all the above types of required information, there are two fundamental situations: either the information is available and can be readily used for modeling purposes, or it is totally or partially not available and thus must be generated through estimation techniques so as to feed the simulation modeling.

3.2 Defining the alternative operation scenarios

The simulation models each key player operating in the targeted territory: manufacturers, retailers, a LSP, and carriers. Each retailer may operate one or more DCs. Each manufacturer may own one or more plants. Orders are placed from a retailer DC to a MC, from a DC to a plant, or from a MC to a plant. Products are shipped from a plant to a MC and a DC, or from a MC to a DC.

As illustrated in Figure 1, it is methodologically proposed to assess the operations of the key players under at least three alternative scenarios: No MC, Dedicated MCs, and Hyperconnected MC. In context three of section 3.1, a fourth scenario would be a Collaborative MC dedicated strictly to the core group of manufacturers. Each scenario must be systematically described, notably in terms of operations, process, flows and transactions.

When operated without a MC, retailer DCs are typically served directly from plants or plant warehouses. The lead time to retailer DCs can be long under this scenario due to the induced distance between plants and retail DCs. Delivery frequency is often bounded due to lack of shipping volume induced by limited consolidation opportunity.

Operating with dedicated MCs usually improves customer proximity, reducing the lead time between shipping from the MC and receiving at the retailer facilities. Also, the manufacturer operating a dedicated MC is better poised to consolidate at the MC where products from all plants are available. The improvement becomes more significant as the number of plants increases and as each plant has a distinctive product mix as contrasted with other plants. However, achieving the improvements typically requires large capital investment by the manufacturer. Only large manufacturers can usually afford and justify such investment through their own economies of scale.

Similar to the dedicated MC scenario, the hyperconnected MC scenario can potentially reduce leadtime through increased customer proximity and more consolidation. However, the consolidation level can be increased significantly as the aggregated multi-manufacturer throughput is higher than that of any single manufacturer. Moreover, there is potential to improve inventory operation at retail DCs. For example, assume that two manufacturers each shipped one truck to a retail DC per week in the previous scenarios and that these two manufacturers now jointly ship two trucks per week in this scenario. Although the same number of shipments is received by the retailer in both scenarios, the hyperconnected scenario reduces the lead time by half. This can notably help retailer facilities to reduce safety stocks. Also, unlike the dedicated MC scenario, no or very little capital investment is required to the manufacturers as they use the service of the HMC as clients.

The scenarios illustrated in this section are the high-order scenarios. Usually they are complemented and enriched by sets of scenario variants testing the impact of key hypotheses. Examples are the expectations of retail clients in terms of delivery frequency, the degree of open consolidation of inbound transportation for supplying the MC and of outbound transportation for delivering to the retail client sites. Each scenario variant must be specified a priori to insure that the modeling will be accommodating its peculiarities,

3.3 Defining key performance indices

The next step in the methodology is to specify the set of key performance indices (KPIs) that are to be used to assess and contrast alternative scenarios. Usually the set of KPIs covers economical, environmental and social efficiency and sustainability. Performance needs to be assessed for the entire business ecosystem within the targeted territory, as well as from the perspective of each key stakeholder.

Examples of typical KPIs include required investments and induced costs; induced travel on roadways and railways; loading of transportation vehicles; inventory requirements (average, variability, peak); MC requirements in terms of space and throughput capacity; induced energy consumption and greenhouse gas emissions; service capability expressed in terms of leadtime, frequency, minimal quantities and in-stock availability. For each KPI must be determined how it is to be explicitly and formally measured.

3.4 Defining simulation framework

To correctly model and assess the operations of a hyperconnected MC using simulation, the scope, key decision makers and key operations must be defined. This step corresponds to the conceptual design of a simulation.

The simulation scope must span all players and operations that are directly and indirectly affected by a HMC. The four key players - retailers, manufacturers, carriers and a LSP – and their pertinent operations and facilities such as retail DC, plants, MCs must be modeled. The carriers need to be modeled explicitly if the carrier make consolidation routing decisions. However, when it only performs delivery operations without making independent decisions, it is sufficient to just model its operations.

Key decision makers can be different from key players. For example, in the HMC, the service provider needs key decision makers such as an order manager, an inventory manager and a shipment manager who respectively receive/place orders, manage inventory, and receive/consolidate shipments. Using an agent oriented simulation approach, each critical decision maker of each key player is modeled as agent. Each agent dynamically makes its own decisions, interacts with the environment and communicates with other agents. The supply chain players, their agents and their relationships are described as a simple class diagram in Figure 2.

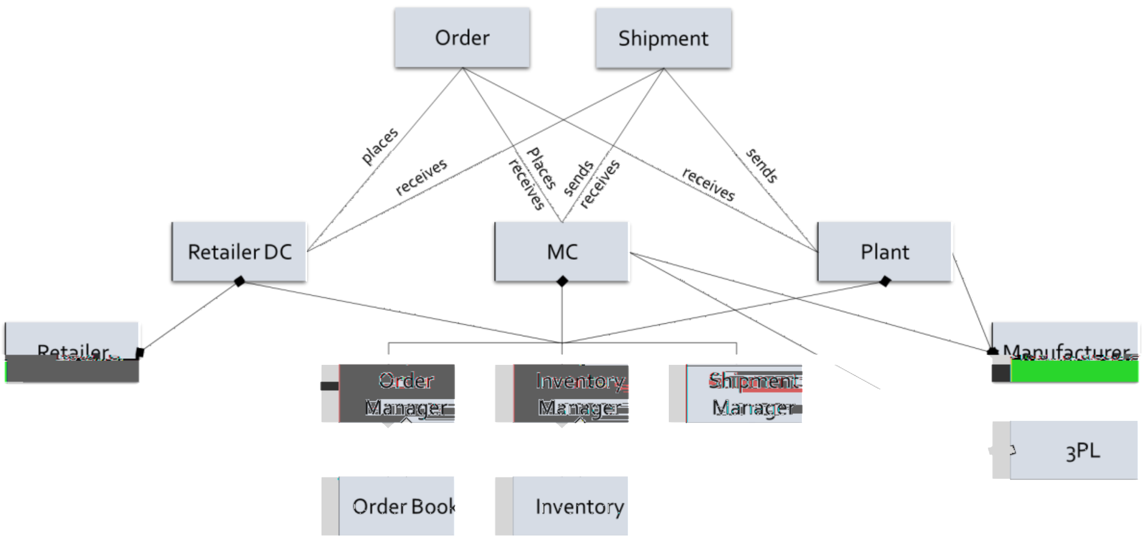

Figure 2; Class diagram of hyperconnected MC simulation

The key operations are the operations that are affected by or constitute the operations of the HMC. It includes inventory operations at the dedicated/hyperconnected MC, plant warehouses, and retail DCs and transportation operations from plant to a MC, from plant to retail DCs, and from a MC to retail DCs. In this case, it is unnecessary to model the transportation operation from retail DCs to retail stores, and to model production at plants. Defining the key operations include setting operational policies such as base stock inventory policy or routing mechanisms.

3.5 Defining experimental scenarios

The experimental scenarios are distinguished from the operation scenarios described in the previous section. The operation scenario defines operational specifications such as logistics network and shipping strategies. Experimental scenarios, on the other hand, are the particular instances for which all operation scenarios are simulated. The experimental scenarios enable to compare operation scenarios by the value of variables of interest. For example, the experimental scenarios can be defined by a different realization of client sets or by a different location of the HMC. When the realization of client sets is the main variable to compare the impact of hyperconnected operation, scenarios can be constructed by selecting clients from potential client pool using different selection rule: randomly selecting certain number of clients, randomly selecting clients until reaching a target throughput, or randomly selecting clients with different selection probabilities. Multiple scenarios can be explored to understand the potential variability on key measures.

4 Case description

As an empirical illustration of the application of the methodology, a specific case is designed. The region encompassing the U.S. western states is set as the target service region for the planned steady hyperconnected MC. This region includes Oregon, Washington, Idaho, Montana, Wyoming, Utah, Nevada, New Mexico and California. Especially, many northwest states such as Montana and Wyoming are typically serviced poorly due to sparse demand that hardly justifies a significant capital investment into a dedicated MC by individual manufacturers. We also limit the potential clients of the HMC to consumer goods manufacturers who would serve retail DCs in the target region from the MC. Plants of a few selected m(s)]TJ singe ET1 1(se)3(le)-(g)19(e-7( )-3-3(on)]TBTy)20( )-31he ted T1 va

Demand seasonality and stochastic variability were are generated to be in line with industry reality.

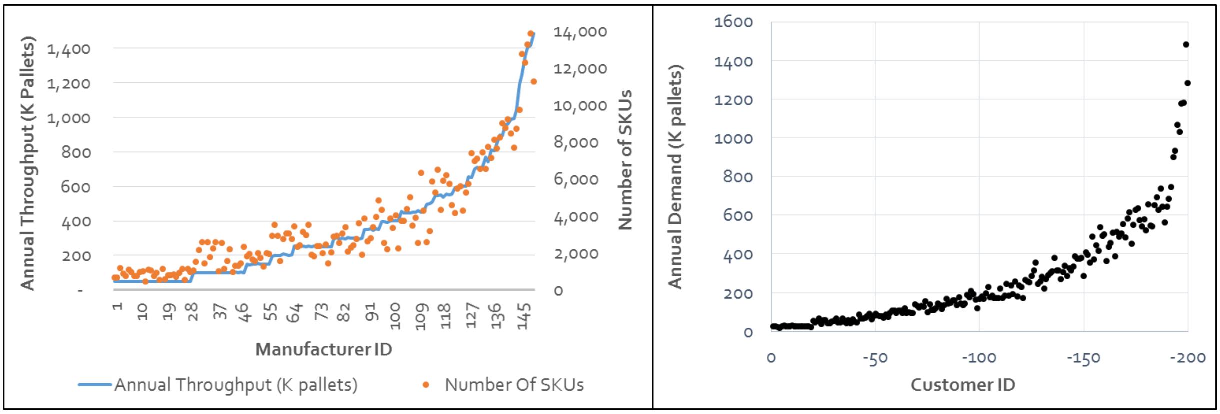

Figure 4: Annual Throughput and # SKUs by Manufacturer (left) and Annual Throughput by Customer (right)

Manufacturers are categorized into small (78), medium (56), and large (16) manufacturer based on their annual pallet throughput according to the following ranges (0,300K), [300K, 800K) and [800K, 1500K).

The demand of customer DCs and manufacturers must be matched for complete market generation. The map in Figure 5 shows relative demand intensity between each manufacturer-customer DC pair: some being zero while others vary in terms of demand intensity. Here demand intensity is colored coded, with the low values being blue while the higher values are intense red. Distinct selections of manufacturers as targeted clients of the HMC would form distinct scenarios.

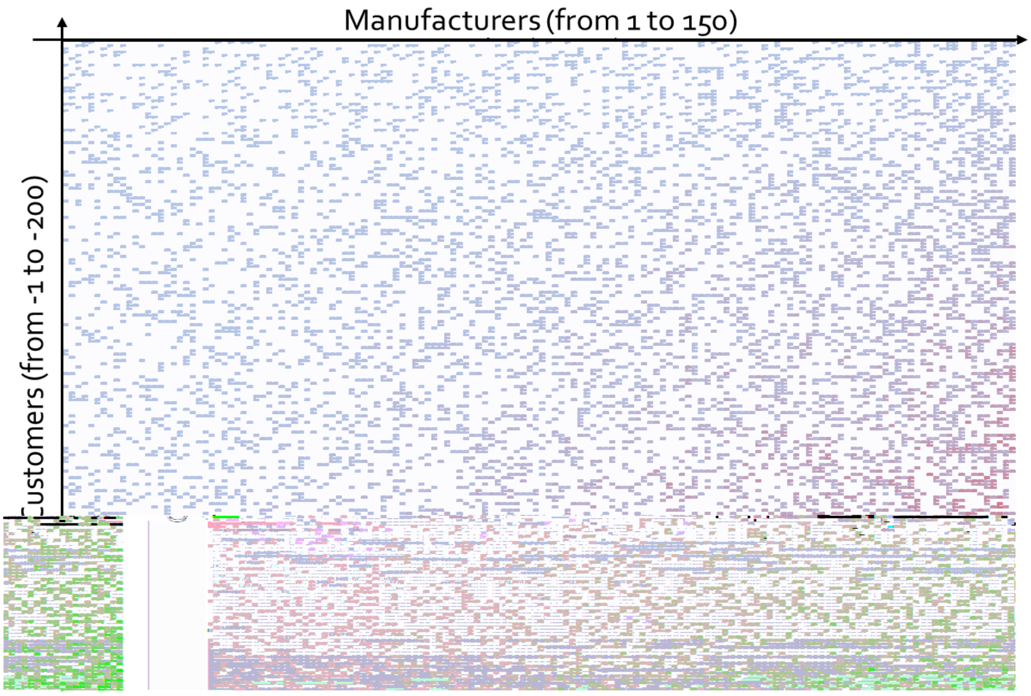

Figure 5: Demand between Manufacturers and Customers (Blue:low demand, Red:high demand, White:no demad)

The locations of manufacturer's facilities are determined by referring to disclosed supply chain networks of large consumer goods companies such as 3M, Nestlé and P&G. The locations of customer DCs are also determined by matching existing DC locations.

4.2 KPIs: capacity requirements and service capabilities

The scenarios are compared primarily in terms of capacity requirements and service capability. The KPIs are selected to measure them. Also, in this section are listed the assumptions on inventory and transportation policies significantly affecting the KPIs.

Storage capacity requirement is measured as the number of pallet spaces required to address inventory peaks with a given level of confidence (e.g. 99%). Each manufacturer and retail DC is assumed to respectively use a (s, S) inventory policy and a base stock policy. It is also assumed that inventories are reviewed on a daily basis.

Service capability is here measured as the average inter-delivery time to retail DCs and inventory peak and variation at retail DCs. Inventory peak and variations at retail DCs are measured as 0.99 percentile and average coefficient variation of on-hand inventory level respectively. These can be an indirect indicator of the space utilization and safety stock level at retail DCs. These KPIs are significantly affected by transportation policies, so here we list several assumptions on inbound and outbound transportation operations, in line with typical operations of consumer goods manufacturers. The transportation policy has impact on the inventory of manufacturers and therefore on the pallet space requirement as well.

For both inbound and outbound transportation, we assume to use 53’ trucks and double-stack pallets. In case of inbound transportation, if the truck is less than 80% full, other products, which are also supplied from the same plant and their expected time of next order is less than 4 days away, are shipped together to increase a fill rate. For outbound operations, we assume orders are received on a daily basis, but shipping is delayed to achieve outbound fill rates higher than 80% or up to 28 days. As used by many manufacturers in practice, we assume single-stop routes. From the HMC, shipments of different manufacturers are consolidated together as long as they are shipped to the same retail DC.

4.3 Operational and Experimental Scenarios

The three operation scenarios illustrated in Figure 1 – no MC, dedicated MCs, and a hyperconnected MC - form the alternative operations to compare the service level improvement and capacity requirements at each experimental scenario. The dedicated MC operation is only simulated for the manufacturers who have multiple plants. Experimental scenarios are defined by a set of clients of the HMC. In each experimental scenario, the MC faces different throughput, inventory level and variation, number of clients, and number of distinct outbound destinations. The capacity requirements and service capability of the MC are to be estimated and compared. In this paper, we explored six experimental scenarios described in Table 1. A more detailed description of the experimental scenarios is attached in Appendix A.

Table 1: Experimental Scenarios

Scenario ID	# of Clients at MC (# Manufacturers)	Average Annual Throughput (M pallets/year)	# of distinct outbound destinations (Customer DCs)
1	2	~2.8	139
2	5	~2.8	173
3	8	~2.8	180
4	12	~5.8	194
5	8	~3.4	195
6	13	~1.0	172

The simulation models are developed in AnyLogic 7.3.7 (University Version). Each simulation runs for three years, from 2017 to 2019, and the 2017 results are excluded from analysis, considered as a warm-up period.

5 Experimental results

The results of simulation experiments are compared using different KPIs in this section.

5.1 Capacity requirements

In each scenario, annual throughput and capacity requirement of the MC to handle 0.99 percentile of inventory peak are measured. Capacity requirement is measured assuming that the pallet storage is not consolidated and therefore at least one pallet space is required for each SKU. This independent pallet space requirement is compared to that of the two alternative operations: no MC and dedicated MC operation. The reduction percentage of capacity requirement for each manufacturer at each scenario is calculated by comparing the responsible pallet space at hyperconnected DC and capacity requirement of the no-MC or dedicated MC operation. A responsible pallet space for manufacturer Mi is calculated by following equation:

$$Responsible\ Capacity\ of\ Mi = Capacity\ Requirement\ of\ MC * \frac{PS(Mi)}{\sum_j PS(Mj)}$$

In above equation, PS(Mi) is 0.99 percentile of pallet space used by Mi at the hyperconnected MC. The responsible capacity charges for average inventory level as well as the variation. We also calculated 0.99 percentile of on-hand inventory (OHI) level that corresponds to the pallet space requirement under perfect storage pallet mix in Table 2.

Table 2: Capacity Requirements of Hyperconnected MC by Scenario

Scenario ID	Annual Throughput /# Clients (M pallets)	Capacity Requirement (K Pallets)	Average Capacity Requirement Reduction		0.99 percentile of OHI (K Pallets)
			From No MC to Hyperconnected	From Dedicated to Hyperconnected	
1	~2.8 / 2	200	0%	2%	185
2	~2.8 / 5	232	0%	0%	217
3	~2.8 / 8	241	5%	6%	222
4	~5.8 / 12	440	6%	7%	408
5	~3.4 / 8	281	13%	14%	259
6	~1.0 / 13	103	16%	16%	94

As seen in Table 2, the capacity requirement is not exactly proportional to annual throughput or the number of clients. Also, the average capacity requirement is reduced by having a HMC in general by pooling effect although the reduction rate of pallet space requirements varies by scenario. Therefore, the service provider must understand the inventory operation of potential clients to better estimate capacity requirements.

The 0.99 percentile of OHI tends to be about 10% smaller than a capacity requirement. This implies the LSP can reduce capacity requirement by consolidating products for storage.

5.2 Service capability

Service capability can be measured by various KPIs. In this paper, we estimate average inter-delivery time to customer DCs and average inventory level and variation at customer DCs.

5.2.1 Average inter-delivery time

Average inter-delivery time and its complement, the average delivery frequency, is one of the indicators of service level. Shorter average inter-delivery time or higher delivery frequency indicate more responsive services and can potentially improve inventory operation at customer DCs. The distribution of average inter-delivery time to customer DCs of selected manufacturers is described in Figure 6. Same graphs for dedicated MC operation scenario and hyperconnected MC operation are attached in Appendix B.

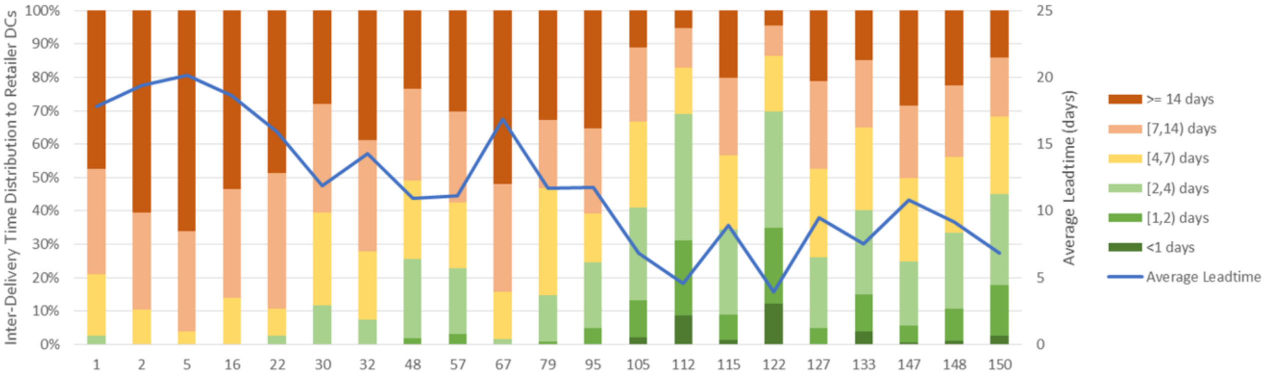

Figure 6: Average Inter-delivery Time to Retailer DCs by Manufacturer (No MC Operation)

In Table 3, it is shown that the average inter-delivery time to customer DCs is reduced significantly with HMC in all scenarios. The consolidation index represents the average number of manufacturers shipping together to same customer DC, over all outgoing trucks.

Table 3: Average Inter-delivery Times and Marginal Reductions

Scenario ID	Consolidation Index	Average Inter-Delivery Time in Days and Marginal Reduction				
		No MC	Dedicated MC		Hyper MC	
1	1.4	8.8	2.6	71%	2.1	18%
2	1.8	6.4	6.4	0%	3.4	46%
3	2.6	13.7	11.4	17%	4.7	59%
4	3.8	11.1	9.1	18%	2.3	75%
5	3.1	12.6	11.4	9%	4.3	62%
6	2.2	16.1	14.9	7%	9.7	35%

By adding a dedicated MC, manufacturers can reduce inter-delivery time when they have multiple plants. However, significant marginal reduction has been again achieved by a HMC in all scenarios. There is a tendency that marginal reduction percentage is larger when consolidation index is larger. In other words, when clients of the HMC have more outbound destinations in common, deliveries can be consolidated better and more benefits from economies of scale be obtained. That is, when defining a target client pool, the service provider can expect to maximize service level improvement by including manufacturers who tend to have more overlapping customers when single-stop routing is used.

The changes in distribution of inter-delivery time and benefits by individual manufacturers in scenario 3 is described in Figure 7. In general, small manufacturers reduced inter-delivery time more significantly. However, larger manufacturers who already have economies of scale on their own also improved inter-delivery time significantly. This results again show the motivation for manufacturers to utilize HMC regardless of their size. Although scenario 3 is selected for demonstration in Figure 7, similar patterns are found in all scenarios.

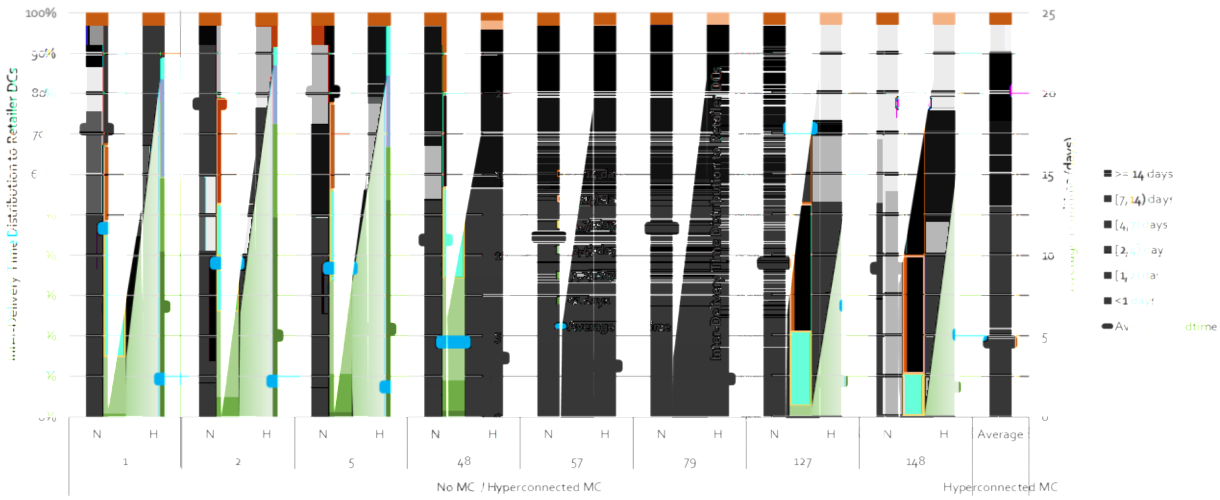

Figure 7: Average Inter-delivery Time to Retailer DC in No MC Operation (N) and in Hyperconnected MC Operation (H) in Scenario 3

In traditional distribution, an increase in delivery frequency is achieved at a cost induced by increased travel distance. However, the reduction in average inter-delivery time is reduced without any significant additional outbound travel distance in the case of HMC over all scenarios. Instead, the outbound travel distances are even reduced. The average marginal reduction in outbound distances by having dedicated MC and having open MC is summarized in Table 4. Here, only the outbound travel distance is compared as the inbound travel distance varies significantly depending on the location of plants of each manufacturer. The relationship between travel distances and shipping cost is less direct for inbound transportation due to potential mode of transportation, e.g. rail transportation can be used for most of the inbound volume which is cheaper than road transportation.

Table 4: Average Marginal Reduction in Outbound Travel Distances by Scenario

Scenario ID	No MC	From No MC to Dedicated MC	From Dedicated MC to Hyper MC
1	-	67%	1%
2	-	0%	59%
3	-	27%	40%
4	-	24%	39%
5	-	18%	51%
6	-	19%	55%

5.2.2 Inventory operation at customer DCs

The increased delivery frequency can lead to more efficient inventory operation at customer DCs. Firstly, consider the equation for base-stock level at customer DC shown below:

$$BS(L) = D * L + 3 * \sigma * \sqrt{L}$$

L is average inter-delivery time, D is average daily demand, and sigma is standard deviation of daily demand. From the equation, it can be seen analytically that when average inter-delivery time is reduced to p*L from L for some 0<p<1, the base-stock level is decreased by more than square root of p. This is shown below analytically.

$$BS(pL) = D * p * L + 3 * \sigma * \sqrt{p * L} \leq \sqrt{p} * BS(L)$$

This implies that inventory peak requirements can be reduced by lowering inter-delivery time. In addition to the analytical bound, the inventory level at customer DC is modeled and tracked in simulation. In Table 5, reduction in average of 0.99 percentile of OHI at customer DCs and in average inventory variation measured as coefficient of variation (COV) compared to no MC and dedicated MC operations is summarized by scenarios.

Table 5: Reduction in Inventory Peak and Variation at Customer DCs with Hyperconnected MC Operation Compared to the Two Alternative Operations by Scenario

Scenario ID	Reduction in 0.99 Percentile OHI at Customer DC		Reduction in Inventory Variation (COV) at Customer DC	
	No MC	Dedicated MC	No MC	Dedicated MC
1	16%	0%	62%	27%
2	15%	15%	46%	46%
3	10%	3%	69%	59%
4	10%	5%	76%	71%
5	9%	6%	70%	68%
6	6%	3%	52%	49%

In all cases, the variations as well as inventory peak at customer DCs are reduced significantly as shown in the Table 5. The results implies that the service capability of the HMC is not limited only to the delivery operation to customer DCs, but also capable of improving the internal logistic operations of customer DCs.

6 Conclusion

This paper has achieved multiple objectives. It has proposed a methodology to assess the potentiality for a logistics service provider to implement a steady hyperconnected MC in a target region. It has provided insights on HMC facility sizing. It has assessed advantages of using the service of the HMC for potential clients. It has demonstrated the benefits that the HMC can potentially bring into logistics operations of the players who are directly or indirectly using the services. The proposed methodology can help understand and assess the impact of hyperconnected storage and distribution.

Analysis of the experimental results has provided insights on potential advantages. Results show the potential of a HMC to improve the operations of manufacturers that currently supply their products from their plants/warehouses or their own dedicated MCs to their customer DCs, by enabling better storage space utilization and consolidation of outbound shipments without substantial capital investment of individual manufacturer. By simulating the operations of such HMCs, capacity requirements of the facility are assessed under different client sets.

The simulations provide insights on HMC service capability. HMCs enable to increase delivery frequency to customer DCs, inducing lower inventory requirements at customer DCs with no significant additional outbound travel. Unlike the common expectation that large manufacturers will not observe significant improvement due to their own scale, the results show that even large manufacturers can benefit as well. As most of logistics operations throughout the entire supply chain are required to be ever more agile and responsive, the service capability can attract many potential clients.

The key limitations of the study are as follows. First, the simulation-based experiments are limited to a single HMC case, limiting the genericity of the results and insights. Second, it does not address the coordination cost to handle the complexity and dynamics of HMCs operations, notable in terms of information and communication technology and service capability. Third, the long term, multi-year evolution of the clientele of HMCs is not addressed. Fourth, it does not model the pricing mechanisms for HMC services which may affect the behavior of clients and the attractiveness of the HMC. Fifth, it does not model competition between HMCs in a region. Sixth, we have limited the study to steady HMCs, not addressing spot HMCs. Seventh, we have not addressed the potential of hyperconnected logistics facilities that encompass the spectrum of mixing and distribution centers as exemplified by ES3 in York, Pennsylvania, USA. Each of these limitations provides avenues for further research.

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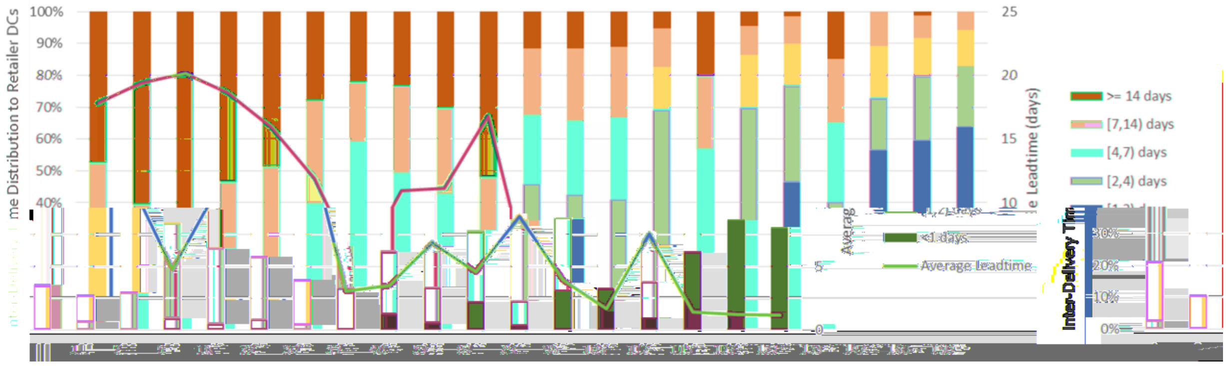
Appendix A: Scenario Description

Scenario ID	# of Clients at MC				Expected Annual Throughput (M pallets/year)	# of distinct outbound destinations (Customer DCs)	Client IDs
	Small	Med	Large	Total			
1			2	2	~2.8	139	147, 150
2		5		5	~2.8	173	105,112,115,122,133
3	5	2	1	8	~2.8	180	1,2,5,48,57,79,127,148
4	5	5	2	12	~5.8	194	1,2,5,48,57,79,105,112, 122,127,147,150
5	7	1		8	~3.4	195	1, 5, 16, 22, 30, 32, 67, 79,95,105,112,115,122
6	7	6		13	~1.0	172	2,5,16,22,30,32,67,95

Appendix B: Inter-delivery Times

Inter-delivery time to retailer DCs from a dedicated MC (same to no MC operation for manufacturers with a single plant):



Inter-delivery time to retailer DCs from a hyperconnected MC by sceanrios: