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Smart locker bank design optimization for urban omnichannel logistics: Assessing monolithic vs. modular configurations

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ABSTRACT

This paper presents optimization based design methods for smart locker banks in the context of omnichannel business-to-consumer logistics and supply chains. It explores two design approaches currently used in the industry: fixed-configuration locker bank and modular tower based locker bank. Contributions include optimization models for both design approaches, providing empirical evidence of their performance, synthesizing strategic insights and identifying avenues for further research, notably further exploiting the concepts and principles of Physical Internet and Hyperconnected City Logistics.

1. Introduction

In the context of omnichannel business-to-consumer (B2C) logistics and supply chains, physical goods are delivered through a variety of channels to meet consumers preferences (Brynjolfsson, Hu, & Rahman, 2013). The consumer retail industry has dramatically changed, notably through the diversification of retail channels available since the digital world transformed retail business models (Verhoef, Kannan, & Inman, 2015). Businesses operating within these channels aim to maximize their profit by analyzing each channels specificities (Tetteh & Xu, 2014). Montreuil (2017) categorizes such delivery channels, including the emerging pick-at-locker (P@L). P@L is based on the large-scale exploitation of smart lockers as pickup and delivery (P/D) points, offering an intermediate solution between in-store pickup and home delivery. The P@L channel requires last-mile delivery capabilities, yet limited to visiting smart locker locations serving several consumers, thus avoiding individual home deliveries and minimizing travel for deliverers. Goods purchased by consumers are typically delivered to a smart locker bank conveniently located nearby the consumers home or workplace, thus mitigating risks of unsuccessful deliveries and the security implications of unattended delivery to the home as reported by McKinnon and Tallam (2003).

In an urban environment, achieving this convenience requires implementing hundreds, even thousands, of smart locker banks across the urban agglomeration. Weltevreden (2008) and Morganti, Seidel, Blanquart, and Dablanc (2014) report the growth of such solutions in Europe, notably in the Netherlands, France, and Germany. Smart lockers are also fast growing in Asia, notably in China (Hua, 2017), and emerging in North America (Amazon, 2017). Fig. 1 provides examples of smart locker banks used for B2C purposes.

Smart lockers are automated, provide secure storage for packages, and are potentially available 24/7 through smart authentication (e.g. using a government-issued ID or a smartphone). By deploying networks of smart locker banks, P@L has the potential of reducing delivery costs, city congestion, and greenhouse gas emissions, as reported by Iwan, Kijewska, and Lemke (2016).

While the challenges of deploying and operating networks of smart locker banks have been studied through empirical and analytical modeling as well as through industry studies, little work has been published on the design of smart locker banks. The design problem is important because smart locker bank networks continue to be widely deployed in cities where prime real-estate is expensive and scarce. It is essential to identify methods to design efficient smart locker bank systems to induce high asset utilization and customer satisfaction.

This paper addresses the design of smart locker banks for urban omnichannel logistics[1] leveraging two conceptual designs proposed by Faugère and Montreuil (2017b) that are currently used in practice: (1) the fixed-configuration locker bank and (2) the modular tower based

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[1] This paper is a significantly extended version of Faugère and Montreuil (2017a), per invitation from the editors.

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Fig. 1. Examples of fixed-configuration smart locker banks.
Source: photographs by authors.

locker bank. The approach embraces a multi-stakeholder perspective and deals with uncertainty through a set of probabilistic scenarios. For logistic service providers delivering orders, it maximizes expected profit, by combining induced costs and revenues. For deliverers and customers, ergonomic costs are taken into consideration, depending on the dimensions and configuration of the smart locker bank itself. For both consumers and logistic service providers, minimum service levels are enforced, as service quality is of primary importance in the context of omnichannel B2C supply chains.

Design optimization models for both fixed-configuration locker bank and modular tower based locker bank configurations are developed. For fixed-configuration locker banks, optimizing the design involves deciding on (1) the global size of the bank (length and height), (2) the set of locker dimensions, (3) the number of lockers of each selected dimension, and (4) the layout of the lockers across the bank, as illustrated in Fig. 2.

The proposed optimization model for fixed-configuration smart locker bank design maximizes expected profits generated by serving a set of probabilistic delivery scenarios. Ergonomic costs and acquisition and implementation costs are modeled, as well as a restricted zone in which to implement the locker bank (e.g. an available space by the wall of a convenience store or in the ground floor hall of a high-rise building). The fixed-configuration locker bank design optimization model is adapted to three distinct contexts:

1. The design of each locker bank is customized for the location in which it is to be implemented.
2. A single design is to be used for all lockers in the urban agglomeration.
3. A limited set of designs is to be implemented, selecting among these the best fitting for each location.

Based on the alternative modular tower locker bank configuration, each locker bank within a territory (e.g. urban agglomeration, country) is designed to leverage a selected set of modular towers for the respective territory, as illustrated in Fig. 3. Standard modular towers can be dynamically purchased, implemented and/or stored, allowing adapting the design of locker banks on a medium-term basis (e.g. monthly, quarterly or yearly). Having a limited number of modular tower designs potentially allows the reduction of acquisition and

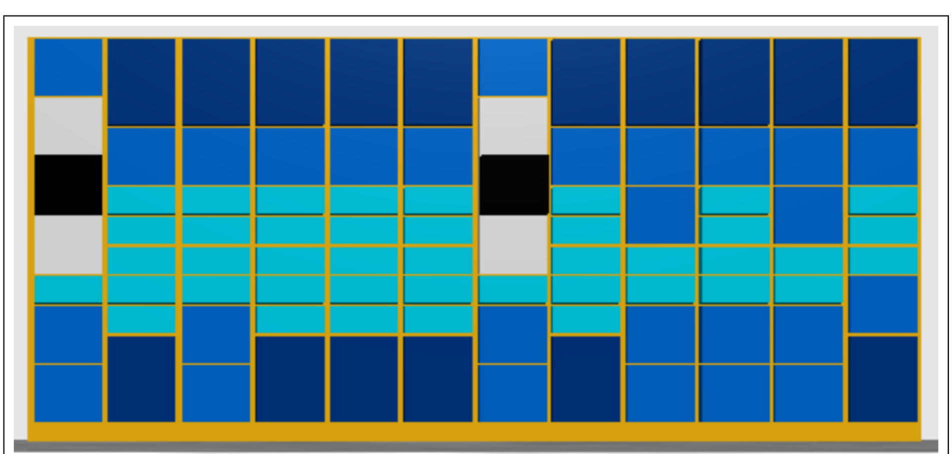


Fig. 2. Illustration of fixed-configuration smart locker bank design optimization (colors represent the different locker sizes).

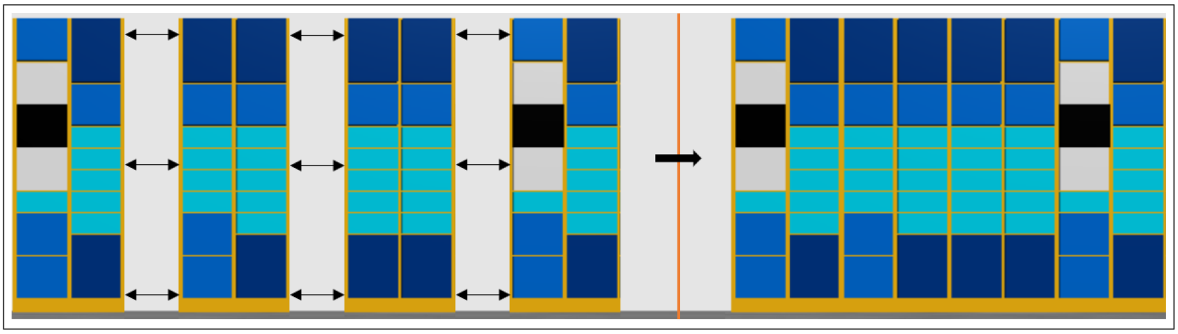


Fig. 3. Illustration of modular towers assembled into a modular tower based locker bank design (adapted from: Faugère and Montreuil, 2017b).

implementation costs through economies of scale.

For this configuration, a set of modular towers is to be optimized for the territory, from which designs for specific locker banks are optimized by concatenating selected modular towers. The proposed optimization model for the design of modular tower locker banks has the same expected profit maximization objective as the fixed-configuration model, yet adapted to the dynamic modular-tower context, allowing to optimize specific modular tower locker bank designs.

The paper contributes to the literature by introducing optimization based methods for designing smart locker banks leveraging two existing conceptual designs, providing empirical evidence of their performance, synthesizing strategic insights and drawing avenues for further research. The paper scope does not include the design and operation of an entire network, rather, it focuses on a singular smart locker bank location.

The paper is structured as follows. Section 2 presents the related literature, while positioning the paper's contribution. Subsequent Sections 3 and 4 respectively formally introduce the optimization modeling for fixed-configuration locker banks and modular-tower locker banks. Section 5 provides empirical results and analysis, with an emphasis on strategic insights. Finally, Section 6 synthesizes the contributions of the paper and discuss avenues for further research, notably further exploiting the concepts and principles of Physical Internet and Hyperconnected City Logistics introduced by Crainic and Montreuil (2016).

2. Literature review

This paper proposes methods to design smart locker banks with a level of detail relevant to omnichannel supply chains that is not yet studied in the existing literature. In fact, research in this area is limited. However, there is extensive research on smart locker network deployment and operations, including industry studies. This section presents recent work on smart locker bank network deployment and operations, relevant work on the design of smart locker bank, and finally addresses related literature from other problem domains.

2.1. Smart locker bank network deployment and operations literature

Kämäräinen, Saranen, and Holmström (2001) and Punakivi, Yrjölä, and Holmström (2001) first introduced the use of "reception boxes" located outside homes for B2C deliveries of groceries, showing a logistics cost reduction between 40 and 60 percent compared to traditional home deliveries. The savings were mainly due to the extension of the delivery window enabled by unattended delivery. Yet, since the reception boxes were household specific, improvement could still be made using communal reception boxes (Punakivi & Tanskanen, 2002). McKinnon and Tallam (2003) assessed the security implications of using communal reception boxes. The introduction of "smart tagging" was perceived as a way to overcome the security problems, thus creating the concept of smart locker banks.

Several papers have examined the development of smart locker bank networks in industry applications, assessing the solutions' efficiency (Weltevreden, 2008; Edwards, McKinnon, Cherrett, McLeod, & Song, 2010; Morganti et al., 2014; Morganti, Dablanc, & Fortin, 2014; Iwan et al., 2016; Lemke, Iwan, & Korczak, 2016). Sustainable networks in operation in Europe, notably in the Netherlands, Poland, France, and Germany are depicted. Smart lockers are also fast growing in Asia, notably in China (Hua, 2017), and emerging in North America (Amazon, 2017). Results show that smart locker banks enabled not only logistics cost savings, but also significant greenhouse gas emissions reduction due to improve delivery efficiency. The success of these existing networks is also attributed to the high coverage of the territory, ensuring convenient access to a pickup location. Convenient locations include main boulevards, shopping centers, commercial streets, locations suited to car access (Lachapelle, Burke, Brotherton, & Leung, 2018). The problem of designing a smart locker bank network for B2C deliveries has been studied by Deutsch and Golany (2017) using an uncapacitated facility location model to find the optimal number, location, and sizes of smart locker banks so as to maximize profits.

2.2. Smart locker bank design literature

Literature on smart locker bank design for B2C supply chains was initiated in the logistics field by the European research project CITYLOG, where monolithic and modular smart locker bank concepts were introduced as a solution called the "Modular BentoBox System". The systen is part of an effort to improve the sustainability and efficiency of city logistics by decoupling the delivery of couriers from the customer pickup of parcels (Dell'Amico, Deloof, Hadjidimitriou, Vernet, & Schoenewolf, 2011). These design concepts were further developed by Faugère and Montreuil (2017b) who extended the monolithic versus modular conceptual dichotomy to differentiate four types of design: the fixed-configuration, the modular tower based, the modular locker based, and the Physical Internet handling container based smart locker banks. The focus in this paper is on the fixed-configuration (monolithic) and the modular tower based (modular) smart locker designs. Bailey, Cherrett, Waterson, and Long (2013) and Bailey, Cherrett, Waterson, Breen, and Long (2014) tackled monolithic locker bank configuration optimization, focusing on a case for internal use by hospitals for medical supply delivery. Bailey et al. (2013) proposed a genetic optimization algorithm to search for the optimal locker partition combination that allow a maximal number of orders to be stored within the smallest space possible ensuring a minimum coverage of demand based on historical hospital supply delivery logs. While the method is relevant for the context of internal supply delivery in a hospital, the objectives (and therefore the resulting configurations) are different from the context of this paper, focused on B2C supply chains. Bailey et al. (2014) compared basic and intuitive hill-climbing models, resulting with smart locker bank configurations partitioned with the same objective.

Pan and Lin (2017) recently proposed an ergonomics optimization approach to the design of monolithic smart locker banks, studying

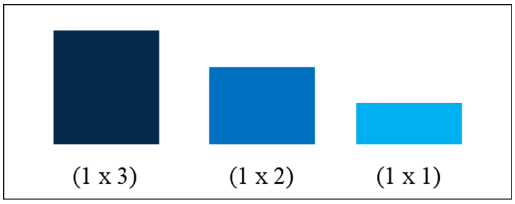


Fig. 4. Illustration of three modular locker sizes; Large (L), medium (M) and small (S).

different locker sizes, and analyzing the standing vision range as well as the impact of height on user ergonomics in the context of B2C deliveries on a university campus. Human factors in industrial and logistic system design are very important (Glock, Grosse, Neumann, & Sgarbossa, 2017) and have been studied in great depth for storage systems (e.g. Calzavara, Glock, Grosse, Persona, & Sgarbossa, 2017) Pan and Lin (2017) tackle this aspect in great depth. The approach taken in this paper encompasses human factors, yet in a broader multi-stakeholder approach integrating consumer and deliverer centric ergonomic cost minimization with the logistic service provider profit maximization and consumer service satisfaction.

2.3. Related literature

The problem of designing smart locker banks is related to the extensively studied two-dimensional and three-dimensional packing problems surveyed by Lodi, Martello, and Monaci (2002) and Martello, Pisinger, and Vigo (2000). These problems address the efficient packing of items in restricted spaces, fitting all items while minimizing wasted space. Efficient algorithms with complex objective functions have been studied for this problem (e.g. Dahmani, Clautiaux, Krichen, & Talbi, 2013). Smart locker bank design requires to choose a set of bins (lockers) for a variety of unknown items (potential deliveries), and to pack them into a restricted space. Moreover, the location of the lockers (e.g. height) have an impact on ergonomics and efficiency that is not reflected in packing problems. Therefore, adapting packing problems to the smart locker bank design problem would not entirely capture the essence of the problem.

Similarly, choosing a set of lockers to serve future demand (packages being delivered into the lockers) is related to inventory problems for equipment rental situations. Indeed, smart locker banks will face demand for empty lockers of a certain capacity (enough space to contain a parcel). Therefore, choosing the set of locker sizes composing a smart locker bank is similar to choosing a product portfolio and corresponding inventory to carry when running a rental business. This problem has been studied in several industries such as bike rental (Yan, Lin, Chen, & Xie, 2017), car rental (Yang, Jin, & Hao, 2008), or consumer goods rental (Slaugh, Biller, & Tayur, 2016). However, these problems focus on inventory questions, and are not fit to model the physical complexity of designing a smart locker bank.

Finally, designing the configuration of a smart locker bank is related to the design of warehouse layout and warehousing storage racks such as in automated storage and retrieval systems (AS/RS). Warehouse problems are often concerned with the utilization of a storage system (i.e. a combination of racks, stacks, etc.). The problem is defined as the allocation of products to storage locations such as in Bartholdi and Hackman (2008) and Horta, Coelho, and Relvas (2016). AS/RS systems enable to store items in a very compact space retrieving them automatically with cranes or robots. However, such systems are meant to provide high storage capacity for standardized unit loads (e.g. totes) and the focus of the research in the field is on overall capacity and retrieval time estimation (De Koster, Le-Duc, & Yugang, 2008; Zaerpour, Yu, & de Koster, 2015). Warehousing systems structure is not a primary point of focus as unit loads tend to be homogeneous. For example, a warehouse may deal with products at the level of standardized pallets or totes, which limits the variety of unit load shapes and sizes one has to deal with and makes the storage system structure less complex to design. The focus of this paper is at the individual product scale (i.e. not like warehouses that deal with pallets of products) in an industry where unit loads are often not standardized (i.e. often custom packages). Therefore, while encompassing storage system utilization (the placement of packages in a specific locker), this paper focuses on designing a storage system structure (the physical configuration of a smart locker bank).

3. Fixed-configuration locker bank design optimization

3.1. Problem statement

The proposed design optimization model for fixed-configuration locker banks maximizes a profit function composed of the expected revenues generated by serving a set of probabilistic delivery scenarios minus the associated ergonomic cost incurred by serving each order of each scenario (inbound and outbound handling ergonomic costs) and associated acquisition and implementation costs for the global dimensions of the bank and per locker implemented.

For illustrative purposes, three different modular sizes of locker are considered, multiples of the unit locker (1×1) as illustrated in Fig. 4.

A smart locker bank is modeled as being composed of three elements: lockers, interactive modules, and facades. Provided the maximal dimensions of a smart locker bank location (e.g. horizontal and vertical dimensions of an available wall), the space is divided in grid units of the size of the unit locker as illustrated in Fig. 5. Allocating lockers at different grid units creates a smart locker bank. For the purpose of avoiding holes in the structure of the bank, allocating a facade to conceal any locker-free grid unit within the limits of the smart locker bank is considered. While the nature of the structure of the bank is often rectangular, it may not be necessary to assign a locker at every grid unit, but an unconcealed space is not desirable to prevent structural complications or access to the interior of the bank. At the same time, a facade acts as a placeholder, and one can later replace it by a locker or other accessory if needed.

Fig. 5 also illustrates a smart locker bank including two interactive modules (light gray rectangles with black insert). Such modules allow the use to interact with the bank through a computer terminal (e.g. for authentication), and has to be included in the design according to input parameters: number of interactive modules needed, and dimensions (1×6 in Fig. 5). While currently an integral part of smart locker banks, future technological innovations may render the need for such interactive modules unnecessary.

The proposed model is developed according to the following set of hypothesis:

- The dimensions of lockers and interactive modules are divisible in grid units. It is assumed that the size of a grid unit has been chosen accordingly.
- Only one unit of demand can be served per a locker in a scenario. This means that only one package at the time can be stored in an individual locker unit. For privacy and anti-theft reasons, it is a reasonable assumption in the context of B2C logistics, as customers are to pickup their respective packages alone.
- Among all considered scenarios, the constructed smart locker bank must satisfy demand with a service level of at least α^G.
- For each individual scenario, the constructed smart locker bank must satisfy demand with a service level of at least α^L. This parameter is shared by all scenarios as it is meant to control the standard deviation of the service level under demand uncertainty.

3.2. Mathematical model

Consider the set of grid unit locations $\mathscr{G}$ available to design a locker

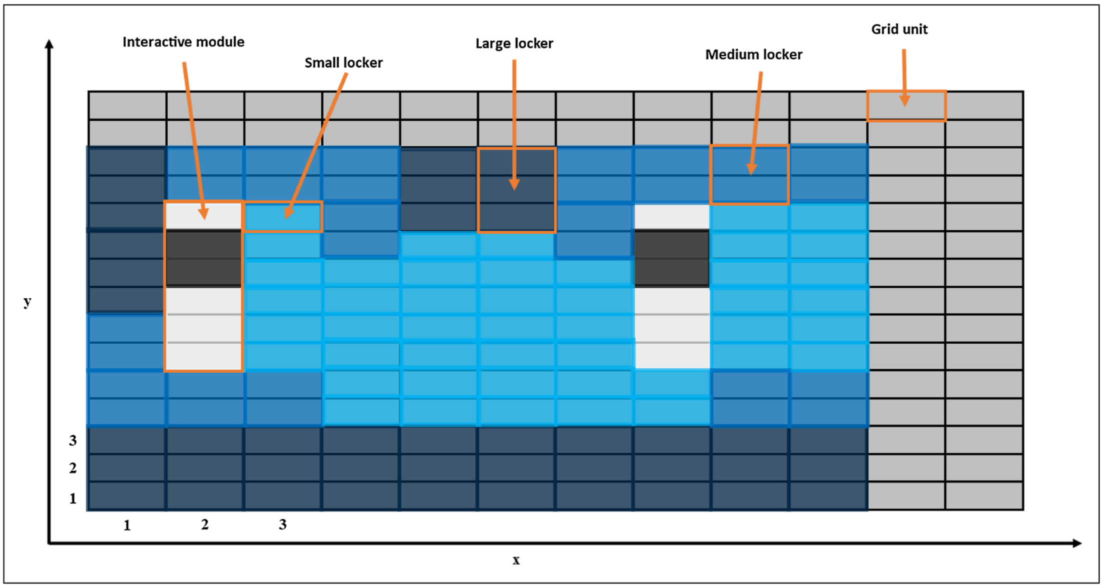


Fig. 5. Illustration of a smart locker bank and its design grid.

bank and the set of locker dimensions $\mathscr{D}$ considered for implementation in the design. In order to construct the locker bank design one needs to decide on the global dimensions (horizontal and vertical) of the bank and for each grid unit location $l \in \mathscr{G}$, one needs to decide whether:

- implement a locker of dimensions $d \in \mathscr{D}$,
- implement an interactive module,
- close the space with a facade,
- keep the space empty, and leaving the entire row/column empty.

Constructing such locker bank will generate amortized (with factor λ) acquisition and implementation costs c_d^L for each locker of dimension $d \in \mathscr{D}$, c^M for each interactive module, and $c^W W + 2c^S(W + H)$ for a bank with global dimensions W (width) by H (height).

Then, for each scenario $s \in \mathscr{S}$, demand for a locker of dimension d can be served by a locker of dimension $d' \in \mathscr{D}_d$ implemented in grid location l, generating a revenue of r_{ds} and an associated ergonomics cost $c_{dd'l}^A A_{dsd'l}$.

Hereafter are introduced the indices, sets, input parameters and decision variables that formulate the overall model.

3.2.1. Indices

d	Locker or order dimension ($d \in \mathscr{D}$)
l	Grid unit location ($l \in \mathscr{G}$)
s	Scenario ($s \in \mathscr{S}$)
x	Column of grid units ($x = 1, \ldots, \bar{w}$)
y	Row of grid units ($y = 1, \ldots, \bar{h}$)

3.2.2. Sets

$\mathscr{D}$	Considered locker dimensions
$\mathscr{D}_d$	Locker dimensions in which a package of dimension d can fit ($\mathscr{D}_d \in \mathscr{D}$)
$\mathscr{G}$	Available grid unit locations
$\mathscr{G}_d$	Locations at which a locker of dimension d can have its lower left corner ($\mathscr{G}_d \in \mathscr{G}$)
$\mathscr{G}_{dl}$	Grid units covered by a locker of dimension d whose lower left corner is location l ($\mathscr{G}_{dl} \in \mathscr{G}$)
$\mathscr{G}^M$	Locations at which an interactive module can have its lower left corner ($\mathscr{G}^M \in \mathscr{G}$)
$\mathscr{G}_l^M$	Grid units covered by an interactive module whose lower left corner is location l ($\mathscr{G}_l^M \in \mathscr{G}$)
$\mathscr{S}$	Considered demand scenarios for the design

3.2.3. Input Parameters

α^G	Minimum average service level
α^L	Minimum service level for each individual scenario
$c_{dd'l}^A$	Ergonomic cost of assigning an order of dimension d in a locker of dimension d' located at l
c^M	Cost of an interactive module
c^S	Unitary bank surface cost
c^W	Unitary bank width cost
d_{ds}	Demand for a locker of dimension d in scenario s (expressed in number of packages)
d_s^T	Total demand in scenario s; $d_s^T = \sum_{d \in \mathscr{D}} d_{ds}$(expressed in number of packages)
$\bar{h}$	Upper bound on the height of the bank
λ	Amortization factor for acquisition and implementation costs over the considered period
$\underline{m}$	Minimum distance required between two consecutive interactive modules
n^M	Number of locker columns an interactive module can cover
p_s	probability of scenario s
r_{ds}	Unit revenue yield by serving an order for dimension d in scenario s
$\bar{w}$	Upper bound on the width of the bank

3.2.4. Decision variables

$A_{dsd'l}$	0–1 Assignment of dimension d package in scenario s to a locker of dimension d' located at l
C_x	0–1 Use of grid unit column x in the locker bank design
F_l	0–1 Covering of grid unit location l with a facade
H	Height of the locker bank (in grid units)
L_{dl}	0–1 Implementation of a locker of dimension d at location l
M_l	0–1 Implementation of an interactive module at grid unit location l
N_d	Number of lockers of dimension d implemented in the design
R_y	0–1 Use of grid unit row y in the locker bank design
S_{ds}	Number of orders of dimension d served in scenario s
W	Width of the locker bank (in grid units)

3.3. Fixed-Configuration Locker Bank Design Problem (LBDP-FC)

The Fixed-Configuration Locker Bank Design Problem (LBDP-FC) can then be modeled as follows:

$$\max \sum_{s\in\mathscr{S}} p_s\left(\sum_{d\in\mathscr{D}} r_{ds}S_{ds} - \sum_{d\in\mathscr{D},d'\in\mathscr{D}_d,l\in\mathscr{G}_{d'}} c^A_{dd'l}A_{dsd'l}\right) - \lambda\left(\sum_{d\in\mathscr{D}} c^L_d N_d + \sum_{l\in\mathscr{G}^M} c^M M_l + c^W W + 2c^S(W+H)\right) \tag{1a}$$

s.t. :

Constraints for the interactive module(s):

$$\sum_{l\in\mathscr{G}^M} M_l \geqslant \frac{W}{n^M} \tag{1b}$$

$$M_l + \sum_{l'\in\mathscr{G}^M:l'\neq l,d(l,l')\leqslant\underline{m}} M_{l'} \leqslant 1, \quad \forall\, l\in\mathscr{G}^M \tag{1c}$$

Assignment of lockers, facades, and interactive modules:

$$\sum_{dl':l\in\mathscr{G}_{dl'}} L_{dl'} + F_l + \sum_{l':l\in\mathscr{G}^M_{l'}} M'_l = Z_l, \quad \forall\, l\in\mathscr{G} \tag{1d}$$

$$N_d = \sum_{l\in\mathscr{G}_d} L_{dl}, \quad \forall\, d\in\mathscr{D} \tag{1e}$$

Constraints controlling binary variable Z_l:

$$Z_l \geqslant R_{y(l)} + C_{x(l)} - 1, \quad \forall\, l\in\mathscr{G} \tag{1f}$$

$$Z_l \leqslant \frac{R_{y(l)} + C_{x(l)}}{2}, \quad \forall\, l\in\mathscr{G} \tag{1g}$$

Structural constraints:

$$xC_x \leqslant W \leqslant \bar{w}, \quad \forall\, x\in\mathbb{N},\, x\leqslant\bar{w} \tag{1h}$$

$$yR_y \leqslant H \leqslant \bar{h}, \quad \forall\, y\in\mathbb{N},\, y\leqslant\bar{h} \tag{1i}$$

Constraints for demand allocation to locker:

$$\sum_{d:d'\in\mathscr{D}_d} A_{dsd'l} \leqslant L_{d'l}, \quad \forall\, s\in\mathscr{S},\ \forall\, d'\in\mathscr{D}_d,\quad \forall\, l\in\mathscr{G}_{d'} \tag{1j}$$

Constraints for demand satisfaction integrity:

$$S_{ds} = \sum_{d'l:d'\in\mathscr{D}_d,l\in\mathscr{G}_{d'}} A_{dsd'l} \leqslant d_{ds}, \quad \forall\, d\in\mathscr{D},\quad \forall\, s\in\mathscr{S} \tag{1k}$$

Service level constraints:

$$\sum_{s\in\mathscr{S}} p_s \sum_{d\in\mathscr{D}} \frac{S_{ds}}{d^T_s} \geqslant \alpha^G \tag{1l}$$

$$\sum_{d\in\mathscr{D}} \frac{S_{ds}}{d^T_s} \geqslant \alpha^L, \quad \forall\, s\in\mathscr{S} \tag{1m}$$

Maximizing the profit expression (1a) corresponds to maximizing the sum, over the set of all probabilistic scenarios $\mathscr{S}$, of the revenues generated by serving each order of dimension d minus the incurred ergonomic cost, minus the amortized acquisition and implementation cost associated with implementing N_d lockers of dimension d, implementing interactive modules, and with the global dimensions of the bank. Note that the acquisition and implementation cost associated with the global dimensions of the bank represent an initial cost for building a structural basis, function of the width W of the bank, and a secondary cost accounting for materials use to build a skeleton of area $2(W+H)$ times the depth (assumed constant) of the bank. Expression (1b) ensures that the total number of interactive modules implemented is sufficient to cover the width of the bank assuming a cover parameter n^M, while (1c) ensures that each interactive module (if two or more) are distant from at least a minimum distance $\underline{m}$ for privacy purposes. $d(l, l')$ represents the horizontal distance between locations l and l'. Constraints (1d) prevent the model from superposing lockers, facades or interactive modules at a same grid unit location, while also avoiding holes in the locker bank structure (empty grid unit). Holes are avoided by preventing the model from leaving a grid unit empty if an element has already been assigned in the same row/column through constraints (1f) and (1g). Expression (1e) counts the number of lockers of each dimension d implemented, which is used in the objective function (1a). Expressions (1f) and (1g) ensure that if a grid unit is used in the design, its corresponding column and row are also used, thus setting the global dimensions of the bank through constraints (1h) and (1i). For all scenarios considered by the model, each order is to be assigned to an available locker if the capacity of the smart locker bank allows it. Constraints (1j) keep track of these assignment through the decision variables $A_{dsd'l}$, and make sure that they are consistent with the capacity of the bank, while constraints (1k) ensure that the total number of orders assigned in each scenario is consistent with the demand. Taking a customer centric approach to the design of smart locker banks for omnichannel B2C supply chains, we aim to maintain a global minimum service level (average demand satisfaction ratio over all scenarios) by implementing constraint (1l), and a lower bound α^G. Moreover, expression (1m) also enforce a lower bound on local service levels to avoid large differences between scenarios.

4. Modular tower based locker bank design optimization

4.1. Problem statement

The proposed optimization model for modular tower based locker bank design maximizes a profit function composed of the expected revenues generated by serving a set of probabilistic delivery scenarios minus the associated ergonomic cost incurred by serving each order of each scenario (inbound and outbound handling ergonomic costs) and associated implementation cost for each modular tower used. Three decisions are required to design a modular tower based locker bank, summarized into three questions:

- What is the horizontal global dimension of the bank?
- How many modular towers of each type is the bank composed of?
- How are the modular towers laid out?

In this paper, a set of predesigned modular towers of width $w = 2$ inspired from field observations is considered (illustrated in Fig. 6). Note that they both include interactive modules of same size as in the design of fixed-configuration smart locker banks.

The design of each individual modular tower is assumed to be ergonomically optimal for human interaction (inbound and outbound

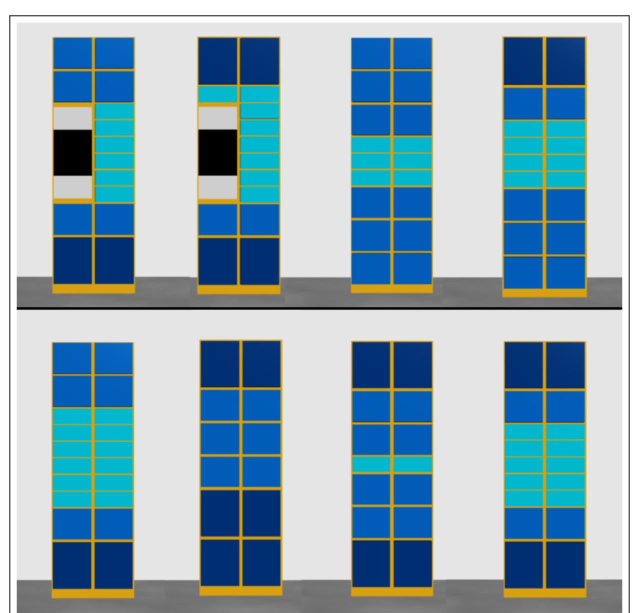


Fig. 6. Illustration of eight modular towers considered for designing modular tower based smart locker banks.

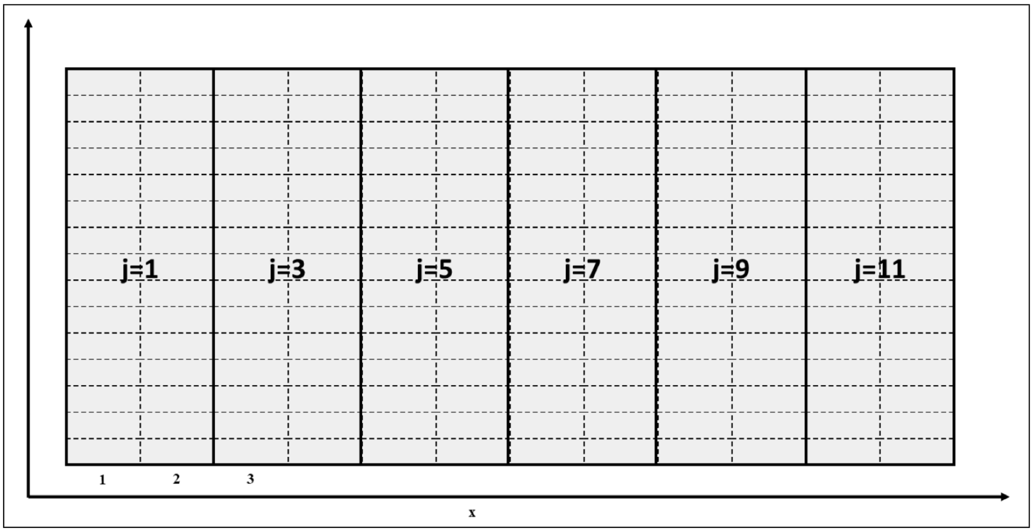


Fig. 7. Illustration of a modular tower based smart locker bank design grid.

lifting efforts). This results in modular towers of predefined constant height (15 grid units in Fig. 6). Now the space available to design a modular tower based smart locker bank can be divided in locations $j \in \mathscr{J}$ at which a modular tower can be implemented, as illustrated in Fig. 7.

4.2. Mathematical model

Consider the set of grid unit locations $\mathscr{G}$ available to design a locker bank, the set of locations at which a modular tower can be implemented $\mathscr{J}$, and the set of modular tower types $\mathscr{I}$ considered for implementation in the design. To construct a locker bank design one needs to decide whether or not to implement a modular tower of type $i \in \mathscr{I}$ at location $j \in \mathscr{J}$. Constructing such locker bank will generate amortized (with factor λ) acquisition and implementation costs c^i for each modular tower of type $i \in \mathscr{I}$ implemented. Then, for each scenario $s \in \mathscr{S}$, demand for a locker of dimension d can be served by a locker of dimension $d' \in \mathscr{D}_d$ implemented in grid location l if and only if a modular tower of type $i \in \mathscr{I}$ with a locker of dimension d' is located in modular tower location $j \in \mathscr{J}$ such that $l \in \mathscr{G}_j$ and $l \in \mathscr{L}^i$. It will generate a revenue of r_{ds} and an associated ergonomics cost $c^A_{dd'l}A_{dsd'l}$.

Hereafter are introduced supplementary indices, sets, input parameters and decision variables not previously defined in Section 3.

4.2.1. Indices

- i — Modular tower type ($i \in \mathscr{I}$)
- j — modular tower location ($j \in \mathscr{J}$)

4.2.2. Sets

- $\mathscr{G}_d$ — Locations at which a locker of dimensions d has its lower left corner in at least one modular tower type
- $\mathscr{G}^j$ — Grid units locations covered by modular tower location j
- $\mathscr{I}$ — Modular tower types available
- $\mathscr{J}$ — Positions at which a modular tower can be implemented
- $\mathscr{L}^i$ — Potential locker assignment (d, l) in the overall grid for modular tower of type i
- $\mathscr{M}$ — Modular tower types i that are composed of an interactive module ($m^i = 1$)

4.2.3. Input parameters

- c^i — Cost of acquiring and implementing a modular tower of type i
- $\delta^{m}_{ii'}$ — Minimum distance between modular towers i and $i' \in \mathscr{M}$ satisfying $\underline{m}$ (depending on the locations of the interactive modules in types i and i')
- λ — Amortization factor for acquisition and implementation costs over the considered period
- $\underline{m}$ — Minimum distance required between two consecutive interactive modules
- m^i — 1 if modular tower i is composed of an interactive module; 0 otherwise
- w — Width of the considered modular tower in terms of grid units

4.2.4. Decision variables

- X^i_j — 0–1 implementation of modular tower of type i at position j

4.3. Modular Tower Based Locker Bank Design Problem (LBDP-MT)

The Modular Tower Based Locker Bank Design Problem (LBDP-MT) can then be modeled as follows:

$$\max \sum_{s\in\mathscr{S}} p_s\left(\sum_{d\in\mathscr{D}} r_{ds}S_{ds} - \sum_{d\in\mathscr{D},d'\in\mathscr{D}_d,l\in\mathscr{G}_{d'}} c^A_{dd'l}A_{dsd'l}\right) - \lambda\left(\sum_{i\in\mathscr{I}} c^i \sum_{j\in\mathscr{J}} X^i_j\right) \tag{2a}$$

subject to:

Constraints for the interactive module(s):

$$\sum_{i\in\mathscr{I}}\sum_{j\in\mathscr{J}} m^i X^i_j \geqslant \frac{W}{n^M} \tag{2b}$$

$$X^i_j + \sum_{i'\in\mathscr{M}}\left(\sum_{k\in J:j+w\leqslant k\leqslant j+\delta^{m}_{ii'}} X^{i'}_k\right) \leqslant 1, \quad \forall\, i\in\mathscr{M}, \quad \forall\, j\in\mathscr{J} \tag{2c}$$

Structural constraints:

$$\sum_{i\in\mathscr{I}} X^i_j \leqslant 1, \quad \forall\, j\in\mathscr{J} \tag{2d}$$

$$\sum_{i\in\mathscr{I}} X^i_j \geqslant \sum_{i\in\mathscr{I}} X^i_{j+w}, \quad \forall\, j\in\mathscr{J}: j+w\in\mathscr{J} \tag{2e}$$

$$W = w\sum_{i\in\mathscr{I}}\sum_{j\in\mathscr{J}} X^i_j \leqslant \bar{w} \tag{2f}$$

Constraints for demand allocation to locker:

$$\sum_{d:d'\in\mathscr{D}_d} A_{dsd'l} \leqslant \sum_{i\in\mathscr{I}:(d',l)\in\mathscr{L}^i} X^i_j,\ j\colon l\in\mathscr{G}^j, \quad \forall\, s\in\mathscr{S}, \quad \forall\, d'\in\mathscr{D}_d, \quad \forall\, l\in\mathscr{G}_{d'} \tag{2g}$$

Constraints for demand satisfaction integrity:1k

Service level constraints:1l, 1m

Maximizing the profit expression (2a) corresponds to maximizing the sum, over the set of all probabilistic scenarios $\mathscr{S}$, of the revenues generated by serving each order of dimension d minus the incurred ergonomic cost, minus the amortized acquisition and implementation cost of modular towers of type $i \in \mathscr{I}$ at location $j \in \mathscr{J}$. Expression (2b) ensures that the total number of interactive modules implemented is sufficient to cover the width of the bank assuming a cover parameter n^M, while (2c) ensures that modular towers composed of an interactive module (if two or more) are distant from at least a minimum distance m. Constraints (2d) prevent the model from superposing modular towers at each location $j \in \mathscr{J}$. Expression (2e) avoid holes in the locker bank. Expression (2f) counts the number of modular towers of width w implemented to assess the global width W of the designed bank.

5. Experiment

The goal of the experiment is to compare the performance of each design optimization over sets of probabilistic scenarios. Exploring their sensitivity to different parameters, insights are identified, shaping recommendations and further research avenues.

5.1. Settings

The experiment considers four alternative locations. For each location, probabilistic scenarios are generated according to the following characteristics:

- The total number of packages follows a normal distribution of parameters (μ, σ)
- There are three sizes of packages according to a generated package mix ratio (% of small packages, % of medium packages, % of large packages)
- The package mixes are randomly generated from a target mix $(S\%,\ M\%,\ L\%)$ and can vary by $\pm$ 5% around the target mix values (i.e. $(S\% \pm 5\%,\ M\% \pm 5\%,\ L\% \pm 5\%$, following triangular distributions, and globally normed to 100%)

For each location, fifty scenarios are probabilistically generated, each having a weight according to a uniform distribution subject to global norming to one. Each scenario at a location is built according to the parameters from Table 1.

Unless stated otherwise, the input parameters used for the following experiments are indicated in Appendix A.

5.2. Solving method

Both the LBDP-FC and LBDP-MT optimization models have been programmed with Python and the package Gurobipy, and solved with Gurobi 7 on a laptop computer with processor Intel(R) Core(TM) i7-6500U and 8 GB of RAM. On a typical case, let say for the design of a smart locker bank for location 1 with default parameters, the LBDP-FC model has about 95k variables and 33k constraints. The LBDP-MT has a number of variables of the same order of magnitude (about 95k) but only about 900 constraints. The LBDP-MT, which has less configuration combinations to explore (concatenating modular towers), is therefore easier to solve. Fig. 8 presents the optimization runtime in seconds for different grid sizes (number of grid units composing the design grid) representing all the experiments performed in this section.

Table 1
Scenario generation parameters for each smart locker bank location.

Location	μ	σ	Average package mix
1	80	20	(60, 25, 15)
2	80	20	(40, 20, 40)
3	60	30	(25, 50, 25)
4	100	30	(15, 25, 60)

Although less experiments were needed for the LBDP-FC problem, Fig. 8a shows that optimal solutions were found within 30 min (1800 s). Fig. 8b confirms that the LBDP-MT model was easier to solve, with runtime never exceeding 350 s, even for larger grid sizes. These results are reasonable in the context of a design optimization at a tactical level, and emphasize the fact that this type of problem can be optimally solved in an efficient manner using available commercial software.

5.3. Contrasting the optimized designs

First let us look at the visual results of the proposed LBDP-FC and LBDP-MT optimization models over the four considered locations. Figs. 9–12 illustrate visual results of optimal fixed-configuration and modular tower based smart locker bank designs side by side for each location indicating the value of the objective function (Obj), the revenues generated (Rev), the ergonomic cost (Erg), and the non-amortized acquisition and implementation cost (A&I) for each locker bank. Acquisition and implementation costs are presented non-amortized for an easier understanding of the range of costs involved by such designs.

The visual outputs of the LBDP-FC (Fixed-Configuration) optimization model at the considered locations have a customized look: designs have very little similarities in terms of configuration. In contrast, the outputs of the LBDP-MT (Modular Tower based) optimization model have a more pleasant look, with lockers of different sizes gathered into clusters, making the smart locker bank look more streamlined. This occurs as look-and-feel is not considered in the proposed optimization models. While the LBDP-MT optimization model has more aesthetic appeal than the LBDP-FC optimization model, it is the only advantage compared with the components of the considered objective functions. Indeed, fixed-configuration designs result in higher profits, with both higher revenues, lower ergonomic cost, and lower acquisition and implementation cost.

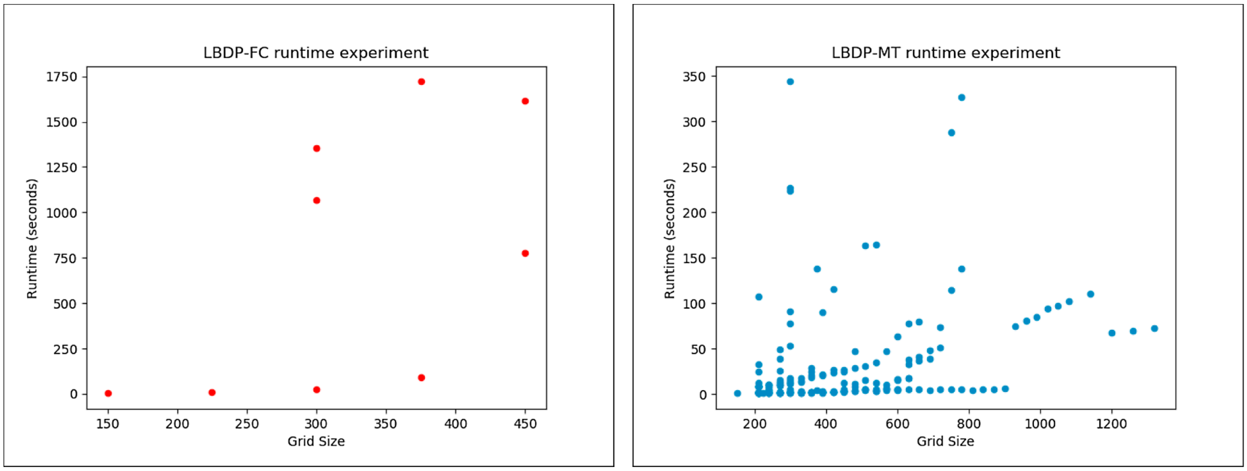
5.4. Profit function and key performance indicators

This section presents the performance of the proposed LBDP-FC and LBDP-MT optimization models over the four considered locations, highlighting the contrast in terms of the objective profitability function, as well as service level and space utilization, two pertinent KPIs in the omnichannel B2C supply chain context. Table 2 presents objective function values, service levels, and space utilization for both fixed-configuration (LBDP-FC) and modular tower based (LBDP-MT) designs at each of the four considered smart locker bank locations. The service level is computed as the weighted average of service levels of the fifty scenarios for each location as in constraint (1l). Space utilization is computed as the sum of accommodated package sizes divided by the sum of locker sizes composing the bank. Space utilization is the weighted average of each space utilization ratio for each scenario.

In Table 2, modular tower based locker bank designs yields a lower objective function value at all four locations, with gaps of respectively 5%, 7.12%, 7.05% and 10.65%. However, it is interesting to note that both models yield similar service levels at all four locations. For space utilization, the LBDP-MT optimization model yields the best ratio for location 1 and 2, and similar ratios for location 3 and 4.

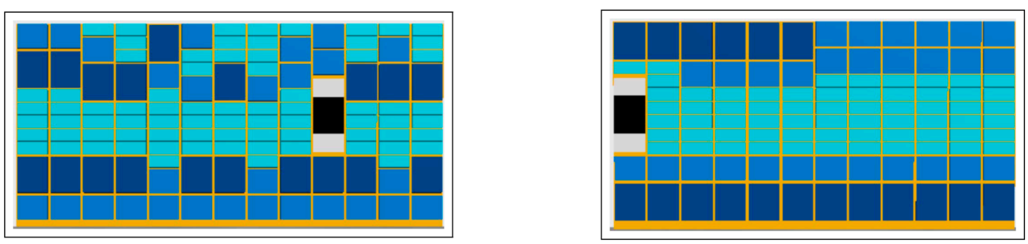
While the acquisition and implementation cost is specific to the considered smart locker bank, the components “revenues - ergonomic cost” are specific to the considered scenarios and can be explored in more detail. Fig. 13 compares the (revenues - ergonomic cost) generated by the LBDP-FC and LBDP-MT optimization models, comparing each by plotting distributions over the sets of fifty scenarios in box-and-whisker diagrams for each location and type of locker design.

These box-and-whisker (Tukey box plot) diagrams graphically



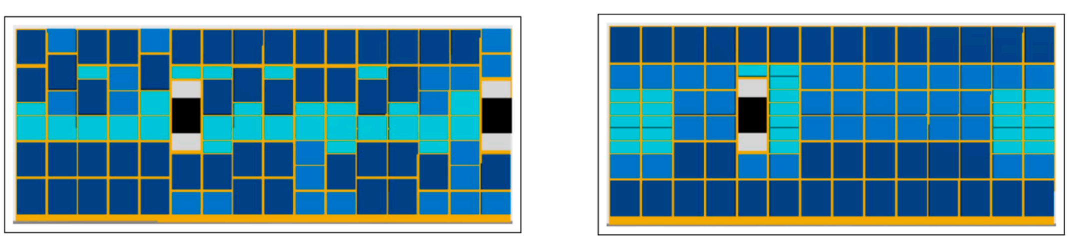
(a) LBDP-FC: 9 experiments (b) LBDP-MT: 184 experiments

Fig. 8. Experiments runtime for the LBDP-FC and LBDP-MT optimization models.



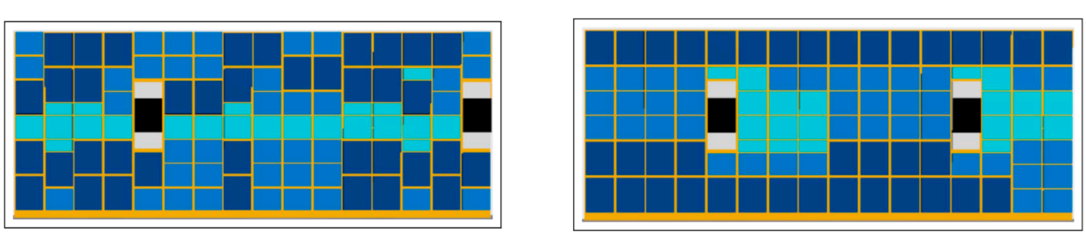
(a) Obj: 690.57, Rev: 781.7, Erg: 23.72, A&I: 8089 (b) Obj: 655.85, Rev: 777.54, Erg: 25.88, A&I: 11496

Fig. 9. Design optimization at location 1: (a) fixed-configuration and (b) modular tower based.



(a) Obj: 714.42, Rev: 813.93, Erg: 18.02, A&I: 9778 (b) Obj: 663.52, Rev: 796, Erg: 20.75, A&I: 13407

Fig. 10. Design optimization at location 2: (a) fixed-configuration and (b) modular tower based.

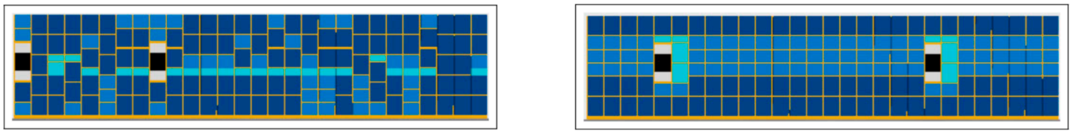


(a) Obj: 690.16, Rev: 789.84, Erg: 18.19, A&I: 9778 (b) Obj: 641.47, Rev: 789.08, Erg: 19.70, A&I: 15349.6

Fig. 11. Design Optimization at location 3: (a) fixed-configuration and (b) modular tower based.

depict groups of numerical data through their quartiles. Thus, one can observe that the first, second and third quartiles for both models have very similar performance. The difference lies in the spread of the distributions, especially for locations 1, 2, and 4, where it can observe that the fixed-configuration design model yields higher results.

The performance of the LBDP-MT optimization model in these illustrative examples is close to the LBDP-FC optimization model, although the acquisition and implementation cost component seem to be the origin of the difference in objective profitability function values.



(a) Obj: 1173.81, Rev: 1338.93, Erg: 27.13, A&I: 16558 (b) Obj: 1048.85, Rev: 1299.90, Erg: 27.58, A&I: 26815

Fig. 12. Design Optimization at location 4: (a) fixed-configuration and (b) modular tower based.

Table 2
Performance of the two proposed design methods over the four locations: KPIs.

Location	Model	Objective value	Service level	Space utilization
1	LBDP-FC	690.57	99.97%	68.32%
	LBDP-MT	655.85	99.45%	73.63%
2	LBDP-FC	714.42	99.67%	59.65%
	LBDP-MT	663.52	98.43%	66.63%
3	LBDP-FC	690.16	99.68%	57.38%
	LBDP-MT	641.47	99.56%	57.33%
4	LBDP-FC	1173.81	99.92%	56.98%
	LBDP-MT	1048.85	98.45%	55.27%

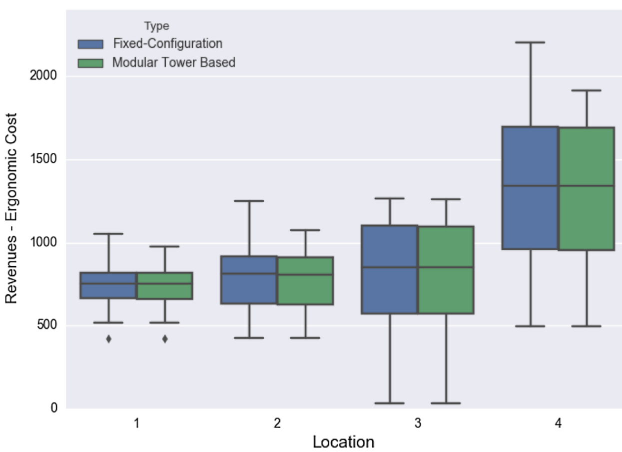


Fig. 13. Performance of the two proposed design methods over the four locations: objective value.

5.5. Sensitivity analysis on acquisition and implementation costs

The authors argue that using modular tower based locker bank designs offer opportunities of acquisition and implementation (A&I) cost savings enabled by economies of scale. It is reasonable to assume that the cost of a modular tower can be driven lower than the cost of a fixed-configuration locker bank of similar configuration. However, because of the structure of the costs in (1a), it can be expected that for a certain length of smart locker bank, a modular tower based design will eventually become more expensive than a fixed-configuration design as more modular towers are added. This happens because a modular tower has a structure supporting the individual tower, while the fixed-configuration design structure supports the entire bank, reducing the cost per column of lockers. Fig. 14 illustrates this concept.

This section explores the impact of the relative cost of a modular tower on the performance of the modular tower based design optimization model. Focusing on location 1, the model is solved with the cost of an individual modular tower being 50%, 70%, 85%, 100% and 120% (c^i (%)) of the cost of acquiring and implementing a fixed-configuration bank of similar configuration. Table 3 summarizes the results of the experiment, presenting the objective values, generated revenues, ergonomic costs, and non-amortized acquisition and implementation costs of the optimal solutions found for both LBDP-FC and LBDP-MT optimization models.

The results show the variation of the cost of individual modular tower impacts mostly the acquisition and implementation cost of the resulting smart locker bank. There is almost no change in the revenues or ergonomic costs. One can also note that the performance of the modular tower based design model yields a bank with performance similar to the fixed-configuration design model with an individual modular tower cost of 50% the value of its equivalent fixed-configuration smart locker bank (objective value within 1%). However, when the ratio is increased to 120%, the performance drop is within 15% (and the cost of the modular tower based bank more than doubles the fixed-configuration bank). This experiment is helpful to understand that the cost of individual modular towers may have a consequent impact on the performance of the modular tower based locker bank design optimization model, at least at the location level. Indeed, when designing a whole network of smart locker banks, the advantages of the modular tower based design become apparent as a large number of the same modular towers can be bought together, potentially enabling highly significant discounts, when the fixed-configuration design is customized for a specific location.

5.6. Importance of modular tower availability

The modular tower based locker bank designs assumes that a set of predesigned modular towers is available for selection. The optimization model then just need to select and concatenate the best set of modular towers available to build a smart locker bank. This section explores the impact of the available types of modular towers by iteratively removing the most used (greatest impact on the structure of designed banks) type from the set of available modular towers. Note that to ensure feasibility, constraints (2f) are iteratively relaxed. That is, if the model is infeasible, or if the solution found has width $W = \bar{w}$, $\bar{w}$ is increased by two units, and the model is solved again. Table 4 presents the iterations performed, and the resulting modular tower based locker bank configurations (modular tower type and number), as well as the objective values, service levels (SL), and space utilization ratio (SU). Next removals are identified in bold.

First it can be observed that in order to maintain the enforced service levels, smart locker bank widths at certain location dramatically increase; for example, from the beginning to the end of the experiment, location 4's bank width increases from 28 to 50 grid units. This clearly shows that the remaining modular tower types are not a good fit for location 4's demand, and its space utilization ratio can be expected to drop as availability is decreasing. However, at location 1, the bank width is steady along all iterations of the experiment, indicating that the availability of modular tower types has little effect, and that there is always a combination of modular tower types that fit location 1's demand in the scope of this experiment (stopping at $|I| = 4$); its space utilization ratio can be expected to be almost steady against the decrease in modular tower type availability. Indeed, location 1's performance is not substantially impacted by the decrease in modular tower type availability; its objective value drops by 1.5% between the beginning and the end of the experiment. In contrast, location 4 is dramatically impacted, and its objective value drops by almost 25%, which mostly comes from the acquisition and implementation cost increase due to the width of the bank almost doubling. Moreover, its service level decreases only by a little, while its space utilization drops from

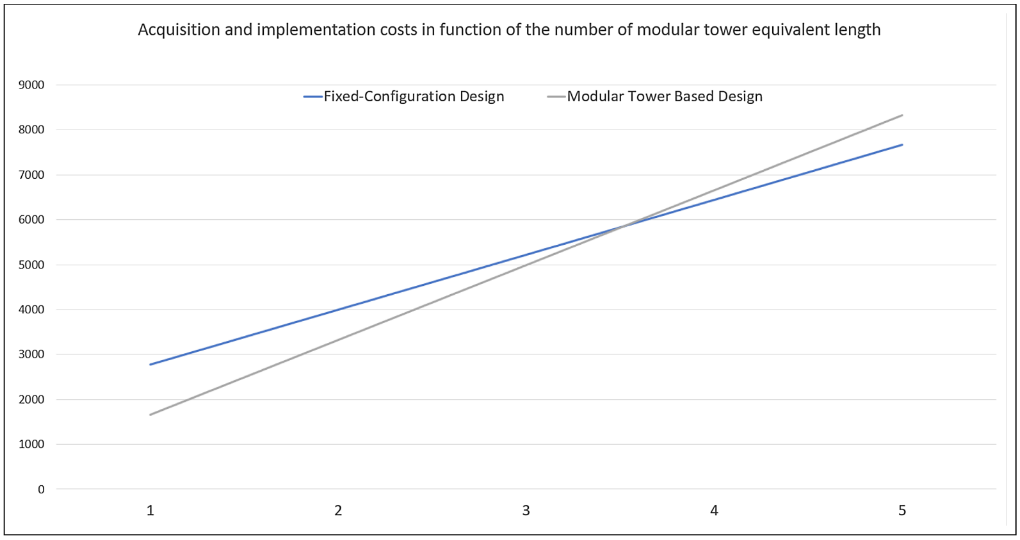


Fig. 14. Acquisition and implementation costs of a modular tower based design vs. fixed-configuration design.

Table 3
Sensitivity analysis on acquisition and implementation costs at location 1

Model	c^i (%)	Objective value	Revenues	Ergonomic cost	A&I cost
LBDP-FC	–	690.57	781.71	23.72	8089.0
LBDP-MT	50%	683.22	777.54	25.89	8212.0
	70%	655.85	777.54	25.88	11496.8
	85%	635.32	777.54	25.88	13960.4
	100%	614.79	777.54	25.88	16424.0
	120%	587.42	777.54	25.88	19708.8

55.27% to 29.21%.

This experiment highlights the importance of the available types of modular towers for the LBDP-MT optimization model, emphasizing the need to be carefully designed to fit multiple smart locker bank locations to benefit from economies of scale. It is even more important as having a large number of modular tower types is potentially harder to manage.

5.7. Space restrictions

Until now, the width of available space (and resulting grid) was never a constraint for both models; resulting smart locker banks for all experiments are not using the full grid available. As a result, for location 4, solutions have widths that could be seen as excessive (28 grid units in Section 5.3). This last experiment explores the impact of space restrictions at location 4 by incrementally decreasing $\bar{w}$, relaxing the service level constraints (1l) and (1m) to ensure feasibility. Table 5 summarizes the results of the experiment, presenting the objective values, service levels, and space utilization ratio of the optimal solutions found for both LBDP-FC and LBDP-MT optimization models.

SWith limited space,less demand can be fulfilled, resulting in the objective value decreasing along with service level. Despite this, however, space utilization increases faster than the decrease of objective value and service level, as more combinations of demand to serve are available as the space is more restricted. It makes it easier to find perfect matches between packages and lockers, thus limiting lost space.

Table 4
Iterations of modular tower availability and resulting smart locker banks (next removal in bold).

Availability	Location	Composition (type(number))	Bank width	Objective	SL	SU
$\|I\| = 8$	1	2(1)–5(3)–8(2)	12	655.85	99.45%	73.63%
	2	2(1)–**6(4)**–8(2)	14	663.52	98.43%	66.63%
	3	2(2)–4(1)–**6(4)**–8(1)	16	641.47	99.56%	57.33%
	4	2(2)–**6(12)**	28	1048.85	98.45%	55.27%
$\|I\| = 7$	1	2(1)–5(3)–**8(2)**	12	655.85	99.45%	73.63%
	2	2(2)–**8(6)**	16	638.31	98.14%	57.51%
	3	2(2)–7(4)–**8(2)**	16	630.67	99.10%	56.50%
	4	2(3)–7(2)–**8(15)**	40	954.34	98.45%	38.69%
$\|I\| = 6$	1	2(1)–5(4)–**7(1)**	12	652.33	99.26%	73.31%
	2	2(2)–**7(6)**	16	636.88	98.14%	57.51%
	3	2(2)–**7(6)**	16	629.76	99.01%	56.47%
	4	2(3)–**7(17)**	40	953.09	98.45%	38.69%
$\|I\| = 5$	1	2(2)–**5(4)**	12	650.79	99.26%	73.31%
	2	2(4)–**5(9)**	26	573.95	98.67%	35.78%
	3	2(3)–4(2)–**5(4)**	18	575.45	96.52%	47.3%
	4	2(7)–**5(18)**	50	811.90	95.41%	29.21%
$\|I\| = 4$	1	2(2)–4(4)	12	646.07	98.73%	73.01%
	2	2(3)–4(8)	22	561.73	96.40%	40.43%
	3	2(3)–4(6)	18	572.37	96.56%	47.35%
	4	2(7)–4(18)	50	790.41	95.41%	29.21%

Table 5
Performance of the models against space restrictions.

$\bar{w}$	Model	Objective value	Service level	Space utilization
30	LBDP-FC	1173.81	99.92 %	56.98 %
	LBDP-MT	1048.85	98.45 %	55.27 %
25	LBDP-FC	1167.80	99.02 %	62.96 %
	LBDP-MT	1028.31	96.29 %	61.89 %
20	LBDP-FC	1103.92	94.79 %	73.56 %
	LBDP-MT	985.99	92.90 %	69.82 %
15	LBDP-FC	959.95	85.01 %	84.67 %
	LBDP-MT	851.98	82.02 %	83.93 %
10	LBDP-FC	716.63	66.58 %	94.45 %
	LBDP-MT	662.33	65.99 %	90.34 %

Table 6
Comparing fixed and modular smart locker bank designs (adapted from Faugère and Montreuil (2017b)).

Design	Main advantages	Main disadvantages
Fixed	• Implementation cost • Economies of scale	• Transportation/installation equipment • Adaptation to demand evolution
Modular	• Modular transportation/ installation • Adaptation to demand evolution	• Capacity management • Modular tower design and inventory

6. Conclusion

Smart locker networks are promising contributors toward solving the last-mile delivery problem brought by a global urbanization of the world's population, and the challenges of e-commerce and omnichannel B2C supply chains. They can be beneficial to cities, in reducing logistic flows by taking advantage of consolidation opportunities; to logistic carriers, reducing the number of failed deliveries and reducing the number of vehicles and deliverers needed to cover a geographic area; to omnichannel retailers, by diversifying the service offerings; and finally to urban citizens, by offering convenient pickup and delivery locations.

This paper contributes to the development of last-mile delivery solutions and complements the smart locker bank network design literature by proposing an optimization based methodology for designing monolithic and modular smart locker banks in the context of omnichannel B2C logistics, and demonstrating that modular designs can perform just as well as fixed-configuration designs while being more flexible.

Optimization models are proposed for two of the smart locker bank designs proposed by Faugère and Montreuil (2017b): the fixed-configuration locker bank and the modular tower based locker bank. The models generate smart locker banks design maximizing profit leveraged by omnichannel supply chains, considering acquisition and implementation components as well as deliverer and consumers physical interactions with lockers (ergonomic efforts).

The authors report on experiments demonstrating that the modular tower based locker banks can perform closely to the fixed-configuration locker banks. The use of modular towers can be an advantage when deploying networks of smart locker banks, assuming one manages to take advantage of economies of scale to produce modular towers cost effectively. The experiments also showed that the set of modular towers available can dramatically impact the performance of a smart locker bank, thus highlighting the importance of well-designing sets of modular towers. Lastly, when the space is limited, the performance of both models drops rapidly, which can be a constraint when deploying a network over a highly priced real estate market, for instance.

Table 6 synthesizes strategic insights highlighted in the paper. From a managerial perspective, modular tower based smart locker banks have the advantage of being more flexible in a market where demand evolves over time. Fixed-configuration designs may be cheaper to implement as they require a one-time implementation of the smart locker bank. However, their monolithic structure may also require special equipment (e.g. truck, handling) for transportation and installation which induces some additional cost. A main disadvantage of fixed-configuration designs is the lack of flexibility regarding demand evolution. The modular tower based design allows expansion and reduction of capacity of a location as time passes, following demand patterns and trends. As suggested by Faugère, Malladi, Montreuil, and White (2018), the overall network's capacity can be dynamically managed, relocating, increasing, or decreasing the number of modular towers deployed (at the cost of dealing with dynamic capacity management). This also requires the careful design of modular towers, and may also require holding a certain amount of modular towers in inventory to avoid delay when the network's capacity needs to be increased. With fixed-configuration, as demand changes, there are three choices: (1) add an adjacent locker bank; (2) replace the current locker bank by a better adapted one, and try to find a better fitting place for the displaced one, sell it or discard it; (3) keep it as it is, reducing service quality as clients will have to rely on other banks or channels.

Finally, there are numerous opportunities for further smart locker research and innovation. The dynamic optimization of the set of modular towers to be used across a locker bank network is a natural extension of this paper. The exploitation of modular lockers and modular containers, introduced by Faugère and Montreuil (2017b) also opens a rich terrain for research on design and operation of such modular lockers, containers and banks, within a rich conceptual framework for Physical Internet enabled hyperconnected omnichannel urban logistics and supply chains. There is significant need for research investigating the relative performance of an overall network of smart locker banks under various set of bank design options in omnichannel B2C environment. Finally, similar research is needed relative to smart logistic locker banks, not designed for consumer access, but rather for exploitation as distributed access hubs for couriers and logistics service providers, notably in hyperconnected urban parcel logistics networks (e.g. Montreuil, Buckley, Faugère, Khir, & Derhami, 2018).

Acknowledgement

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Appendix A. Default input parameters

A.1. Simple parameters

Parameter	Description	Value (location)
α^G	Minimum average service level	90%
α^L	Minimum service level for each individual scenario	75%
c^M	Cost of an interactive module	50
c^S	Unitary bank surface cost	50

c^W	Unitary bank width cost	500
$\bar{h}$	Upper bound on the height of the bank	15
λ	Amortization factor for acquisition and implementation costs over the considered period	$1/2 * 5 * 12$
$\underline{m}$	Minimum distance required between two consecutive interactive modules	7
n^M	Number of locker columns an interactive module can cover	14
$\bar{w}$	Upper bound on the width of the bank	20(1), 20(2), 25(3), 30(4)
w	Width of the considered modular tower in terms of grid units	2

A.2. Revenues

r_{ds} Unit revenue yield by serving an order for dimension d in scenario s

Package Dimensions	1 (1 × 1)	2 (1 × 2)	3 (1 × 3)
Revenue associated*	6.10	11.95	16.35

*Considered independent of the scenario for the experiment.

A.3. Ergonomic costs

$$c^A_{11l} = \begin{cases} 0.01 * (115 - 15y(l)) & \text{if } y(l) \leqslant 7 \\ 0.01(-95 + 15y(l)) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{12l} = \begin{cases} 0.01 * ((75 + (65/6)) - (65/6)y(l)) & \text{if } y(l) \leqslant 7 \\ 0.01(10 - 7(65/6)) + (65/6)y(l) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{13l} = \begin{cases} 0.01 * ((50 + (40/6)) - (40/6)y(l)) & \text{if } y(l) \leqslant 7 \\ 0.01(10 - 7(40/6)) + (40/6)y(l) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{22l} = 0.01 * ((10 - (65/14)) + (65/14)y(l))$$

$$c^A_{23l} = 0.01 * ((10 - (90/14)) + (90/14)y(l))$$

$$c^A_{33l} = 0.01 * ((10 - (90/14)) + (90/14)y(l))$$

where $y(l)$ is the height of location l, in grid units.

A.4. Modular towers

Type	1	2	3	4	5	6	7	8
Cost*	1941.8	1941.8	1911	1911	1911	1911	1911	1911
m^i	1	1	0	0	0	0	0	0

*As 70% of the equivalent fixed-configuration locker bank design cost.
$\delta^m_{ii'} = 7$.

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