# The Design of Flexible Production-Distribution Networks

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**Abstract.** This research investigates the strategic opportunities in resilience investments in order to enhance operations efficiency and responsiveness of production-distribution networks under uncertainty. A two-stage stochastic location-allocation model with multiple products and capacitated production activities on alternative platforms is considered. In addition, a reengineering context is considered which adds the decisions of platforms upgrade on existing sites and their mission adaptation, to the classical decisions on sites location and platforms selection decisions. A scenario-based approach is employed to consider uncertainty into a set of plausible future scenarios considering potential demand surges and disrupted production-distribution capacities. Alternative mathematic constructs are proposed to include the concepts of chaining, and strategic production buffers with the aim to foster resiliency.

**Keywords:** *Production-distribution Network Design, Network Disruptions, Two-stage Stochastic Programming, Flexibility, resilience.*

## 1 Introduction

Companies nowadays face a complex global business environment, characterized mainly by larger number of suppliers with questionable reliability, more volatile demand, and more exposure to unpredictable high-impact disruptive events. It is to cope with these issues that companies must adapt the structure of their production-distribution networks and planning systems. A production-distribution network (PDN) is a configuration of production and distribution platforms geographically deployed in order to serve a customer base. At the strategic level, the design of the PDN involves the determination of the number, location, capacity and mission of these facilities. However, at that level, the future environment under which the PDN will evolve in time is difficult to predict which could alter the performance of the design decisions made at the beginning of the planning horizon. The classical approaches to tackle this strategic problem assumed that the environment is deterministic (Klose and Drexl, 2005) or includes random factors (Klibi et al., 2010). In the recent years, a significant interest was observed for supply chain models taking into account facility failures and network disruptions (Snyder, 2005). These models are commonly using stochastic programming (Birge and Louveaux, 2011) to optimize the problem under uncertainty. However, the major part of these models considers extending the well-known facility location model, which tends to dismiss some key features of the production and distribution activities within a supply chain. These models also assume that the network is designed from scratch and that the set of activities and capabilities of each potential site are predetermined, which is unrealistic. A recent review of supply chain networks design problems under uncertainty is found in Klibi et al., (2010). Figure 1 depicts the activity graph of a given company involving multi-product production and distribution system, and links it to the potential resources available to deploy them.

Furthermore, a major preoccupation of current businesses when designing PDNs is the consideration of risk of business interruption. In the past, multiple catastrophic events have disrupted supply chains networks, causing the interruption of production activities and/or disturbance of distribution operations for a significant period of time. Several papers (Sheffi, 2005; Bode and Wagner, 2015) examined the case of numerous companies that suffered from the US blackout in 2004, hurricane Katrina in 2005 and recent earthquakes in Haiti, Chile and Japan. These works among others underlined the fact that when PDNs are geographically dispersed across large regions, their exposure to extreme events is high and, thus the impact, will be significant to the company supply chain operations when such events occur. However, supply chain research considering a comprehensive and accurate modeling of random events and high impact disruptions is still in its infancy. In these circumstances, the PDNs must be designed with the objective to foster risk mitigation and resilience. Resilience is the ability of a PDN to bounce back from disruptions (Sheffi, 2005). Several strategies concerned by the predisposition of network resources in order to avoid risky location or incorporating redundancy and flexibility have been proposed in the literature (Tang and Tomlin, 2008; Sodhi and Tang, 2012). However, only few of these strategies are explicitly incorporated in PDN design models. In Klibi and Martel (2012b) several resiliency distribution strategies were tested on a stochastic location-transportation problem considering a single product. Additionally, other works considered the chaining concept to enhance the flexibility of production networks with multiple products. Following the work of Jordan and Graves (1995), several authors (Benaicha et al., 2010; Lim et al., 2011) investigated how to enhance the flexibility/reliability of facility location problems based on novel product-allocation rules. However, to the best of our knowledge none of these rules and/or strategies was applied in a scenario-based PDN design optimization framework.

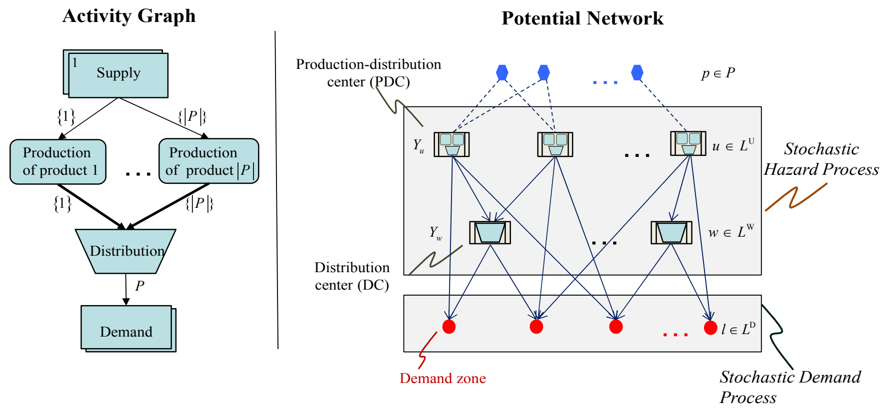


**Fig. 1.** Production-Distribution Networks under uncertainty

This research proposes an approach for modeling this strategic problem with the objective to reengineer an existing PDN in order to enhance its resiliency. It considers that the future business environment is shaped by a planning horizon prone to juxtaposed disruptions that impacts on the production and distribution capacity of the network. We consider a modeling approach that takes into account the option to deploy new flexible production technologies providing modular capabilities and more process responsiveness thanks to strategic buffers. The mathematical models build on stochastic programing to consider uncertainty into a set of scenarios with specific constraints for each resilience strategy investigated. This gives rise to a two-stage stochastic location-allocation model with multiple products and multiple activity capacitated platforms.

The rest of the paper is organized as follows. Section 2 describes the PDN design problem under uncertainty and characterizes demand and disasters processes. It presents the deterministic design model and a scenario-based PDN design model. Section 3 proposes two alternative design models to improve PDN resilience. Section 4 presents an illustrative case that validates the approach and provides insights on the design solutions produced. Finally, section 5 concludes the paper.

## 2 Modeling Approach

As mentioned earlier, the problem involves the production of several product families at a set of production-distribution centers (PDCs) under a make-to-stock policy. It considers next the distribution of these product families from these PDCs or from a set of distribution centers (DCs) as well as the replenishment of the DCs by the PDCs. Let us define $P$ the set of products families produced ( $p \in P$ ) and $L_p^D$ the set of demand zones ordering the product $p$ (with $L^D = \cup_p L_p^D$). Also the total set of the production-distribution network sites is given by $L^S = L^U \cup L^W$, where $L^U$ is the set of production-distribution sites (PDCs) and $L^W$ is the set of distribution sites (DCs).

An important modeling feature of the reengineering context considered here is that it was not assumed that the PDN is designed from scratch and that the DC/PDC platform of each potential site is predetermined. Consequently, for each site $s \in L^{\mathrm{S}}$, it is assumed that a set $O_s$ of platform options are considered and selecting the best option for each site to be opened is part of the PDN design problem. Let $P_o \subset P$ denotes the subset of product families that could be produced within the platform $o \in O$. Each potential platform corresponds to a combination of the triplet: technological choices, subset of activities selected, and predetermined layout. The fixed costs associated with a given platform are defined in accordance to the capabilities offered by such a triplet configuration. In addition, we assume that a dedicated production capacity per product $p \in P$ is considered and that shared storage/distribution capacity for all the product families is used. The following parameters and relevant costs are defined:

$y^+_{so}$, $y^-_{so}$, $y_{so}$ : The fixed cost incurred when, at the beginning of the planning period, site *s* with platform *o* is opened, closed or kept operating, respectively.

$d_{pl}$ : Demand of product *p* for demand zone $l \in L^{\mathrm{D}}$ during the planning horizon considered

$\underline{e}_p$ : Average size of the products family *p* (in a standard unit)

$b_{so}$ : Maximum annual expeditions from $s \in L^{\mathrm{S}}$ (in standard product unit) to demand zones imposed by the storage space available when platform $o$ is selected

$\overline{b}_{puo}$ : Production capacity for product *p* in PDC *u* when platform $o$ is selected

$c^{\mathrm{P}}_{puo}$ : Average unit production cost of product *p* in PDC *u* with platform $o$

$c^{\mathrm{S}}_{pso}$ : Average storage cost for product *p* per unit of flow in site *s* with platform $o$

$c_{psl}$ : Unit transportation cost of product *p* from site $s \in L^{\mathrm{S}}$ to node $l \in L^{\mathrm{W}} \cup L^{\mathrm{D}}$

$c_{puw}$ : Unit inbound transportation cost of product *p* from PDC $u \in L^{\mathrm{u}}$ to DC $w \in L^{\mathrm{W}}$

In what follows, the set of decision variables necessary to formulate the problem is provided.

$Y_{so}$ : 1 if the platform *o* is exploited on site $s \in L^{\mathrm{S}}$ during the period, 0 otherwise

$Y^+_{so}$ : 1 if the platform *o* is implemented on site $s \in L^{\mathrm{S}}$ at the beginning of the period, 0 otherwise

$Y^-_{so}$ : 1 if the platform *o* is closed on site $s \in L^{\mathrm{S}}$ at the beginning of the planning period, 0 otherwise

$X^{\mathrm{P}}_{puo}$ : Annual quantity of products *p* produced in site $u \in L^{\mathrm{U}}$ when the platform $o \in O_u$ is selected

$X^{\mathrm{S}}_{pso}$ : Annual flow of product *p* in the storage zone of site $s \in L^{\mathrm{S}}$ when $o \in O_s$ is selected

$F_{pwl}$ : Annual flow of product *p* delivered to demand zone *l* from DC *w*

$F_{pul}$ : Annual flow of product *p* delivered to demand zone *l* from PDC *u*

$F_{puw}$ : Annual flow of product *p* shipped by PDC *u* to DC *w*

We notice that $Y^0_{so}$ is a binary parameter set to 1 if the platform is already in operation at the beginning of the planning period and 0 otherwise, and that the index *up*(*o*) specifies the new platform if it is an upgrade of a current platform.

### 2.1 Deterministic Model

Under the assumptions above, the deterministic model of the PDN design problem is given by:

$$C^{PDN} = \min \sum_{s \in L^{\mathrm{S}}} \sum_{o \in O_s} \left( y^+_{so} Y^+_{so} + y_{so} Y_{so} + y^-_{so} Y^-_{so} \right) + \sum_{u \in L^{\mathrm{U}}} \sum_{o \in O_u} \sum_{p \in P_o} c^{\mathrm{P}}_{puo} X^{P}_{puo} + \sum_{s \in L^{\mathrm{S}}} \sum_{o \in O_s} \sum_{p \in P_o} c^{\mathrm{S}}_{pso} X^{S}_{pso} + \sum_{p \in P} \sum_{u \in L^{\mathrm{U}}} \sum_{w \in L^{\mathrm{W}}} c_{puw} F_{puw} + \sum_{p \in P} \sum_{s \in L^{\mathrm{S}}} \sum_{l \in L^{\mathrm{D}}_p} c_{psl} F_{psl} \quad (1)$$

subject to

$$\sum_{o\in O_s} Y_{so} \le 1 \qquad s \in L^{S} \qquad (2)$$

$$\left.\begin{array}{ll} Y_{so} + Y^{-}_{so} + Y^{+}_{s,up(o)} = 1 & \text{if } Y^{0}_{so} = 1 \\ Y_{so} - Y^{+}_{so} = 0 & \text{if } Y^{0}_{so} = 0 \end{array}\right\} \qquad s \in L^{S},\ o \in O_s \qquad (3)$$

$$\sum_{s\in L^{S}} F_{psl} = d_{pl} \qquad p \in P,\ l \in L^{D}_{p} \qquad (4)$$

$$\sum_{o\in O_u} X^{P}_{puo} = \sum_{l\in L^{D}_{p}} F_{pul} + \sum_{w\in L^{W}} F_{puw} \qquad u \in L^{U},\ p \in P_o \qquad (5)$$

$$\sum_{o\in O_s} X^{S}_{pso} = \sum_{l\in L^{D}_{p}} F_{psl} \qquad s \in L^{S},\ p \in P \qquad (6)$$

$$X^{P}_{puo} \le \overline{b}_{puo} Y_{uo} \qquad u \in L^{U},\ o \in O_u,\ p \in P_o \qquad (7)$$

$$\sum_{p\in P} e_p X^{S}_{pso} \le \overline{b}_{so} Y_{so} \qquad s \in L^{S},\ o \in O_s \qquad (8)$$

$$\sum_{u\in L^{U}} F_{puw} = \sum_{o\in O_w} X^{S}_{pwo} \qquad w \in L^{W},\ p \in P \qquad (9)$$

$$Y_{so}, Y^{-}_{so}, Y^{+}_{so} \in \{0,1\},\ s \in L^{S},\ o \in O_s \qquad (10)$$

$$F_{puw}, F_{psl}, X^{P}_{puo}, X^{S}_{pso} \ge 0,\ p \in P,\ s \in L^{S},\ l \in L^{D},\ u \in L^{U},\ w \in L^{W} \qquad (11)$$

The objective function (1) minimizes the sum of fixed costs of selected platforms, production costs at PDCs, storage costs at DCs and PDCs, and transportation costs based on product flows. Constraints (2) are added because only one platform option could be selected if a site is opened and are related to constraints (3) which manage closing and transforming existing platforms, as well as implementing new platforms on new sites. Constraints (4) are classical demand satisfaction constraints, per demand zone and per product, based on the outbound flows from PDCs and DCs. In constraints (5) and (6), the left hand side corresponds to the activity level of production and distribution, which must be equal to the sum of outflows from PDC for production and from PDCs and DCs for distribution, respectively. Constraints (7) and (8) represent the production capacity available for product *p* and the total distribution capacity per site, respectively. Constraints (9) link the inbound flows to replenish the DCs with the outbound flows from DCs to the demand zones. Finally, nonnegativity constraints are given by (10) and (11).

## 2.2 Scenario Building Approach

As mentioned, this work considers random demand as well as extreme events that shape future PDN environment. The proposed approach is based on the framework developed in Klibi and Martel (2012a) which implies the modeling of natural disasters impact in space and time on the network resource capacities. It involves the estimation of natural hazards arrival processes, and the assessment of their consequences on PDCs and DCs exposed to disasters. Figure 2 illustrates two examples of disrupted capacity behavior in time at PDCs shaping a total capacity loss (a) and a partial capacity loss with recovery process (b), respectively. As mentioned, a disruptive event is characterized by a physical impact (based on the intensity of the event) and by a time to recovery (based on the recovery predispositions).

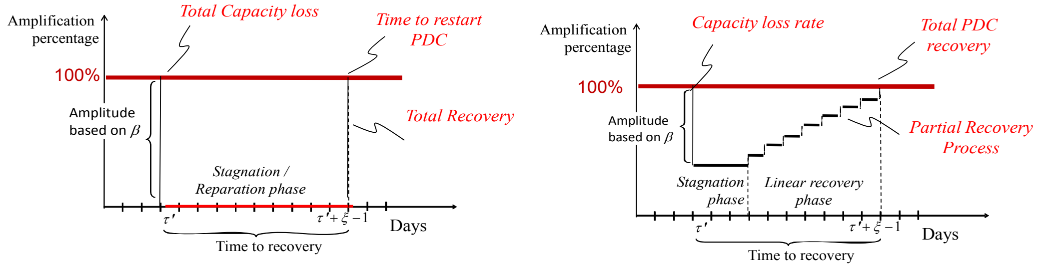


**Fig. 2.** a) Case of total loss of the PDC; b) Case of partial loss-recovery of the PDC

The instantiation of demand and disaster processes over all the possible values of the random variables involved yields a set $\Omega$ of plausible future scenarios with associated probabilities $\pi(\omega), \omega \in \Omega$. When these stochastic processes are characterized explicitly, a Monte Carlo procedure could be used to generate a scenario instance $\omega \in \Omega$ along the planning horizon for customers demands : $[d_{pl}(\omega)]_{p\in P,\, l\in L^D}$, production capacities : $[\overline{\mathrm{b}}^{\mathrm{P}}_{puo}(\omega)]_{p\in P, u\in L^u, o\in O_u}$ and storage capacities : $[\overline{\mathrm{b}}^{\mathrm{S}}_{so}(\omega)]_{s\in L^s, o\in O_s}$.

This section assumes that the uncertainty is captured through a set of scenarios, whereas deterministic modeling relies on point estimates of parameters. Stochastic models are solved using the Sample Average Approximation method (Shapiro, 2008). With this method, for a each sample of scenarios $\omega \in \Omega^m$, generated using Monte-Carlo procedure (Shapiro, 2003), the stochastic design model could be formulated as an equivalent MIP. The next section proposes two alternative resilience seeking strategies that are formulated based on the design model (1)-(11).

## 3 Flexibility-based Resilience Strategies

A PDN is resilient if it is designed to continue operating efficiently when random events and extreme events-based perturbations occur in time. In other words, it is resilient if these events do not generate huge economic losses due to the recourse costs engaged to satisfy customers demand during perturbations. In fact, when a disruption occurs, a subset of PDCs/DCs may lose part of (or all) their capacity during a period of time, and thus, some orders may have to be reallocated by the company. Such reallocation decisions should be based on predetermined contingency plans, assuming that an internal recourse exists to cover the missing capacity or that an external emergency recourse is necessary to engage in order to continue fulfilling the orders received. The execution of these contingency plans along the planning horizon is crucial to the performance of the PDN due to the additional operational costs generated. Once scenarios are elaborated, we need to build stochastic PDN design models to take into account uncertain production and distribution capacity and demand levels, as well as the associated recourses. Thus, when designing the PDN, the investments required to open sites and select the appropriate platforms on each one of them, must integrate the opportunities of the product-allocation rules under disruption and their associated costs. To do so, two alternative flexibility-based strategies are discussed and modeled in what follow.

### 3.1 Multi-sourcing allocation-based strategy with external emergency recourse

In this case, the strategy is to allow multi-sourcing production-distribution flows in order to increase the flexibility of the network. In addition, the model could offer the possibility of paying external recourse shipping costs to satisfy demand under disruptions. A recourse decision variable is associated with the second-stage model, denoted by $F^+_{pl}(\omega)$ which corresponds to the amount of product *p* to ship in urgency to demand zone *l* from an external resource to the PDN. The usage of this recourse (i.e. extra shipment) is penalized by a cost, denoted by $\delta_{pl}$ for each product *p* and demand zone *l* where $e_{pl} >> c_{psl}$. A typical PDN design model minimizing the expected costs is obtained by solving the following two-stage stochastic program with recourse:

$$\mathrm{E}_{\Omega}(C^{\mathrm{PDN}}) = \min_{\mathbf{Y},\mathbf{X}} \sum_{s\in L^{\mathrm{S}}} \sum_{o\in O_s} \left( y^+_{so} Y^+_{so} + y_{so} Y_{so} + y^-_{so} Y^-_{so} \right) + \sum_{\omega\in\Omega} \pi(\omega) \mathrm{C}(\mathbf{Y}, \omega) \quad (12)$$

subject to constraints (2), (3) and (10), and
where the value $\mathrm{C}(\mathbf{Y},\omega)$ of the second stage program for design $\mathbf{Y}$ and scenario $\omega$ is given by:

$$C(\mathbf{y},\omega) = \min_{\mathbf{X},\mathbf{F}} \sum_{u\in L^{\mathrm{U}}} \sum_{o\in O_u} \sum_{p\in P_o} c^{\mathrm{P}}_{puo} X^{P}_{puo}(\omega) + \sum_{s\in L^{\mathrm{S}}} \sum_{o\in O_s} \sum_{p\in P_o} c^{\mathrm{S}}_{pso} X^{S}_{pso}(\omega)$$
$$+ \sum_{p\in P} \sum_{u\in L^{\mathrm{U}}} \sum_{w\in L^{\mathrm{W}}} c_{puw} F_{puw}(\omega) + \sum_{p\in P} \sum_{s\in L^{\mathrm{S}}} \sum_{l\in L^{\mathrm{D}}_p} c_{psl} F_{psl}(\omega) + \sum_{p\in P} \sum_{l\in L^{\mathrm{D}}_p} \delta_{pl} F^+_{pl}(\omega) \quad (13)$$

$$\sum_{s\in L^{\mathrm{S}}} F_{psl}(\omega) + F^+_{pl}(\omega) = d_{pl}(\omega) \qquad p\in P, l\in L^{\mathrm{D}}_p \quad (14)$$

$$\sum_{o\in O_u} X^{\mathrm{P}}_{puo}(\omega) = \sum_{l\in L^{\mathrm{D}}_p} F_{pul}(\omega) + \sum_{w\in L^{\mathrm{W}}} F_{puw}(\omega) \qquad u\in L^{\mathrm{U}},\ p\in P \quad (15)$$

$$\sum_{o\in O_s} X^{\mathrm{S}}_{pso}(\omega) = \sum_{l\in L^{\mathrm{D}}_p} F_{psl}(\omega) \qquad s\in L^{\mathrm{S}},\, p\in P \qquad (16)$$

$$X^{\mathrm{P}}_{puo}(\omega) \le \overline{b}_{puo}(\omega) Y_{uo} \qquad u\in L^{\mathrm{U}},\ o\in O_u,\ p\in P_o \qquad (17)$$

$$\sum_{p\in P} e_p X^{\mathrm{S}}_{pso}(\omega) \le \overline{b}_{so}(\omega) Y_{so} \qquad s\in L^{\mathrm{S}},\ o\in O_s \qquad (18)$$

$$\sum_{u\in L^{\mathrm{U}}} F_{puw}(\omega) = \sum_{o\in O_w} X^{\mathrm{S}}_{pwo}(\omega) \qquad w\in L^{\mathrm{W}},\, p\in P \qquad (19)$$

$$F_{puw}(\omega), F_{psl}(\omega), X^{\mathrm{S}}_{pso}(\omega), X^{\mathrm{P}}_{puo}(\omega) \ge 0 \qquad p\in P, s\in L^{\mathrm{S}}, o\in O_s, l\in L^{\mathrm{D}} \qquad (20)$$

In the first term of objective function (12) the sum of fixed costs related to first stage decisions is calculated and in the second term the expected operational costs related to production, storage and transportation activities are added to get expected total design costs. For design $\mathbf{Y}$, under scenario $\omega$, expression (13) estimates the operational costs by solving the second stage program (14)-(20). In addition to operational costs, the objective function (13) computes emergency shipment costs. The novelty of these constraints, compared to its deterministic counterpart, is that constraints (14) insure demand satisfaction for each scenario using regular flows (open DCs or PDCs) or using the recourse from an external source.

### 3.2 Strategic Production Buffers using Flexible platforms

Production buffers are known as operational hedges against variability in the production orders. Strategic production buffers could be seen as a resiliency strategy that consists in investing in platforms that can offer a larger production activity level when necessary (not necessarily employed on a day to day basis). It is only used as a contingency plan on an internal PDC when a disruption hits the production capacity of the company for one or several product family on other PDCs. This offers an additional recourse, different from the emergency outsourcing (external recourse) employed when using $F^{+}_{.}(\omega)$ variables in the previous design model. The idea behind this strategy is to consider from the strategic level the design of potential flexible layout platforms that could be selected by the model under risk, as opposed to forced layout platform incorporating a redundant capacity. Let $\rho_{uo}$ denote a parameter that takes value 1 if the platform layout enable flexibility at PDC *u* under platform *o*, and, 0 otherwise. When $\rho_{uo}$=1, let $X^{P+}_{puo}(\omega)$ denotes the extra production level of product *p* insured as a local recourse from PDC *u* when platform *o* is selected. The extra capacity available at site *u* when the flexible layout is implemented is denoted by $\overline{b}^{+}_{puo}$ and its utilization incurs an extra unitary cost denoted by $c^{\mathrm{P+}}_{puo}$. Thus, the stochastic PDN model (12)-(20), must be adapted with additional constraints to take into account the local recourse opportunity on each potential flexible platform layout. Constraints (21) provide the bound on extra production available on each site *u* with flexible platform *o* (stated by $\rho_{uo}$) for a given product *p*, which is also linked to the site-platform selection decision. In addition, constraint (15) must be modified to add the quantity of extra production in the flow equilibrium equation as given in (22). Constraints (23) set the nonnegativity restriction. All the other constraints remain similar.

$$X^{P+}_{puo}(\omega) \le \overline{b}^{+}_{puo}\rho_{uo}Y_{uo} \qquad u\in L^{\mathrm{U}},\ o\in O_u,\ p\in P_o,\, \omega\in\Omega \qquad (21)$$

$$\sum_{o\in O_u}\left(X^{\mathrm{P}}_{puo}(\omega) + X^{P+}_{puo}(\omega)\right) = \sum_{l\in L^{\mathrm{D}}_p} F_{pul}(\omega) + \sum_{w\in L^{\mathrm{W}}} F_{puw}(\omega) \qquad u\in L^{\mathrm{U}},\ p\in P,\, \omega\in\Omega \qquad (22)$$

$$X^{P+}_{puo}(\omega) \ge 0 \qquad u\in L^{\mathrm{U}},\ o\in O_u,\ p\in P_o,\, \omega\in\Omega \qquad (23)$$

Also the second stage objective function (13) is replaced by (24) where a new term assessing the cost of the local production recourse incurred (last term).

$$\begin{aligned} C(\mathbf{y},\omega) = \min_{\mathbf{X},\mathbf{F}} & \sum_{u\in L^{\mathrm{U}}}\sum_{o\in O_u}\sum_{p\in P_u} c^{\mathrm{P}}_{puo}X^{P}_{puo}(\omega) + \sum_{s\in L^{\mathrm{S}}}\sum_{o\in O_s}\sum_{p\in P} c^{\mathrm{S}}_{pso}X^{S}_{pso}(\omega) \\ & + \sum_{p\in P}\sum_{u\in L^{\mathrm{U}}}\sum_{w\in L^{\mathrm{W}}} c_{puw}F_{puw}(\omega) + \sum_{p\in P}\sum_{s\in L^{S}}\sum_{l\in L^{\mathrm{D}}_p} c_{psl}F_{psl}(\omega) \\ & + \sum_{p\in P}\sum_{l\in L^{\mathrm{D}}_p} \delta_{pl}F^{+}_{pl}(\omega) + \sum_{u\in L^{\mathrm{U}}}\sum_{o\in O_u}\sum_{p\in P_u} c^{\mathrm{P+}}_{puo}X^{P+}_{puo}(\omega) \end{aligned} \qquad (24)$$

## 4 Illustrative Case and Future Work

This section presents the experiments made on an illustrative case to compare the design solutions produced by the models proposed in the previous sections and it analyses the results obtained. First, the case considered involves 2 potential PDCs, 6 potential DCs and 48 demand zones, scattered realistically over North-East and Midwest regions in the USA, such as the distances between the network nodes are based on existing road networks. A one year planning horizon is used. For each demand zone, two products are requested with an annual demand level ranging between 3K and 19K unit each. For each PDC site, two dedicated platforms (one per product) and two integrated platforms for both products are proposed which offer various sizes in terms of production as well as distribution capacity. The production capacities are defined per product unit in the interval [193K, 329K] and the distribution capacity of PDCs is fixed to 50K unit per year. These latter are proposed with opening costs ranging between in [922K, 1300K]. Similarly for each potential DC, three platform sizes (ranging in [93K, 143K]) are proposed with opening costs ranging between [16K, 20K]. For each site, the closing cost is fixed to 25% of the opening cost and the operating cost is estimated annually to 10% of the opening cost. Moreover, the unitary production cost is selected in [19, 20] for each PDC and the unitary inventory holding cost is selected in [11.5, 12.5]. Also the transportation costs are correlated to the distance travelled and are ranging in [0.5, 11.5] per flow unit. The value of all products shipped in emergency from the external supplier is ranging in [0.3, 11.5] per unit and per demand zone, and the extra production recourse cost is considered 2 times the regular production costs for all the PDCs. The additional production capacity, available for local recourse, is fixed to 5 % of the regular capacity level. Finally the demand level is generated randomly in the range of [3K, 15K] to reflect small and large sized zones. The capacity level under disruptions is following the same procedure as Klibi and Martel (2012b) and reflects an average yearly decrease of the capacity of about 10%. Finally, a sample of 100 scenarios is generated for each stochastic model and used in the optimization. The experiments reported in this section were performed on a 64 bits computer with a 2.4 GHz Intel XEON processor and 8 Go of RAM. All the models were generated with OPL Studio 6.5 and solved with CPLEX-12.6 and the Monte-Carlo procedure were programmed in R software (R-3.2.2).

Given the illustrative case described previously, the quality of the designs obtained by the PDN design models proposed is discussed here. The solutions of three models are discussed hereafter: *DS* produced by the deterministic model (1)-(11); *MSS* produced by the stochastic model (12)-(20); and *PBS* produced by the stochastic model incorporating production buffers at PDCs. **Table 1** provides, for each design, DC opening and configuration decisions, the number of opened PDCs and DCs and their configuration, and the partition of the costs incurred. In this table P1 (P2) denotes production platform dedicated to product 1 (2), and P3 and P4 denote integrated platforms where the latter has an increased size. Similarly D1, D2 and D3 denote distribution platforms of small, moderate and large size, respectively. First our results show that the stochastic and deterministic formulations do not produce the same design, which is to be expected because the latter doesn't capture the risk of disruptions. The difference comes from the PDC and DC platforms to open, and the assignment of demand zones to these sites. Although in most cases, the location decisions are similar the platforms selected are quite different in terms of activities for the PDCs and in terms of size for the DCs, which underlines the importance of modeling the platforms options in the sites at the strategic level. For instance *DS* requires the opening of the two PDCs with platforms P1 and P2 (dedicated) and the six DCs with platforms D1 or D2 (Low or moderate capacity platforms). On the other hand, although *MSS* proposes the same locations, it suggests different configurations with more capacity buffers. As can be seen from Table 1, *MSS* suggests opening two PDCs with platforms P4 and P3 (two integrated platforms for both products offering significant production and distribution capacity) and the six DCs with platforms D1, D2 and D3. The total PDN cost of DS for the year considered is \$22,092,280 whereas the total costs of MSS come to \$22,915,720 which corresponds to the investment in resiliency. In this case, the external recourse costs are about 0.5 % of the total expected design costs.

Next, one could inspect the design solution obtained by the alternative flexibility seeking model. The *PBS* uses the same locations as *MSS* but the PDC platforms to open differ due to the usage of production buffers. It suggests opening two PDCs with P3 configuration. The total PDN design costs of the *PBS* strategy is \$22,788,201, which is lower than *MSS* one. In fact, the strategic production-based buffers performs extremely well since it gives the best design in terms of total costs comparing to the *MSS*. The difference in expected design costs is about 0.55%. This is explained by the use of production buffers and the use of less external recourses.

**Table 1.** Design solutions produced for the illustrative case

| | *DS* | *MSS* | *PBS* |
|---|---|---|---|
| Fixed Costs | 2 189 700 | 2 903 600 | 2 842 900 |
| Number of opened PDCs | 2 | 2 | 2 |
| Number of opened DCs | 6 | 6 | 6 |
| Inventory holding Costs | 7 160 700 | 7 194 300 | 7 190 700 |
| Transportation Costs | 1 220 900 | 957 400 | 928 820 |
| Extra shipment Costs | | 111 720 | 91 174 |
| Extra production Costs | | | 74 107 |
| **Sites** | | **Platform Decisions** | |
| 1 AKRON | P1 | P4 | P3 |
| 2 AMSTERDAM | P2 | P3 | P3 |
| 3 BEECH GROVE | D1 | D1 | D1 |
| 4 BELLEVUE | D1 | D2 | D2 |
| 5 BRIDGEPORT | D2 | D2 | D2 |
| 6 CAPITOL HEIGHTS | D2 | D1 | D1 |
| 7 DECATUR | D1 | D1 | D1 |
| 8 EAST ELMHURST | D1 | D3 | D3 |

In conclusion, this paper studied a PDN design modeling approach under uncertainty which considers flexibility strategies and platforms characterization. The models formulated are based on alternative flexibility seeking strategies at the production and distribution levels. Our preliminary results are based on an illustrative case that show that the inclusion of the platforms selection in the design model is a critical issue. It provided significant differences in terms of activities in the sites, of size, and of assignment of demand zones to sites. As future work, more extensive experiments will be developed to compare the design solutions produced and derive managerial insights on their efficiency and their resiliency. Other modeling approaches to get resilient PDNs could be investigated.

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