Optimal Design of Low-Cost Supply Chain Networks on the Benefits of New Product Formulations

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Abstract

Formulated products usually comprise a high amount of low-cost ingredients, e.g., water, which could be removed by concentration, and the resulting concentrated products could generate economic advantages, especially in long-distance transportation. This work examines the economic benefits of new product formulations resulted from a new process and product design technology through the optimal design of low-cost formulated product supply chain networks for different product formulations, including traditional formulations and new formulations via concentration. Based on mixed-integer linear programming techniques, an optimisation-based framework is proposed to determine the optimal locations and capacities of plants, warehouses, and distribution centres, as well as the production and distribution planning decisions, by minimising the unit total cost, including raw material, packaging, conversion, inventory, transportation and depreciation costs. In order to deal with the computational complexity, a tailored hierarchical solution approach is developed, in which facility locations and connections are determined by an aggregated static model, and a reduced dynamic model is then solved to determine the facility capacities and the production amounts, distribution flows, and inventory levels in each time period. A case study of a fast-moving consumer goods supply chain is investigated to demonstrate the economic benefits of new product formulations by implementing and comparing different production and distribution structures. The computational results from scenario and sensitivity analysis show that the manufacturing of final products, using a simple concept based on intermediate concentrated

formulations produced at a centralised location, results in large supply chain benefits of an economic nature.

Keywords: supply chain network design; new product formulation; concentrated formulation; mixed-integer linear programming; hierarchical approach; fast-moving consumer goods

1. Introduction

With the progress of manufacturing, process, and product technology, more new product formulations are developed for formulated products, i.e., concentrated formulations by removing a large number of low-cost ingredients, which benefit production process in terms of cost and environment, etc. Moreover, new product formulations also require the transformation and improvement of supply chain networks to achieve more advantages from a wider perspective. The success of a supply chain network is greatly dependent on how its production and distribution configurations are designed, including the locations of plants, warehouses, and distribution centres (DCs), and the connections between them, which determines 80% of the supply chain cost (Watson et al., 2012). Strategic supply chain network design is regarded as one of the most important stages, which has significant effects on all the future strategies at tactical and operational levels (Farahani et al., 2014). This work, inspired by a real East Asian case study in the fast-moving consumer goods industry, aims to study the optimal design of low-cost supply chain networks using an optimisation-based framework, in order to gain insights into the economic benefits of a new process and product design technology and new product formulations from supply chain perspective.

In the literature, the supply chain network design problem has attracted lots of attention from both academic and practitioner communities. A large number of models and methodologies to design supply chain networks have been developed and applied in the past decades, as reviewed in several literature works (Vidal and Goetschalckx, 1997; Beamon, 1998; Meixell and Gargeya, 2005; Papageorgiou, 2009; Klibi et al., 2010; Farahani et al., 2014; Eskandarpour et al., 2015; Ivanov et al., 2015; Gan and Grunow, 2016). In particular, mathematical programming-based models and approaches, especially using mixed-integer programming (MIP) techniques, have been widely utilised for the design and planning of the supply chain networks. Table 1 presents a number of mixed-integer (non)linear programming (MI(N)LP) models in the literature on the design of optimal supply chain networks. It can be found that the MIP models have been applied to the optimisation of global or regional supply chain network design problems in different industries, such as computer and electronic product (Arntzen et al., 1995; Yan et al., 2003; Mota et al., 2018), chemicals and pharmaceuticals (Papageorgiou et al., 2001; Tsiakis and Papageorgiou, 2008; Zahiri et al., 2018), biomass and biofuel (Ekşioğlu et al., 2009; Akgul et al., 2012; Sharifzadeh et al., 2015), natural gas (Calderón et al., 2017), manufacturing (Tsiakis et al., 2001; Georgiadis et al., 2011), and consumer goods (Aaron et al., 2008; Longinidis and Georgiadis, 2014; Allaoui et al., 2018). To obtain the optimal number, locations, and capacities of production and storage facilities in the supply chain networks of specific products in specific regions, a number of different supply chain characteristics have been considered in the literature supply chain network design optimisation models. For example, Artzen et al. (1995) addressed the design of a global supply chain network considering duty avoidance. Yan et al. (2003) considered bills of materials in logical constraints of the proposed strategic production–distribution model for supply chain design. Tsiakis and Papageorgiou (2008) addressed several financial issues, including import duties, plant utilisation, exchange rates, etc. Azaron et al. (2008) modelled uncertainty of demands, supplies, processing, transportation, shortage and capacity expansion costs, in the proposed multi-objective optimisation model. Liu and Papageorgiou (2013) considered three supply chain performance metrics, including cost, responsiveness, and custom service level, to find the optimal strategic capacity expansion decisions. Longinidis and Georgiadis (2014) considered the sale and leaseback method in the optimisation of the supply chain networks design. Allaoui et al. (2018) considered sustainable agro-food supply chain network design considering economic, environmental and social criteria. According to the above literature review, no literature optimisation model has addressed new product formulations and their advantages through designing the optimal supply chain networks at the strategic level, which is a key novel contribution of this work.

Table 1. Literature MIP models on supply chain design optimisation

Literature work	Model type	Problem characteristics	Application industry	Country/ region
Akgul et al. (2012)	MILP	Multiobjective optimisation; hybrid biofuel production	Bioethanol	UK
Allaoui et al. (2018)	MILP	Multiobjective optimisation; sustainable supply chain	Agro-food	n/a
Arntzen et al. (1995)	MILP	Global supply chain; duty drawback; duty avoidance	Computer	Worldwide
Azaron et al. (2008)	MINLP	Multiobjective optimisation; uncertain demands, supplies, and costs	Wine	n/a
Calderón et al. (2017)	MILP	Nationwide production of synthetic natural gas; government incentives	Natural gas	UK

Ekşioğlu et al. (2009)	MILP	Deterioration, supply seasonality, and supply availability of biomass	Bioenergy	Mississippi, USA
Georgiadis et al. (2011)	MILP	Uncertain transient demand variations	Manufacturing	Europe
Guillén et al. (2005)	MILP	Multiobjective optimisation; uncertain demand; financial risk	General	Europe
Liu and Papageorgiou (2013)	MILP	Global supply chain; multiobjective optimisation; responsiveness; capacity expansion	Agrochemicals	Worldwide
Longinidis and Georgiadis (2014)	MILP/ MINLP	Sale and leaseback; uncertain demand, asset's fair value lessee's incremental borrowing rate, and interest rate implicit in the lease	Consumer goods	Europe
Mota et al. (2018)	MILP	Multiobjective optimisation; Closed-loop supply chain	Electronic components	Europe; South America
Salema et al. (2010)	MILP	Closed-loop supply chain; uncertain demand	Glass	Portugal
Sharifzadeh et al. (2015)	MILP	Uncertain demands and biomass availability; fast pyrolysis of biomass	Biofuel	UK
Tsiakis and Papageorgiou (2008)	MILP	Production balancing amongst sites; exchange rates; duties	Chemicals	Worldwide
Tsiakis et al. (2001)	MILP	Uncertain demand; economies of scale in transportation	Manufacturing	Europe
Yan et al. (2003)	MILP	bills of materials; supplier selection	Computer	Southeast Asia
Zahiri et al. (2018)	MILP	Multiobjective optimisation; uncertain costs and demand	Pharmaceuticals	n/a

The above reviewed MIP models were solved using exact methods, e.g., the classic Branch & Bound algorithm. It requires high computational effort to solve real-world large-scale problems, and therefore various classic techniques have been used to develop efficient solution approaches and methods for the optimisation of supply chain network design problems in the literature, as shown in Table 2, including genetic algorithm (Syarif et al., 2002; Truong and Azadivar, 2005), simulated annealing (Javid and Azad, 2010; Fattahi et al., 2015; Kaya and Urek, 2016), decomposition (Santoso et al., 2005; You and Grossmann, 2008; Baptista et al., 2019), Lagrangean relaxation (Amiri, 2006; Lashine et al., 2006), etc. In particular, a number of works implement hierarchical and sequential approaches for the solutions of large-scale optimisation problems. For example, Sousa et al. (2008) conducted an optimisation-based two-stage approach that integrated pharmaceutical supply chain network design, medium-term planning and tactical scheduling decisions. Costantino et al. (2013) developed a hierarchical procedure, integrating direct graph modelling, MILP, and analytic hierarchy process techniques, for the optimal healthcare supply chain distribution network configuration. Moreno-Benito et al. (2017) developed a hierarchical solution procedure for computationally changeling problems in the hydrogen supply chain infrastructure development. Liu and Papageorgiou (2018) presented an efficient hierarchical solution approach for production, distribution and capacity planning of agrochemical supply chain networks to obtain a fair profit distribution. In this work, a tailored hierarchical solution approach will be developed for the proposed optimisation model for designing supply chain networks with new product formulations.

Table 2. Literature solution approaches and techniques for supply chain network design optimisation problems

Literature work	Model type	Solution approach and technique
Amini and Li (2011)	MINLP	Outer approximation
Amiri (2006)	MILP	Lagrangean relaxation
Baptista et al. (2019)	MILP	Decomposition
Costantino et al. (2013)	MILP	Hierarchical/sequential approach
Devika et al. (2014)	MILP	Imperialist competitive algorithm; variable neighbourhood search
Fattahi et al. (2015)	MILP	Simulating annealing; linear relaxation
Javid and Azad (2010)	MINLP/mixed-integer convex programming	Tabu search; simulated annealing
Kaya and Urek (2016)	MINLP	Piecewise linearisation; simulated annealing; genetic algorithm
Liu and Papageorgiou (2018)	MILP	Hierarchical/sequential approach
Lashine et al. (2006)	MILP	Lagrange relaxation; sub-gradient search
Moreno-Benito et al. (2017)	MILP	Hierarchical/sequential approach
Santoso et al. (2005)	MILP	Sample average approximation; Benders decomposition
Sousa et al. (2008)	MILP	Hierarchical/sequential approach
Syarif et al. (2002)	MILP	Genetic algorithm
Truong and Azadivar (2005)	MILP	Genetic algorithm; simulation
You and Grossmann (2008)	MINLP	Lagrangean relaxation; decomposition

As discussed earlier, there exists a gap in the literature on the optimal design of supply chain networks considering new product formulations and the evaluation of their economic benefits at the supply chain level. We aim to fill this gap to study, quantify, and analyse the benefits of new product formulations from supply chain perspectives by developing novel MIP-based models and solution approach for the optimal design of low-cost supply chain networks, inspired by a real-world case study.

In this work, we consider the optimal supply chain design and performance for different product formulations and investigate a real case study in East Asia for a low-cost supply chain network in the fast-moving consumer goods industry with the availability of a new process and product technology. Optimisation-based decision-making models and an efficient hierarchical solution approach are developed in the framework for the optimal locations of plants, warehouses, and DCs, as well as the operational production and distribution planning decisions, in order to minimise the unit total cost. Three different production and distribution structures will be considered and compared, one of which involves a new process technology and new product formulations involving concentrated intermediate products. The main novel contributions of this work to the existing literature are as follows:

- New product formulations based on new process and product technology and their economic benefits at the supply chain level are studied from the perspective of the optimal design of supply chain networks;
- A novel optimisation-based decision framework, which is flexible to describe the production and distribution configurations for different product formulations, is developed for the integrated strategic design and operational production and distribution planning of supply chain networks;
- A tailored computationally efficient hierarchical solution approach is proposed, incorporating an aggregated static model for the strategic decisions, and a dynamic model for the operational decisions;
- Different production and distribution structures in supply chains based on both traditional and new product formulations are studied and their economic performance is analysed;
- A real-world case study of a supply chain network in the fast-moving consumer goods industry is investigated to provide insights into the benefits of new product formulations.

The remainder of this paper is organised as follows: Section 2 provides the problem statement. The mathematical formulation of the developed MILP optimisation model is described in Section 3, followed by the introduction of an efficient hierarchical solution approach for large instances in Section 4. In Section 5, an industrial case study in East Asia is provided, and the computational results are presented as discussed in Section 6. Finally, the concluding remarks, including the limitations and recommendations for future research, are given in Section 7.

2. Problem description and assumptions

In this work, we consider a regional supply chain network of fast-moving consumer goods, involving three types of facilities: plant, warehouse, and DC. A number of cities with local city DCs in the region are considered as markets in the supply chain.

2.1 Product formulations

For each product in the supply chain network, two types of product formulations are considered in this work:

- Traditional product formulations: final products are directly produced from raw materials;
- New product formulations: with the introduction of a new process and product technology, some low-cost materials are removed by concentration first to create intermediate concentrated products, and then final products are produced from them.

Currently, the existing conventional plants are able to produce final products using traditional product formulations. Based on new process technology, intermediate concentrated products can also be formulated in the conventional plants from raw materials, and are converted to final products in the potential finishing plants to be built in the new region of interest.

2.2 Production and distribution structures

The regional supply chain network is to be established based on one of three potential production and distribution structures depending on the aforementioned product formulations, denoted as Traditional Route, Local Route and Concentrated Route. The three routes (as illustrated in Figure 1) are described as follows:

- Traditional Route: final products are directly produced from raw materials at existing conventional plants outside the region, and then shipped to the DCs at local city markets for sales, with or without temporary storage at warehouses in the region.

- Local Route: final products are only produced from raw materials directly at potential conventional plants within the region, and then shipped to DCs (via warehouses or directly) for sales.
- Concentrated Route: intermediate concentrated products are produced at existing conventional plants firstly, and then shipped to potential regional finishing plants to be converted to final products. Finally, final products are transported to warehouses and/or DCs for sales.

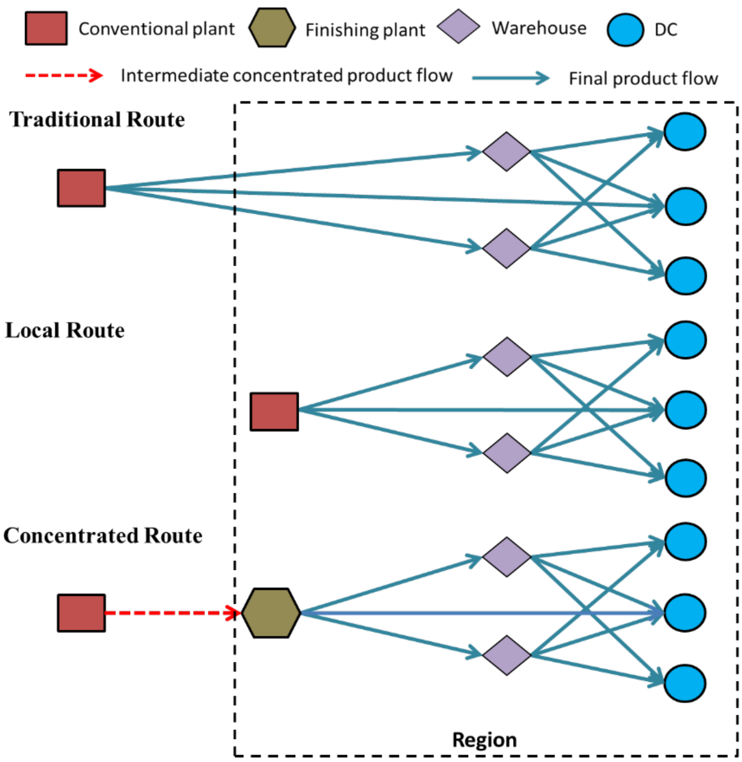

Figure 1. Illustrations of the three production and distribution structures in the regional supply chain network

In this problem, the product demands in the considered region are relatively smaller, in comparison with other regions covered by existing conventional plants. It is assumed that the existing plants can always produce sufficient intermediate concentrated and/or final products for the considered region in the Traditional Route and Concentrated Route. Note that in all the three routes, final products produced at a plant can be shipped to a DC directly if the distance between them is relatively small. Otherwise, products should be shipped to warehouses for temporary storage before shipment to DCs.

In this supply chain network design problem, all the cities in the considered region are the candidate locations of plants, warehouses and DCs. For each type of facility, at most one instance can be built in each city. The locations of any newly built plants in the region are to be determined in the Local Route (for conventional plants) and Concentrated Route (for finishing plants), and the locations of warehouses and DCs are to be optimised in all three routes. Also, there are predetermined limits on the number of each facility type in the supply chain network.

The final products are categorised into a number of product types. There are a number of candidate production capacity sizes for each plant, determined by the available formulation lines of each product type. The production time of each product type is determined by the selected capacity size and the production amount. The inventory capacity of a plant is assumed to be proportional to its production capacity. For warehouses and DCs, there are also a set of candidate inventory capacity sizes.

In the Concentrated Route, intermediate concentrated products can be stored at both conventional and finishing plants, while final products can be kept at all facilities. The inventory of each intermediate concentrated or final product should be no less than its safety stock at each facility in each time period. Also, for the security of supply, it is assumed that the initial inventory is the same as the ending inventory at the end of the planning horizon for both intermediate concentrated and final products. In addition, the shelf life is considered for each intermediate concentrated and final product. When the shelf life is reached, all remaining unsold products are wasted with cost incurred.

2.3 More assumptions

Besides the assumptions described above, the following assumptions are also considered in this problem:

- The whole planning horizon is divided into a number of time periods with equal lengths;
- Each city in the region can host at most one facility of each type;
- Material loss during the production of intermediate concentrated products and final products are not considered in all production routes;
- The production rate and setup time of each product are constant, regardless of where and when the production takes place;
- If a product is produced in a time period, it is only processed once per time period to minimise the setup time;

- Safety stock at each facility is known and determined by the demands at cities where it is located;
- All demands in the region are satisfied, with no lost sales allowed;
- Lead times between two facilities, expressed in number of time periods, are considered, which are not longer than the shelf lives of any product;
- All facilities are depreciated at a constant rate.

Overall, this supply chain network design and planning problem is summarised in Figure 2:

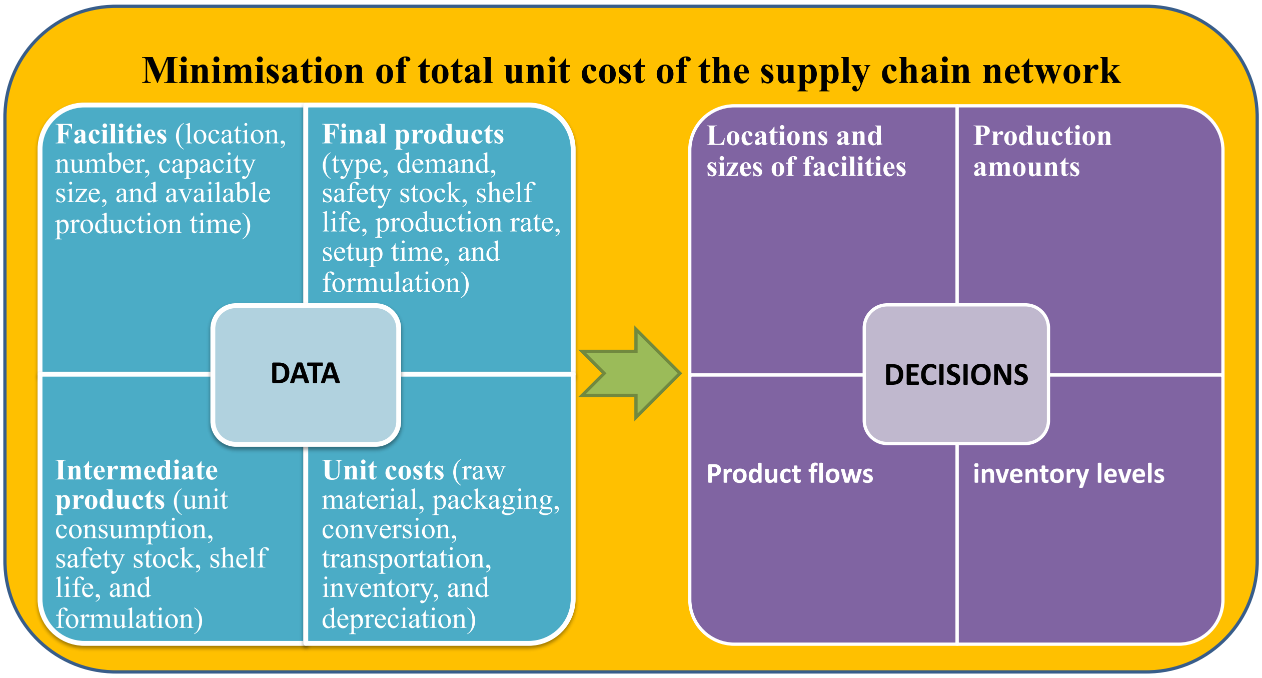

Figure 2. Illustration of problem statement

3. Mathematical formulation

In this section, the mathematical formulation of the proposed MILP model is presented. The proposed model determines the optimal locations and sizes of the plants, warehouses, and DCs, as well as the production, distribution and inventory planning by minimising the unit total cost. In the model below, the 'node' concept is adopted, where each node represents the potential location of one facility. Thus, each city is divided into three separate nodes to locate a plant, a warehouse and a DC, respectively. The demands and sales only occur in the DC nodes. The notation used in the mathematical formulation is as follows:

Notation

Indices

c	intermediate concentrated product
i, i'	node, facility location
j	product type
p	final product
r	raw material
t, t'	time period

Sets

C	set of intermediate concentrated products
I^{EP}	set of nodes for existing conventional plant locations
I^{DC}	set of nodes for new DC locations
I^{P}	set of nodes for new plant locations
I^{W}	set of nodes for new warehouse locations
$Link$	set of allowed links of flows
P_j	set of products of type j
S_i	set of available capacity sizes at node i
SC_r	set of intermediated concentrated products consuming raw material r when converted from raw materials
SPC_r	set of final products consuming raw material r when converted from intermediated concentrated products
SPR_r	set of final products consuming raw material r when converted from raw materials

Parameters

A_{ijst}	available production time for products of type j in a plant of size s at node i in time period t
$ACTC$	average unit transportation cost of intermediate concentrated products
$AFTC$	average unit transportation cost of final products
$Depr$	depreciation rate of facility
$CapI_{si}$	inventory capacity of size s of facility at node i
CCC_{ci}	unit conversion cost of intermediate concentrated product c at node i
$CCOG_c$	unit cost of goods of intermediate concentrated product c
CIC_{ci}	unit inventory holding cost of intermediate concentrated product c at node i

$CPCC_{pi}$ unit conversion cost of final product p from intermediate concentrated products at node i

CSL_{ci} shelf life of intermediate concentrated product c at node i

CTC_c unit transportation cost of intermediate concentrated product c

D_{pit} demand of final product p at node i in time period t

$Dis_{ii'}$ transportation distance from node i to i'

$FCOG_p$ unit cost of goods of final product p

FIC_{pi} unit inventory holding cost of final product p at node i

$FP_{pi}^{min}/FP_{pi}^{max}$ minimum and maximum production limits of final product p at node i

FSL_{pi} shelf life of final product p at node i

FTC_p unit transportation cost of final product p

FV_{si} value of the facility at node i

LN_{sj} number of formulation lines of product type j

NDC^{min}/NDC^{max} minimum and maximum number of DCs

NP^{min}/NP^{max} minimum and maximum number of plants

NW^{min}/NW^{max} minimum and maximum number of warehouses

OE overall effectiveness of plants

Int interest rate per time period

PPC_{pi} unit cost of packaging for final product p at node i

RPC_{ri} unit cost of raw material r at node i

$RPCC_{pi}$ unit conversion cost of final product p from raw materials at node i

SS_{pit} safe stock of final product p at node i in time period t

$TCap_{si}$ annual production capacity of size s of plant at node i

TD_i annual product demand of all final products at node i

WC number of time periods covered by safety stock

αACP average unit consumption of an intermediate concentrated product for production of a final product

αCP_{cp} unit consumption of intermediate concentrated product c for production of final product p

αRC_{rc} unit consumption of raw material r for production of intermediate concentrated product c

αRCP_{rp} unit consumption of raw material *r* for production of final product *p* from intermediate concentrated products

αRP_{rp} unit consumption of raw material *r* for production of final product *p* from raw materials

β_{pj} utilisation ratio of final product *p* of type *j*

$\theta_{ii'}$ lead time between node *i* and *i'*

τ_{pj} setup time of final product *p* of type *j*

Continuous Variables

CC conversion cost

CI_{cit} inventory of intermediate concentrated product *c* at node *i* in time period *t*

CP_{cit} production of intermediate concentrated product *c* at node *i* in time period *t*

$CPCC$ conversion cost of intermediate concentrated products

$CQ_{cii't}$ flow of intermediate concentrated product *c* from node *i* to *i'* in time period *t*

CW_{cit} wasted amount of intermediate concentrated product *c* at node *i* in time period *t*

FDC depreciation cost of facility

FI_{pit} inventory of final product *p* at node *i* in time period *t*

FP_{pit} production of final product *p* at node *i* in time period *t*

FPC_{pit} production of final product *p* from intermediate concentrated products at node *i* in time period *t*

$FPCC$ conversion cost of final products

FPR_{pit} production of final product *p* from raw materials at node *i* in time period *t*

$FQ_{pii't}$ flow of final product *p* from node *i* to *i'* in time period *t*

FW_{pit} wasted amount of final product *p* at node *i* in time period *t*

IC inventory cost

IHC inventory holding cost

PKC packaging cost

R_{rit} consumption of raw material *r* at node *i* in time period *t*

RMC raw material cost

S_{pit} sales of final product *p* at node *i* in time period *t*

TC transportation cost

TCP_i total final product production at node *i*

$TCQ_{pii'}$	total intermediate concentrated product flow from node *i* to *i'*
TFP_i	total final product production at node *i*
$TFQ_{pii'}$	total final product flow from node *i* to *i'*
WCC	working capital cost

Binary Variables

E_i	1 if node *i* is selected for plant; 0 otherwise
W_{si}	1 if capacity size *s* is selected for facility at node *i*; 0 otherwise
X_{pit}	1 if final product p is produced at node *i* in time period *t*; 0 otherwise
Y_i	1 if node *i* is selected for warehouse; 0 otherwise
Z_i	1 if node *i* is selected for DC; 0 otherwise

3.1 Production constraints

The total production time of each product type j in time period *t* in a plant at node *i*, equalling to the sum of utilisation ratio (β_{pj}) multiplied by production amount (FP_{pit}) of all products p in type *j*, is limited by the total available production time in that time period (A_{ijst}) at the selected capacity size, minus the setup time (τ_{pj}) of all produced products:

$$\sum_{p\in P_j} \beta_{pj} \cdot FP_{pit} \leq OE \cdot \sum_{s\in S_i} A_{ijst} \cdot W_{si} - \sum_{p\in P_j} \tau_{pj} \cdot X_{pit}\,, \quad \forall i \in I^P, j \in J_i, t \qquad (1)$$

where *OE* represents the overall effectiveness of the plants; X_{pit} and W_{si} are binary variables to indicate the production allocations of products to plants and time periods, and the selection of plant capacity sizes.

If final product p is produced in a plant at node i, its production amount (FP_{pit}) in time period *t* is limited by lower (FP_{pi}^{min}) and upper bounds (FP_{pi}^{max}); otherwise, there is no production.

$$FP_{pi}^{min} \cdot X_{pit} \leq FP_{pit} \leq FP_{pi}^{max} \cdot X_{pit}, \quad \forall i \in I^P, p \in P_j, t \qquad (2)$$

In any plant in the region, final products can be converted from intermediate concentrated products, or directly from raw materials. Thus, the production amounts of final products are the sum of conversion from intermediate concentrated products (FPC_{pit}) and from raw materials (FPR_{pit}).

$$FP_{pit} = FPC_{pit} + FPR_{pit}, \quad \forall p, i \in I^P, t \qquad (3)$$

If a plant is not built at node i in the region, i.e., binary variable $E_i = 0$, then there is no product assigned for production in any time period, i.e., binary variable $X_{pit} = 0$.

$$X_{pit} \leq E_i, \quad \forall i \in I^P, p \in P_j, t \tag{4}$$

At an existing conventional plant, the production of final products in the Traditional Route for the considered region is only from raw materials.

$$FP_{pit} = FPR_{pit}, \quad \forall p, i \in I^{EP}, t \tag{5}$$

3.2 Raw material constraints

The consumption of raw material *r* at each plant at node *i* (R_{rit}) is the sum of its consumed amounts for the production of all intermediate concentrated and final products. The three terms on the right-hand side of the following equation refers to the raw material consumption for final product production from raw materials (FPR_{pit}), for final product production from intermediate concentrated products (FPC_{pit}), and for production of intermediate concentrated products (CP_{cit}), respectively.

$$R_{rit} = \sum_{p \in SPR_r} \alpha RP_{rp} \cdot FPR_{pit} + \sum_{p \in SPC_r} \alpha RCP_{rp} \cdot FPC_{pit}\Big|_{i \in I^{FP}} + \sum_{c \in C \cap SC_r} \alpha RC_{rc} \cdot CP_{cit}\Big|_{i \in I^{CP}}, \quad \forall r, i \in I^{EP} \cup I^P, t \tag{6}$$

where αRP_{rp}, αRCP_{rp} and αRC_{rc} are the corresponding unit consumption rates.

3.3 Final product inventory constraints

The inventory of final product *p* at node *i* in time period *t* (FI_{pit}) is equal to its inventory in the previous time period *t*-1, plus production amounts at a plant node (FP_{pit}) and all incoming flows ($FQ_{pi'it}$), minus the sales at a DC node (S_{pit}), all outgoing flows ($FQ_{pii't}$), and wasted amount (FW_{pit}).

$$FI_{pit} = FI_{piT}\Big|_{t=1} + FI_{pi,t-1}\Big|_{t>1} + FP_{pit}\Big|_{i \in I^{EP} \cup I^P} - S_{pit}\Big|_{i \in I^{DC}} + \sum_{i':(i',i) \in Link} FQ_{pi'i,t-\theta_{i'i}} - \sum_{i':(i,i') \in Link} FQ_{pii't} - FW_{pit}, \quad \forall p, i, t \tag{7}$$

Note that the inventory at the end of the planning horizon is taken as the initial inventory. Also, the inventory considered at the existing conventional plants is stored for the considered region only.

The final product inventory should be greater than or equal to the safety stock at a node i, if it is chosen to build a facility ($E_i = 1$ at a plant node, $Y_i = 1$ at a warehouse node, and $Z_i = 1$ at a DC node), as below:

$$FI_{pit} \geq SS_{pit} \cdot (E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}} + 1|_{i\in I^{EP}}), \quad \forall p, i, t \tag{8}$$

where safety stock SS_{pit} is determined by demands in the following *wc* time periods, i.e., $SS_{pit} = \sum_{t'=t+1}^{t+WC} D_{pit'}$.

It is assumed that any product stored longer than its shelf life is wasted. To simplify the problem, we consider the shelf life of each final product at each stage (FSL_{pi}). Thus, the inventory of product p at each node i cannot exceed the total sales at a DC node (S_{pit}), and outgoing amount shipped in the following FSL_{pi} time periods.

$$FI_{pit} \leq \sum_{t'=t+1}^{t+FSL_{pi}} \sum_p \left(S_{pit'}\big|_{i\in I^{DC}} + \sum_{i':(i,i')\in Link} FQ_{pii't'} \right), \quad \forall p, i, t < T - SL_{pi} \tag{9}$$

3.4 Concentrated product inventory constraints

Similarly, the inventory of concentrated product c at plant node i in time period t (CI_{cit}) is equal to its inventory in the previous time period, plus its production amounts (CP_{cit}) and incoming flows ($CQ_{ci'it}$), minus the consumption for final product production at plants (with a unit consumption rate of αCP_{cp}), the outgoing flows and wasted amounts (CW_{cit}). Similar to final products inventory, the initial inventory of intermediate concentrated products is equal to the ending inventory.

$$CI_{cit} = CI_{ciT}|_{t=1} + CI_{ci,t-1}\big|_{t>1} + CP_{cit} - \sum_p \alpha CP_{cp} \cdot FPC_{pit}\big|_{i\in I^P} + \sum_{i'\in I^{EP}:(i',i)\in Link} CQ_{ci'i,t-\theta_{i'i}} - \sum_{i'\in I^P:(i,i')\in Link} CQ_{cii't} - CW_{cit}, \quad \forall c \in C, i \in I^{EP} \cup I^P, t \tag{10}$$

Also, any intermediate concentrated product stored longer than its shelf life (CSL_{ci}) is wasted.

$$CI_{cit} \leq \sum_{t'=t+1}^{t+CSL_{ci}} \left(\sum_p \alpha CP_{cp} \cdot FPC_{pit'}\big|_{i\in I^P} + \sum_{i'\in I^{EP}\cup I^P:(i,i')\in Link} CQ_{cii't'} \right), \quad \forall c \in C, i \in I^{EP} \cup I^P, t < T - CSL_{ci} \tag{11}$$

3.5 Sales constraints

The sales at a local DC should meet the demand (D_{pit}) there.

$$S_{pit} = D_{pit}, \quad \forall p, i \in I^{DC}, t \tag{12}$$

3.6 Capacity constraints

For each facility in the considered region, there are a number of candidate capacity sizes for selection. The capacity sizes affect the available inventory capacities of the facilities, as well as the production capacities of plants. Only one capacity size can be selected for each facility, if located at node *i*:

$$E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}} = \sum_{s\in S_i} W_{si}, \quad \forall i \notin I^{EP} \tag{13}$$

where binary variable W_{si} indicates whether or not size s is selected. Note that for each new facility location node i, only one term at the left-hand side of the above equation can be activated.

The total inventory of both intermediate concentrated and final products at each node is limited by the selected inventory capacity ($CapI_{si}$):

$$\sum_p FI_{pit} + \sum_{c\in C} CI_{cit} \le \sum_{s\in S_i} CapI_{si} \cdot W_{si}, \quad \forall i \notin I^{EP}, t \tag{14}$$

3.7 Facility number constraints

The total number of each type of facility in the region is restricted by given upper and lower bounds, respectively. Thus, we have the following constraints for the number of plants, warehouses and DCs:

$$NP^{min} \le \sum_{i\in I^P} E_i \le NP^{max} \tag{15}$$

$$NW^{min} \le \sum_{i\in I^W} Y_i \le NW^{max} \tag{16}$$

$$NDC^{min} \le \sum_{i\in I^{DC}} Z_i \le NDC^{max} \tag{17}$$

Note that if both bounds are the same, then the facility number is fixed.

3.8 Logical constraints

If a node is not selected for any facility, then there is no incoming/outgoing flow of any product to/from that node:

$$\sum_p \sum_{i':(i',i)\in Link} \sum_t FQ_{pi'it} \le M \cdot (E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}}), \quad \forall i \notin I^{EP} \tag{18}$$

$$\sum_p \sum_{i':(i,i')\in Link} \sum_t FQ_{pii't} \le M \cdot (E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}}), \quad \forall i \notin I^{EP} \tag{19}$$

$$\sum_{c\in C} \sum_{i'\in I^{EP}:(i',i)\in Link} \sum_t CQ_{ci'it} \le M \cdot E_i|_{i\in I^P}, \quad \forall i \in I^P \tag{20}$$

3.9 Cost constraints

The total cost includes raw material cost, packaging cost, conversion cost, inventory cost, transportation cost, and depreciation cost.

The raw material cost (RMC) is equal to unit raw material cost (RPC_{ri}) multiplied by raw material consumptions at plants.

$$RMC = \sum_r \sum_{i \in I^{EP} \cup I^P} \sum_t RPC_{ri} \cdot R_{rit} \quad (21)$$

The packaging cost (PKC) is proportional to the production amount of final products, with corresponding cost rates of PPC_{pi}.

$$PKC = \sum_p \sum_{i \in I^{EP} \cup I^P} \sum_t PPC_{pi} \cdot FP_{pit} \quad (22)$$

The conversion cost (CC) includes the costs for conversion of final products ($FPCC$) and conversion of intermediate concentrated products ($CPCC$).

$$CC = FPCC + CPCC \quad (23)$$

The conversion costs of final and intermediate concentrated products are calculated as follows, using the unit conversion costs of final products from raw materials ($RPCC_{pi}$) and intermediate concentrated products ($CPCC_{pi}$), and of intermediate concentrated products (CCC_{ci}):

$$FPCC = \sum_p \sum_{i \in I^{EP} \cup I^P} \sum_t RPCC_{pi} \cdot FPR_{pit} + \sum_p \sum_{i \in I^P} \sum_t CPCC_{pi} \cdot FPC_{pit} \quad (24)$$

$$CPCC = \sum_{c \in C} \sum_{i \in I^{EP}} \sum_t CCC_{ci} \cdot CP_{cit} \quad (25)$$

The inventory cost (IC) includes the inventory holding cost (IHC) and the working capital (WCC).

$$IC = IHC + WCC \quad (26)$$

The inventory holding cost is calculated by the unit inventory costs (FIC_{pi} for final products and CIC_{ci} for intermediate concentrated products) multiplied by the inventory amounts of both final and intermediate concentrated products.

$$IHC = \sum_p \sum_i \sum_t FIC_{pi} \cdot FI_{pit} + \sum_{c \in C} \sum_{i \in I^{EP} \cup I^P} \sum_t CIC_{ci} \cdot CI_{cit} \quad (27)$$

The working capital is the cost of goods of the stored products multiplied by the interest rate, *Int*.

$$WCC = \left(\sum_p \sum_i \sum_t FCOG_p \cdot FI_{pit} + \sum_{c \in C} \sum_{i \in I^{EP} \cup I^P} \sum_t CCOG_c \cdot CI_{cit}\right) \cdot Int \quad (28)$$

where $FCOG_p$ and $CCOG_c$ are the unit cost of goods of final product *p* and intermediate concentrated product *c*, respectively, which calculated from unit raw material, packaging and conversion costs.

The transportation cost of products (TC) is dependent on the unit transportation costs of final products (FTC_p) and concentrated intermediate products (CTC_c), as well as transportation distances ($DIS_{i'i}$):

$$TC = \sum_p \sum_{i'} \sum_{i:(i',i)\in Link} \sum_t FTC_p \cdot Dis_{i'i} \cdot FQ_{pi'it} + \sum_{c\in C} \sum_{i'\in I^{EP}} \sum_{i\in I^P:(i',i)\in Link} \sum_t CTC_c \cdot Dis_{i'i} \cdot CQ_{ci'it} \quad (29)$$

The depreciation cost of new facilities built (FDC) determined by the facility values (FV_{si}) of selected sizes and the depreciation rate ($Depr$):

$$FDC = \sum_s \sum_{i\notin I^{EP}} FV_{si} \cdot W_{si} \cdot Depr \quad (30)$$

3.10 Objective function

The objective function considered in this problem is the unit total cost, which is the total cost divided by the total demand in the region.

$$OBJ = (RMC + PKC + CC + IC + TC + FDC) / \sum_p \sum_{i\in I^{DC}} \sum_t D_{pit} \quad (31)$$

Thus, the proposed model is an MILP model, including Eq. (31) as objective function and Eqs. (1)-(30) as constraints. The binary variables involved in the model determine the strategic decisions, i.e., locations and sizes of plants, warehouses and DCs built in the region. The key contribution of the above model is the development of an integrated framework which incorporates different supply chain production and distribution configurations for different production formations, and is generalised enough to facilitate the what-if analysis to investigate and compare different circumstances and scenarios. The proposed model simultaneously considers two types of product formulations, i.e., traditional and new product formulations, and incorporates the modelling of all three production and distribution structures considered in this work, i.e., Traditional, Local and Concentrated Routes. The integrated decision-making framework model has the flexibility and comprehensiveness to obtain the optimal low-cost supply chain network under different assumptions and restrictions on the product formulations and production and distribution structures, and is able to demonstrate the benefits of the new product formulations.

4. Hierarchical solution approach

In order to overcome the high computational expense, we propose an efficient hierarchical solution approach, in which an aggregated static model is solved first to determine the optimal locations of facilities and their transportation links, and then the reduced dynamic MILP model introduced in

Section 3 is solved with the fixed locations of facilities and allowed links. Firstly, the aggregated model is presented.

4.1 Aggregated model

In the aggregated model, all intermediate concentrated products are aggregated, as well as all final products. Only the total production, flow and consumption of all intermediate concentrated products and the total production and flows of all final products are considered. Also, the aggregated model treats the whole planning horizon as one time period, which is a static model. Thus, the inventory is not considered in the aggregated model.

4.1.1 Capacity constraints

The total production amount of all final products at each new plant (TFP_i) is limited by the corresponding selected plant capacity ($TCap_{si}$), a parameter roughly approximated by the available formulation lines and production times:

$$TFP_i \leq \sum_{s \in S_i} TCap_{si} \cdot W_{si}, \quad \forall i \in I^P \tag{32}$$

4.1.2 Mass balance constraints

Due to the initial inventory being equal to the ending inventory, the total production amount of all final products (TFP_i), plus the total incoming flows ($TFQ_{i'i}$), is equal to the total outgoing flows plus the total local demand at a DC (TD_i).

$$TFP_i|_{i \in I^{EP} \cup I^P} + \sum_{i':(i',i) \in Link} TFQ_{i'i} = TD_i|_{i \in I^{DC}} + \sum_{i':(i,i') \in Link} TFQ_{ii'}, \quad \forall i \tag{33}$$

Similarly, for intermediate concentrated products, the total production (TCP_i) plus the total incoming flows ($TCQ_{i'i}$), is equal to the total outgoing flows plus the total consumption for final product production:

$$TCP_i|_{i \in I^{EP}} + \sum_{i':(i',i) \in Link} TCQ_{i'i} = \alpha ACP \cdot TFP_i|_{i \in I^P} + \sum_{i':(i,i') \in Link} TCQ_{ii'}, \quad \forall i \in I^{EP} \cup I^P \tag{34}$$

where αACP is the average unit consumption of intermediate concentrated products for production of final products.

4.1.3 Logical constraints

If a node is not selected to build any facility, then there is no incoming/outgoing flow to/from the node:

$$\sum_{i':(i',i)\in Link} TFQ_{i'i} \leq M \cdot (E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}}), \quad \forall i \notin I^{EP} \tag{35}$$

$$\sum_{i':(i,i')\in Link} TFQ_{ii'} \leq M \cdot (E_i|_{i\in I^P} + Y_i|_{i\in I^W} + Z_i|_{i\in I^{DC}}), \quad \forall i \notin I^{EP} \tag{36}$$

$$\sum_{i'\in I^{EP}:(i',i)\in Link} TCQ_{i'i} \leq M \cdot E_i|_{i\in I^P}, \quad \forall i \in I^P \tag{37}$$

In addition, the aggregated model includes the constraints related to capacity size selection (Eq. 13) and the number of facilities (Eqs. 15-17).

4.1.4 Objective function

As the detail of specific products is not considered in this aggregated model, it is difficult to estimate the raw material, packaging, conversation and inventory costs. Thus, they are not taken into account. Here, we only focus on the costs that mainly depend on the logistic networks. The objective function here is to minimise the unit cost of transportation and depreciation.

$$OBJ = (\sum_i \sum_{i':(i',i)\in Link} AFTC \cdot Dis_{i'i} \cdot TFQ_{i'i} + \sum_{i\in I^{EP}} \sum_{i'\in I^P:(i',i)\in Link} ACTC \cdot Dis_{i'i} \cdot TCQ_{i'i} + \sum_s \sum_{i\notin I^{EP}} FV_{si} \cdot W_{si} \cdot Depr)/\sum_i TD_i \tag{38}$$

where $AFTC$ and $ACTC$ are average unit transportation costs of final and intermediate concentrated products, respectively. Thus, the aggregated static model includes the objective function (38) and the constraints, Eqs. (13), (15)-(17), and (32)-(37), which is denoted as *ASM* here. Note that the seasonality is ignored in the model *ASM*, resulting in much shorter computational time to solve.

4.2 Solution procedure

By the introduction of both aggregated and full models, we developed a hierarchical solution approach. In this approach, the model *ASM* is solved first for the facility locations and links. With the fixed locations and links, the reduced full dynamic model as given in Section 3 (denoted as *FDM*) is then solved for facility capacities and other operational decisions. The whole solution procedure is presented as follows:

Step 1: Initialise the sets I^{EP}, I^P, I^W, I^{DC}, and *Link*;

Step 2: Solve the model *ASM* and obtain the optimal locations, E_i, Y_i, and Z_i, and flows, $TFQ_{ii'}$ and $TCQ_{ii'}$;

Step 3: Update the sets *Link*, I^P, I^W, and I^{DC}: if $TFQ_{ii'}$=0 and $TCQ_{ii'}$=0, remove pair *(i, i')* from set *Link*; if E_i=0, Y_i=0, or Z_i=0, remove node *i* from the corresponding sets I^P, I^W, or I^{DC}.

Step 4: Solve the reduced model *FDM* with fixed E_i, Y_i, and Z_i *as obtained in Step 2*.

5. Case study

In this section, in order to demonstrate the economic benefits of the new product formulation, we investigate a case study in the fast-moving consumer goods industry based on a real-world supply chain network in East Asia. We consider the strategic plant allocations and weekly operational decisions within one year, which is divided into 52 weeks (T1-T52). In this supply chain network, there are two existing conventional plants outside the region, denoted as CP1 and CP2. In the region, we consider 21 cities (denoted as A-U), as illustrated in Figure 3, which are treated as the candidates of facility locations. Thus, each city is divided into three separate nodes as the candidate locations of a plant, a warehouse and a DC, respectively. The distance between the nodes in the same city is assumed to zero. The transportation times between cities are neglected, as they are much smaller than the one-week discretisation.

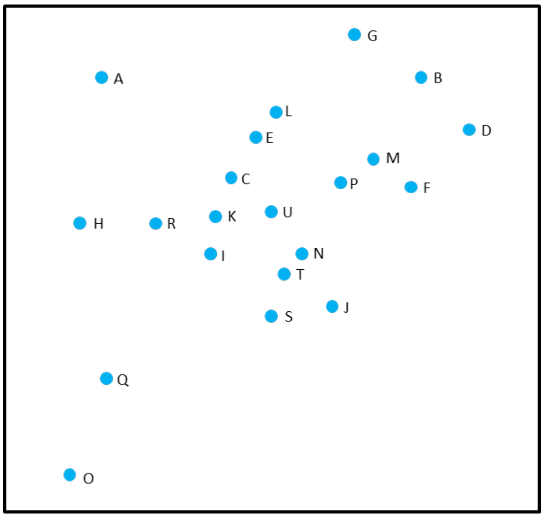

Figure 3. Cities in the case study

In this problem, there are 44 final products (P1-P44), which belong to 3 types (J1-J3), and the allocations of products to types are given in Table 3. These final products can be produced from 14 different raw materials. Also, in the Concentrated Route, there are 44 intermediate concentrated products (C1-C44), which are produced from several raw materials, and each of them is converted to one final product at finishing plants.

Table 3. Product types and production rates

Types	Products	Production rate (m^3/h)
J1	P1-P6	1.224
J2	P7-P21	1.399
J3	P22-P44	2.250

The established plants are closed for production in the last eight weeks of the year when the demand is low. It is assumed that the products in each type have the same production rate, as given in Table 3. The setup time is assumed to be 2 h for each product. The minimum production time for each product on a product line is 2 h. There are three capacity sizes (small, medium and large) available for plants. The investment cost (in cu, currency unit) of each capacity size and its available production time of each type in each time period are presented in Table 4. There is only one capacity size available for warehouses and DCs, and the inventory capacities of warehouses and DC are 2448 m^3 and 680 m^3, respectively. The investment for one warehouse is 28.1 million cu (mcu), and for one DC is 11.5 mcu. A depreciation rate of 7% is used for calculation. The safety stock is kept to cover demand for 2 weeks.

Table 4. Available production time (h/week)

Sizes	Investment (mcu)	Time periods								
		T1-T32			T33-44			T45-52		
		J1	J2	J3	J1	J2	J3	J1	J2	J3
S1	287.2	288	720	720	240	600	600	0	0	0
S2	187.3	144	432	432	120	360	360	0	0	0
S3	99.9	144	144	144	120	120	120	0	0	0

The demands of the final products are assumed to be satisfied at DCs. The annual total demand for all products is 9600 m^3. The distributions of the total demands between all cities are given in Figure 4, showing that the highest demand occurs in city C, the most populous city in the region, while the lowest demand is in city A, the least developed area in the region. Also, the weekly total demands are shown in Figure 5.

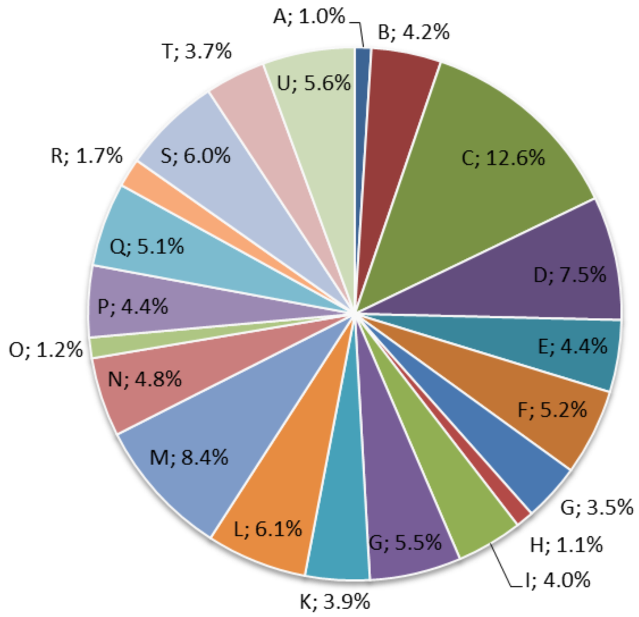

Figure 4. Demand distributions among cities

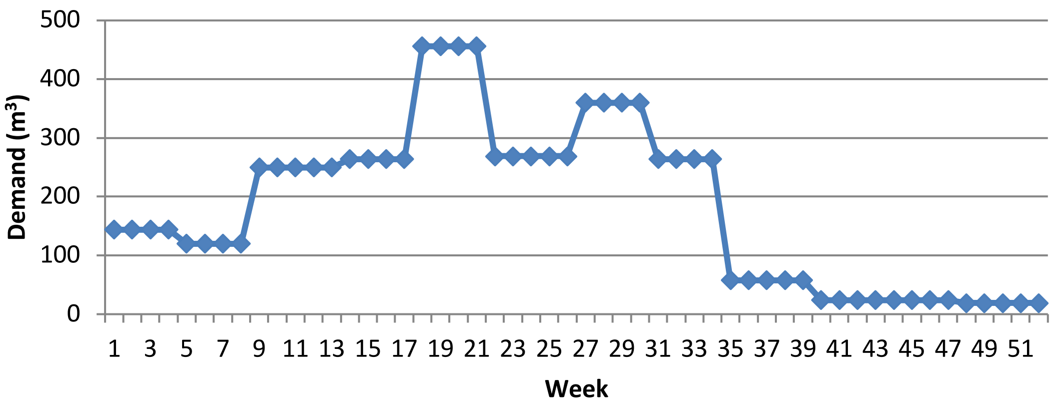

Figure 5. Weekly total demands

The proposed models and approaches are solved for the three production and distribution structures, Tradition Route, Local Route and Concentrated Route, separately. In each route, all cities are treated as the potential warehouse locations, i.e., $|I^W| = 21$. It is also assumed that each city with demand has a DC established, i.e., $|I^{DC}| = 21$, and we fix $Z_i = 1$ for all $i \in I^{DC}$.

The three production and distribution structures require different network configurations, including the candidate locations of plants and allowed links between them. For each specific route, some sets in the proposed model are re-defined as follows:

- Traditional Route: There are two existing conventional plants at CP1 and CP2, i.e., $I^{EP} = \{PN_{CP1}, PN_{CP2}\}$, and no plant is built in the region, i.e., $I^P = \emptyset$. The allowed transportation links are between existing conventional plants and warehouse locations, and between warehouse locations and DC locations, i.e., $Link = \{(i,i'): i \in I^{EP}, i' \in I^{W}\} \cup \{(i,i'): i \in I^{W}, i' \in I^{DC}\}$. As no intermediate concentrated product exists, the set of intermediate concentrated products $C = \emptyset$,

- Local Route: There is no existing conventional plant to be used, i.e., $I^{EP} = \emptyset$, while all cities are considered as candidate plant locations, i.e., $|I^{P}| = 21$. Transportation of products is allowed between plant locations and warehouse locations, between warehouse locations and DC locations, and between plant locations and DC locations if their distances are less than 200 km, i.e., $Link = \{(i,i'): i \in I^{P}, i' \in I^{W}\} \cup \{(i,i'): i \in I^{W}, i' \in I^{DC}\} \cup \{(i,i'): i \in I^{P}, i' \in I^{DC}, Dis_{ii'} \leq 200\}$. In addition, there is no intermediate concentrated product, i.e., $C = \emptyset$.
- Concentrated Route: Two existing conventional plants only produce intermediate concentrated products, i.e., $I^{EP} = \{PN_{CP1}, PN_{CP2}\}$ and FP_{pit} are fixed to 0 for $i \in I^{EP}$, and all cities are considered as candidate finishing plant locations to convert intermediate concentrated products to final products, i.e., $|I^{P}| = 21$. As the finishing plants to build do not produce any final product directly from raw materials, we fix $FPR_{pit} = 0$ for $i \in I^{P}$. In addition, we define set $Link = \{(i,i'): i \in I^{EP}, i' \in I^{P}\} \cup \{(i,i'): i \in I^{P}, i' \in I^{W}\} \cup \{(i,i'): i \in I^{W}, i' \in I^{DC}\} \cup \{(i,i'): i \in I^{P}, i' \in I^{DC}, Dis_{ii'} \leq 200\}$, including the connections between conventional plants and finishing plant locations, between finishing plant locations and warehouse locations, between warehouse locations and DC locations, and between finishing plant locations and DC locations if the distances between them are less than 200 km.

All computational runs were implemented in AIMMS 4.22 (Roelofs and Bisschop, 2017) on a 64-bit Windows 7 based machine with 3.00 GHz Intel Core i5-3330 processor and 8.0 GB RAM. The optimality gap was set to 1% and the CPU limit for each run is 10,000 s.

6. Results and discussion

In this section, we present the computational results of the case study and analyse the supply chain performance of different product formulations. Firstly, the scenario with at most one local plant and one warehouse (denoted as 1P1W) is considered with an economic analysis. Next, we further investigate the Concentrated Route with additional scenario analysis and discussion.

6.1 1P1W scenario

In this scenario, the Traditional Route does not exist any local plant in the region and the location of the single warehouse to store final products from existing conventional plants is to be determined. In the Local Route, a new conventional plant is to be built in one of the candidate locations in the region, as well as one warehouse. In the Concentrated plant, a new finishing plant is to be located to produce final products from intermediate concentrated products produced at existing convention plants, as well as a warehouse.

6.1.1 Optimal supply chain networks

We apply the proposed full MILP model and hierarchical approach to find the optimal supply chain network configurations of all three routes. The computational statistics of the model for all production and distribution structures are given in Table 5. The MILP model only finds a feasible solution in the Traditional Route, while no solution is returned within the given CPU limit in the other two routes. Meanwhile, the hierarchical approach is able to find solutions within 7 minutes for all three routes. In the Traditional Route, the hierarchical approach only takes 9s to find the optimal solution, which is in line with the current practice of this supply chain network and validates the problem assumptions and model formulation introduced in previous sections. The obtained result shows a slightly better quality than the MILP model, with a 1.9% cost saving. It can be seen that the size of the model *ASM* in the hierarchical approach is quite small, and therefore it is computationally easy to achieve good facility locations and flow links. In addition, the reduced MILP model in the hierarchical approach is also much smaller than the full MILP model, especially in terms of the number of variables, which is lower by one order of magnitude. Thus, the proposed hierarchical approach demonstrates significant computational advantages.

Table 5. Computational statistics and results in 1P1W scenario

	Traditional Route		Local Route		Concentrated Route	
	MILP model	Hierarchical approach	MILP model	Hierarchical approach	MILP model	Hierarchical approach
Unit total cost (cu/m^3)	11,310.7^a	11,096.9	-^{b}	10,506.7	-^{b}	9,532.8
Unit supply chain-controlled cost (cu/m^3)	4,095.2	3,906.5	-^{b}	2,222.0	-^{b}	1,450.1
CPU (s)	10,000^a	9.1 (0.1^c/9.0^d)	10,000^b	411.3 (0.1^c/411.2^d)	10,000^b	378.5 (0.1^c/378.4^d)
No of equations	324,877	152^c/192,675^d	647,687	257^c/200,101^d	750,431	303^c/214,690^d
No of continuous variables	1,363,802	528^c/208,338^d	2,728,962	1019^c/209,042^d	3,041,586	1105^c/228,074^d
No of discrete variables	63	63^c/22^d	48,195	147^c/2313^d	48,195	147^c/2313^d

[a] feasible solution returned with a gap of 2.3% when the CPU limit is reached; [b] no solution returned when the CPU limit is reached; [c] model *ASM*; [d] model *FDM*.

The optimal supply chain network configurations of the three routes are given in Figures 6–8 (flows within one city are not shown). Note that for better visualisation, the positions of the existing conventional plants in these figures do not reflect their actual distances to the considered region. With respect to the existing conventional plant production, the Traditional Route selects CP1 to supply final products for the new region, while CP2 is selected by Concentrated Route for providing intermediate concentrated products. We can also find that only in the Traditional Route, the single warehouse is built in city G, which is the closest location to the plant CP1, while in the other two routes, the plant and warehouse are both located in city C, where the highest demand occurs. In addition, due to the relatively small demand in the region, the smallest capacity size is selected for the plant in city C. As to the optimal flows, in the Local Route, there are eight DCs served by the new regional conventional plant directly, including cities E, I, K, L, N, P, R, and U, while in the Concentrated Route, 6 cities (E, K, L, N, T, and U) receive direct shipments from the finishing plant in city C.

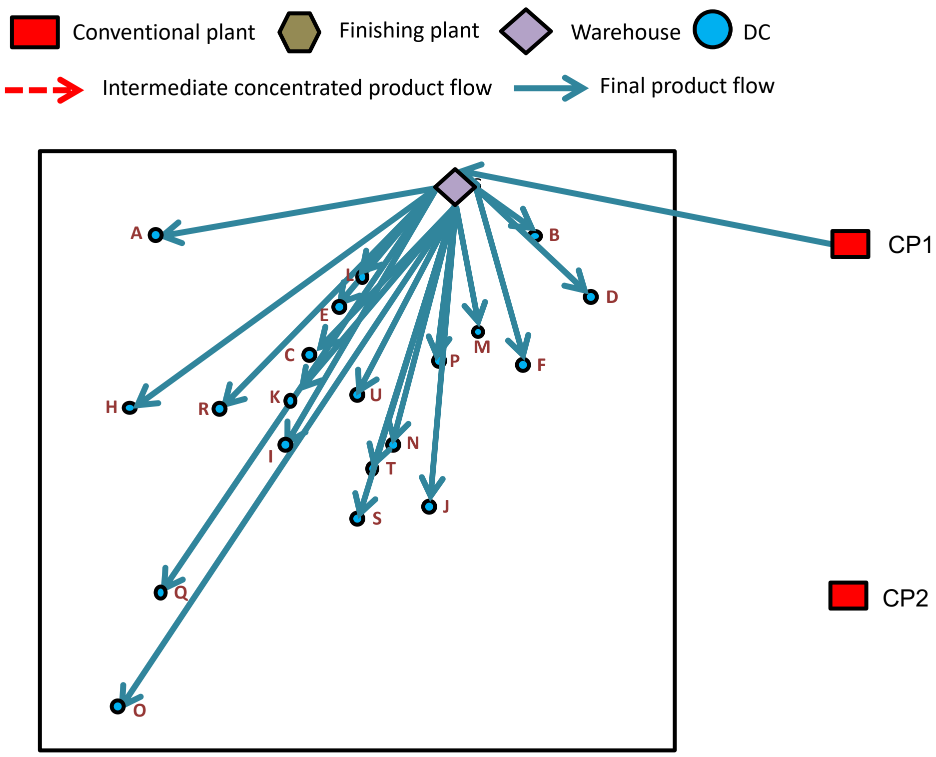

Figure 6. Optimal supply chain network configuration of the Traditional Route in 1P1W scenario

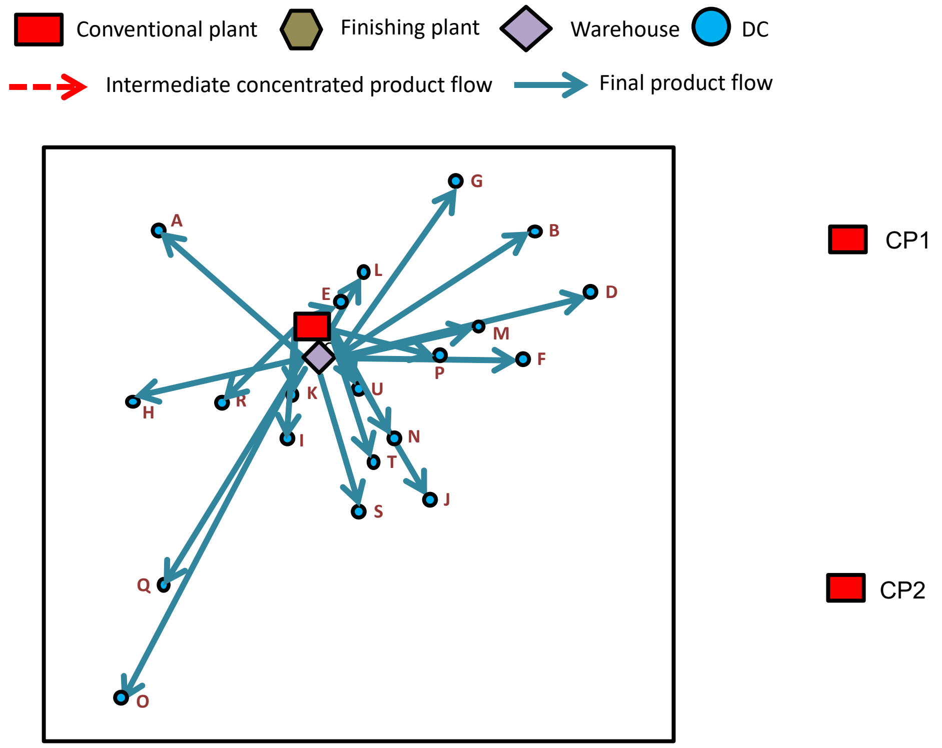

Figure 7. Optimal supply chain network configuration of the Local Route in 1P1W scenario

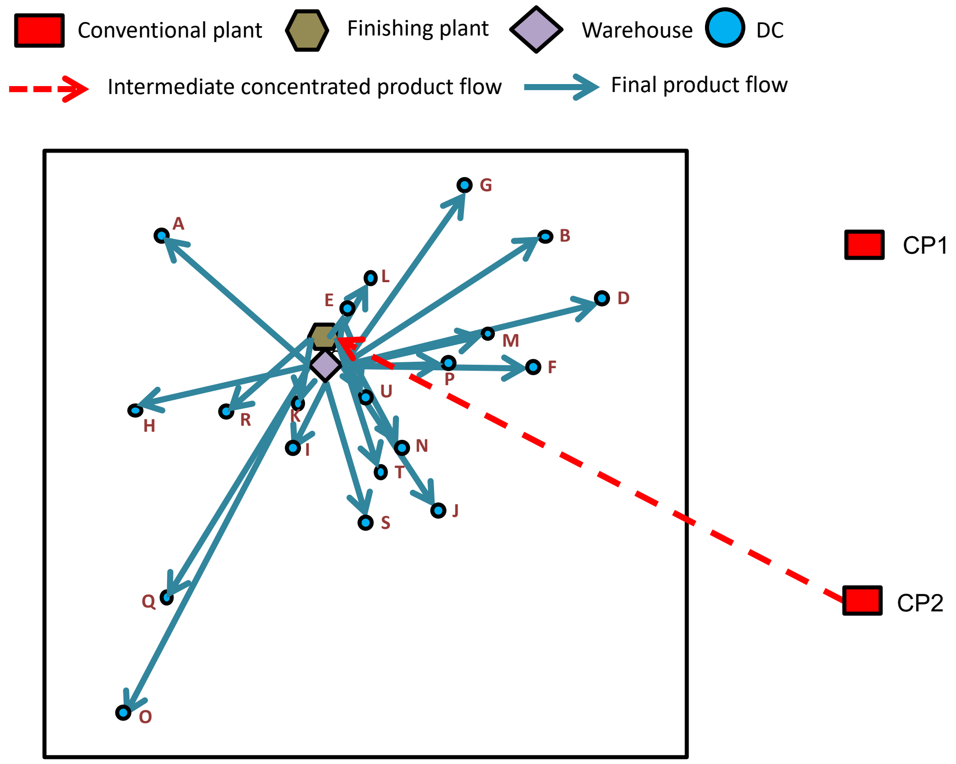

Figure 8. Optimal supply chain network configuration of the Concentrated Route in 1P1W scenario

Figure 9 compares the optimal total inventory in each week of all three routes. Here, the inventory patterns of the Local and Concentrated Routes are quite similar. The newly established plants build inventory in week 18, in advance of the peak demand, due to limited production capacity. In the Traditional Route, as the existing conventional plants have much larger production capabilities, they can deal with the peak demands without producing more in advance. In addition, inventory increases within a couple of weeks before week 45 in order to build enough inventory by week 52 to cover the demands for the next year.

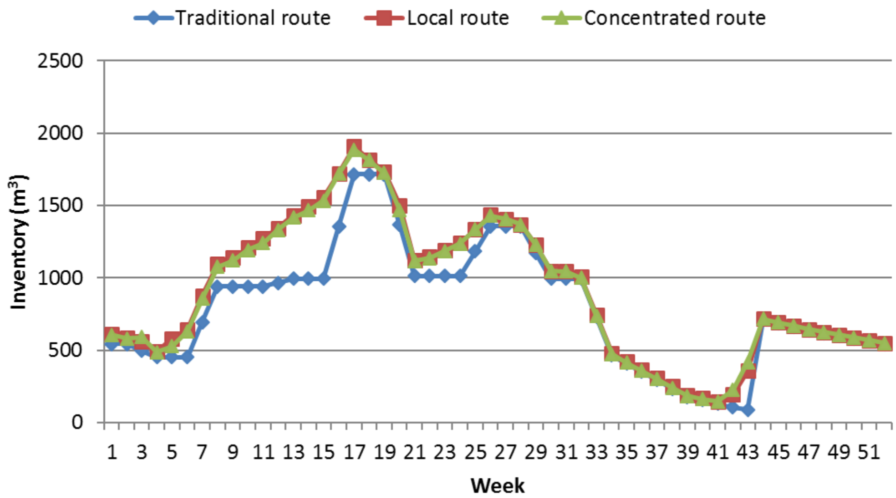

Figure 9. Optimal total inventories in the supply chain network in 1P1W scenario

6.1.2 Economic analysis

Comparing the optimal unit total costs of all three production and distribution structures obtained by the hierarchical approach in Table 5, the Concentrated Route achieves the lowest cost among all three routes, which is 14.1% and 9.3% lower than the Traditional Route and the Local Route, respectively. In addition, we look at the unit supply chain-controlled cost, defined as the unit total cost of the conversion, inventory and transportation costs, which are most related to the logistics and supply chain networks. The Concentrated Route's supply chain-controlled cost is only 37.1% and 65.3% of that of the Traditional Route and Local Route, respectively. Focusing on the breakdowns of the optimal unit total costs in Figure 10, in the all three routes, the majority of cost comes from the raw material and depreciation costs, which represent 34 – 40% and 18 – 28% of the total cost, respectively. In the Traditional Route, the transportation cost is much higher than the other two routes, due to the long-distance shipment of final products from the existing conventional plant CP1 to the local warehouse at city C in the region. Although there are also long-distance shipments from the existing conventional plant CP2 in the Concentrated Route, the transportation cost is relatively much lower than the Traditional Route. The lower transportation cost results from lower unit transportation costs, due to easier shipping conditions of intermediate concentrated products, and much smaller transportation amounts of the shipped intermediate concentrated products than the final product; this is the key feature of the product design innovation. In addition, the conversion cost in the Concentrated Route is lower than the other two routes, because the new technology using intermediate concentrated products is cheaper than the traditional technology converting final products from raw materials directly. The Local and Concentrated Routes also have higher depreciation costs than the Traditional Route, mainly due to the new plant established in city C.

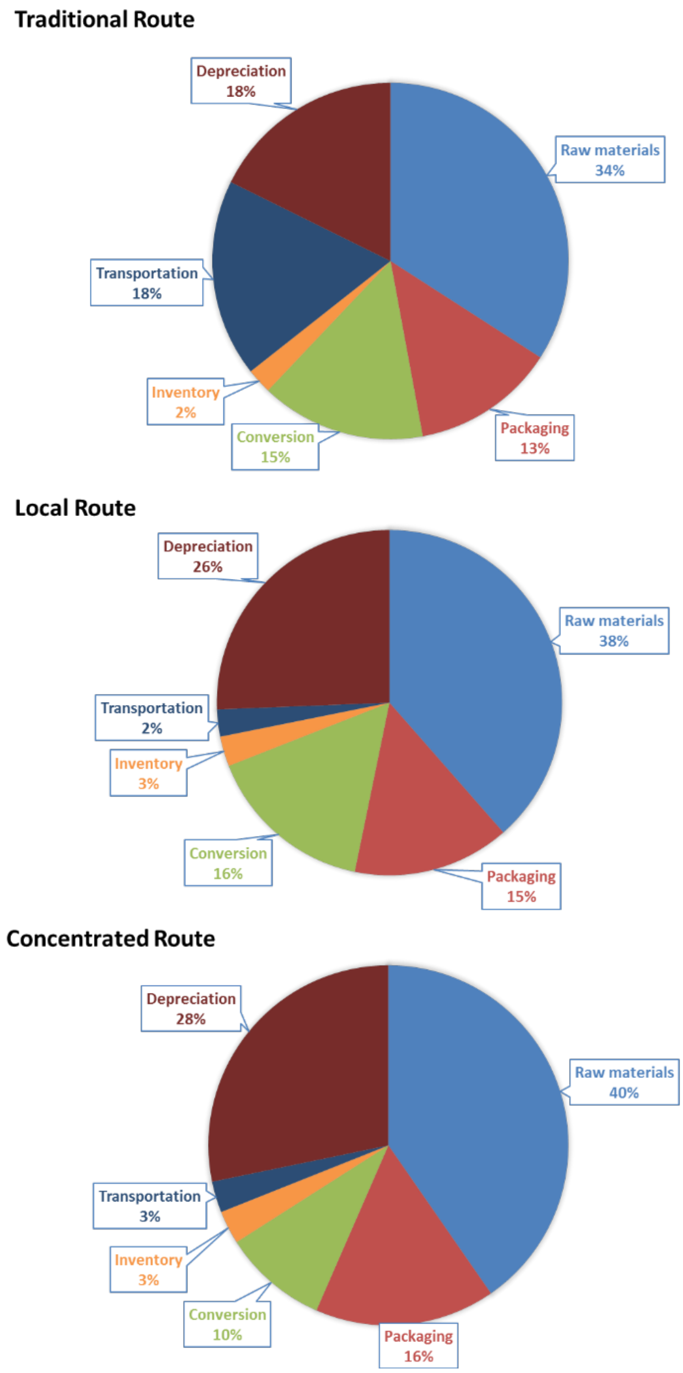

Figure 10. Optimal cost breakdowns in 1P1W scenario

The above results show that by introducing the new technology and production formulations using intermediate concentrated products, the cost of the whole supply chain can be significantly saved. Comparing the Concentrate Route to the Traditional Route, which is considered as the base case, their difference in the unit total cost is 11096.9 - 9532.8 = 1564.1 cu/m^3. Thus, for a total demand of 9,600 m^3 in the region, the margin of the Concentrated Route in the total supply chain cost is 1564.1 × 9600 = 15.0 mcu per year. Moreover, the supply chain configurations of both routes need one warehouse and 21 DCs, while in the Concentrated Route, 99.9 mcu is invested in one additional small-size finishing plant. Table 6 shows the calculation of the additional annual net cash flow generated by the Concentrated Route, and the cash payback period (Weygandt et al., 2009) for the additional finishing plant investment. It can be seen that 5.7 years will be taken to recoup the investment of the new finishing plant. From the above analysis, we can conclude that the manufacturing process using the new technology is economically beneficial, and the additional investment can be earned back quickly in a few years.

Table 6. Payback period calculation of the Concentrated Route

Annual margin (mcu/year)		15.0
Annual tax (mcu/year)	= Margin × tax rate (30%)	4.5
Annual depreciation added back (mcu/year)	= Investment × depreciation rate (7%)	7.0
Annual net cash flow (mcu/year)	= Margin – Tax + Depreciation	17.5
Investment (mcu)		99.9
Cash payback period (year)	= Investment / Net cash flow	5.7

6.2 Additional analysis and discussion on the Concentrated Route

As shown in the above results, the Concentrated Route is most cost-efficient in all three routes. In this section, we further analyse the Concentrated Route, considering the scenarios with multiple warehouses first, and then studying the impacts of plant sizes.

6.2.1 Scenarios with multiple warehouses

From the above analysis of the 1P1W scenario, the Concentrated Route shows obvious advantages in lower cost. Next, we investigate the scenarios with multiple warehouses to explore the effect of the number of warehouses on solutions. Here, we examine two more scenarios, with at most one local plant, and two and three potential warehouses in the region, denoted as 1P2W and 1P3W, respectively. The results of these two scenarios are compared with 1P1W scenario in Table 7. With more warehouses built, both unit total cost and unit supply chain-controlled cost increase, due to the depreciation cost of the additional warehouses and higher inventory cost. With respect to the optimal supply chain network configurations, city C is always chosen to locate the only finishing plant and one of the warehouses. City M is also selected to locate an additional warehouse, which covers DCs in cities D, F and M. In the 1P3W scenario, a third warehouse is established at city Q, which serves DCs in cities O and Q. The optimal supply chain flows in the 1P2W and 1P3W scenarios are presented in Figures 11 and 12 using Sankey diagrams, respectively, where the four layers from left to right represent existing conventional plants, local plants, warehouses, and DCs, and the links between them are the total flows coloured in their destinations. They show that different existing conventional plants are chosen for the supply of intermediate concentrated products.

Table 7. Solutions of the Concentrated Route in 1P1W, 1P2W and 1P3W scenarios

	1P1W	1P2W	1P3W
Unit total cost (cu/m^3)	9,532.8	9,766.7	10,018.0
Unit supply chain-controlled cost (cu/m^3)	1,450.1	1,479.1	1,524.3
Local plant locations	C	C	C
Local warehouse locations	C	C, M	C, M, Q

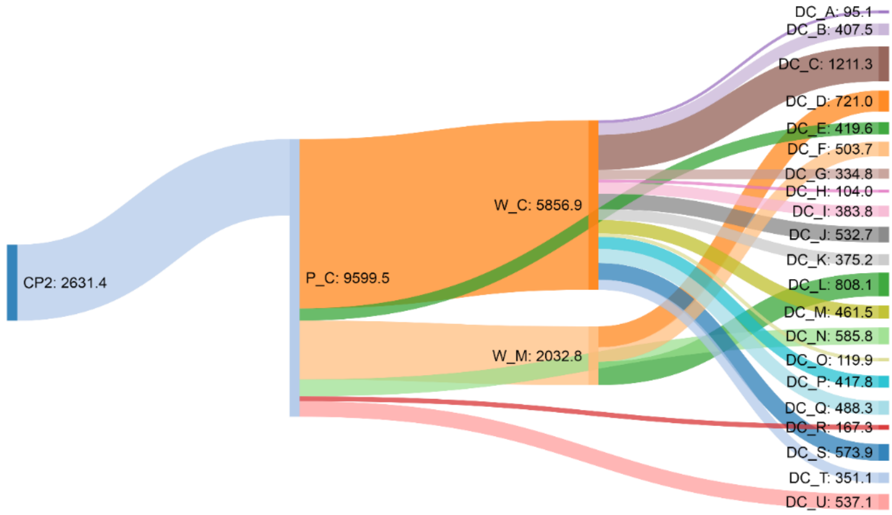

Figure 11. Optimal supply chain flows of the Concentrated Route in 1P2W scenario (in m^3)

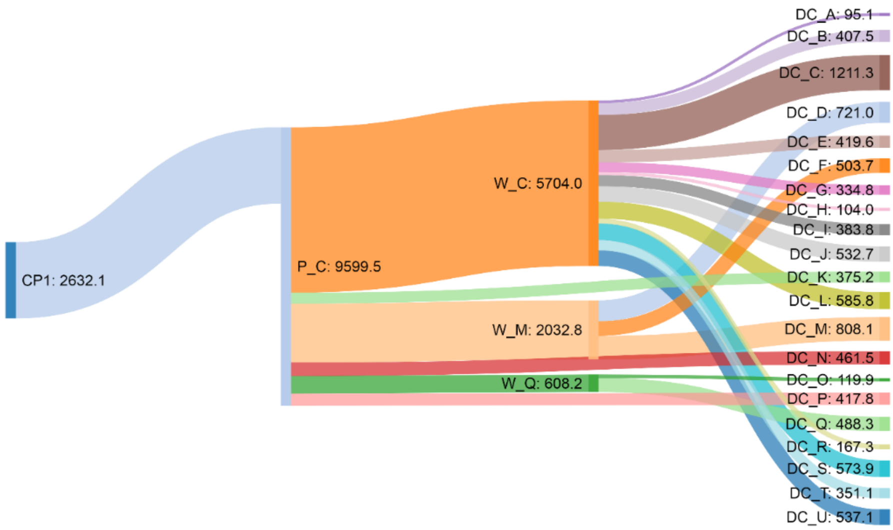

Figure 12. Optimal supply chain flows of the Concentrated Route in 1P3W scenario (in m^3)

6.2.2 Sensitivity analysis of plant sizes in the Concentrated Route

Next, we further investigate the Concentrated Route by doubling the annual total demand, which is an anticipated long-term outcome, and compare the supply chain performance with one medium-size finishing plant and two small-size finishing plants. For the scenarios with two warehouses allowed in the region, denoted as DD-1P2W and DD-2P2W, respectively, the optimal solutions, including the optimal facility locations and flows are shown in Figures 13 and 14 using circular visualisation, where the built facilities are represented by the coloured circular segments, and the total flows between them are illustrated as the coloured links whose widths are proportional to the flow amounts. Figures 13 shows that, in the DD-1P2W scenario, the medium-size finishing plant is located at city C and served by the existing conventional plant CP2, and the two warehouses are built at cities C and M. For the optimal solution of DD-2P2W scenario in Figure 14, both cities C and M are chosen for the two small-size finishing plants, receiving intermediate concentrated products from the plant CP2, and each of cities C and Q hosts one warehouse.

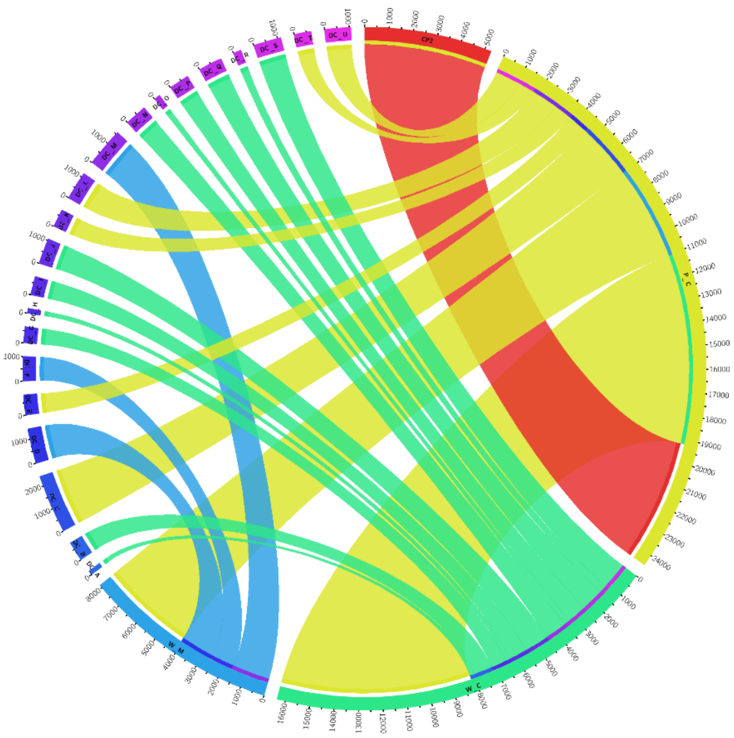

Figure 13. Optimal supply chain flows of the Concentrated Route in DD-1P2W scenario under doubled demand scenario (in m^3)

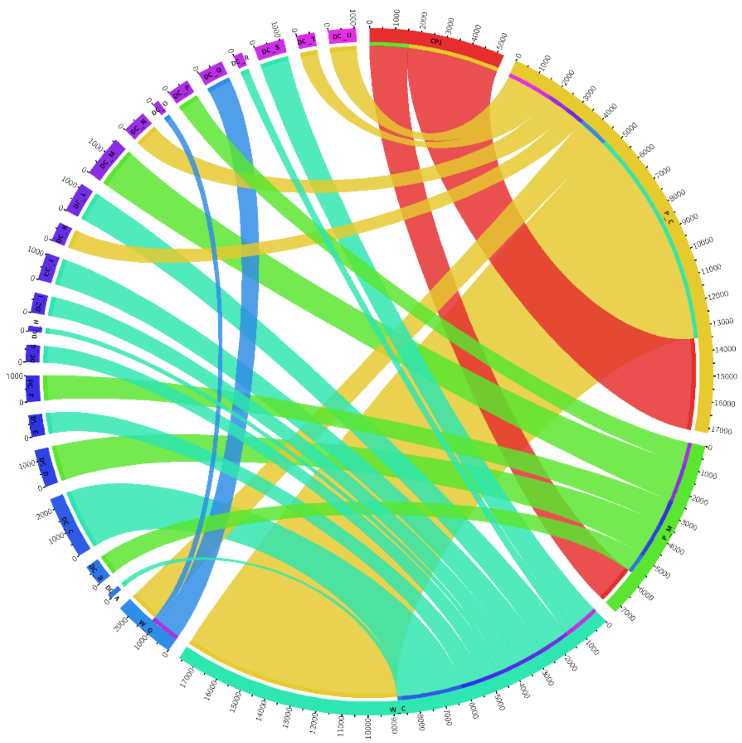

Figure 14. Optimal supply chain flows of the Concentrated Route in DD-2P2W scenario under doubled demand scenario (in m^3)

Table 8 shows that it is more cost competitive to build one medium-size finishing plant, than two small-size finishing plants, with a slight saving of 2.2% in unit total cost and a significant saving of 10.5% in unit supply chain-controlled cost. Furthermore, the computational results of the scenarios with a single warehouse (named as DD-1P1W and DD-2P1W) show a similar trend, with a cost saving in one medium-size finishing plant. Due to one fewer warehouse is established, their costs are lower than the DD-1P2W and DD-2P2W scenarios, respectively. Also, it is interesting to see that the DD-1P2W scenario generates a lower cost than the DD-2P1W scenario, due to the difference between the facility values of a finishing plant and a warehouse. It is concluded that in the current circumstance, the centralised manufacturing of final products based on intermediate concentrated formulations followed by a finishing plant results in economic benefits, compared to distributed manufacturing.

Table 8. Solutions of the Concentrated Route with the doubled demand under different plant-warehouse scenarios

Scenarios	DD-1P2W	DD-2P2W	DD-1P1W	DD-2P1W
Unit total cost (cu/m^3)	9,484.6	9,699.8	9,359.4	9,557.0
Unit supply chain-controlled cost (cu/m^3)	1,447.4	1,617.0	1,424.6	1,576.2
Finishing plant locations	C	C, M	C	C, M
Warehouse locations	C, M	C, Q	C	C

7. Concluding remarks

In this work, the optimal design of low-cost supply chain networks, involving the integrated production and distribution configurations of intermediate concentrated and final products, has been addressed. Our investigation focused on the positive supply chain benefits of a new product/process concept and demonstrated how to link product formulation research to supply chain research. In order to find the optimal strategic logistic networks and operational decisions of the supply chains, an MILP optimisation model has been developed to minimise the unit total cost of whole supply chain network. Next, a hierarchical approach has been developed to cope with the computational challenges of large instances. The proposed hierarchical approach involves an aggregated static optimisation model, in which the facility locations and flow links are determined, and a reduced dynamic optimisation model, determining the facility capacities and operational production, distribution and inventory decisions.

The newly proposed models and solution approaches have been applied to a real-world case study in East Asia. In the three production and distribution structures investigated, the proposed hierarchical approach has shown a significant computational advantage to the single MILP model, with more than two orders of magnitude CPU savings. In addition, computational results showed that the novel Concentrated Route with one finishing plant and one warehouse is the best option for the investigated case study. The new product formulations based on intermediate concentrated formulations by new technology and the establishment of a local centralised finishing plant lead to significant economic savings at the supply chain level.

In the proposed model, some detailed decision-making of supply chain network design was not considered, e.g., the number and types of formulation lines and transportation modes. The future research could take them into account to have a more detailed analysis of the benefits of new product formulations. Also, this work only considers the economic benefits of the new product formulations, while other benefits, e.g. those from the environmental and social perspectives, were not considered. This work could be extended by developing multiobjective optimisation models and approaches to consider environmental and social benefits. Moreover, the proposed model is deterministic and does not consider the uncertain parameters, e.g., demand, production rate, transportation time. The optimisation under uncertainty of the production and distribution networks could be a future research direction.

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