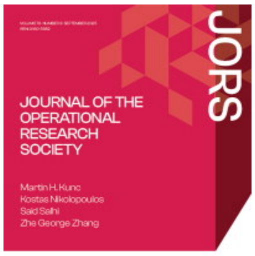

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The impact of product deterioration on the (re)design of food supply chain networks: an application to a perishable food supply chain

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ABSTRACT

Given the increasing demand for freshness, the need to reduce food waste, and ensure food safety, it is crucial to consider quality deterioration processes in the (re)design of food supply chains (FSCs). Past developments in FSCs focused foremost on efficiency and economic profitability, resulting in large-scale centralized processing facilities. This has become a liability as efficiency in large-scale processing limits product differentiation and flexibility. Decentralized (upstream) pre-processing and improved pre-treatments can affect product deterioration in an early stage, resulting in more diverse and intermediate product flows that can be used in existing and new value chains and provide new markets. To identify the benefits of alternative supply chain structures, we propose a generic model based on mixed-integer linear programming. The modelling structures are applicable to a broad variety of different (food) supply chains. Both strategic network design aspects and gradual quality deterioration processes can be incorporated. We demonstrate the applicability of the model through an existing fruit supply chain in China. The results show that decentralized pre-processing can mitigate quality deterioration processes and enhance the total profit of the chain, reduce the energy use in the supply chain, and have a positive impact on social equity.

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KEYWORDS
Food supply chain; network (re)design; quality deterioration; perishable food

1. Introduction

In recent years, research on the (re)design of food supply chain (FSC) networks has received increasing interest (Yadav et al., 2022). Network (re)design encompasses the location of facilities, allocation of product flows, and the (re)design of processing and distribution systems (Yadav et al., 2022; Yakavenka et al., 2020). To address FSC network (re)design problems, a wide range of operational research approaches are utilized, with (non-)linear (mixed-integer) programming playing a dominant role (Plà et al., 2014; Soto-Silva et al., 2016; Yadav et al., 2022; Yakavenka et al., 2020).

An ongoing challenge faced by FSCs is the gradual and irreversible deterioration of product quality, which distinguishes them from many other non-fresh product supply chains (Yu & Nagurney, 2013). Food quality deterioration affects customer satisfaction, leads to (food) waste, and causes inefficiencies in resource use, resulting in substantial economic losses in the supply chain (Chen & Chen, 2021; Jonkman et al., 2019; Yu & Nagurney, 2013). Given the high perishability of fresh foods (e.g., fruits), these FSCs require special attention to mitigate quality deterioration (Chen & Chen, 2021; Fu et al., 2019). Although the quality deterioration of fresh foods has been addressed in supply chain planning models for medium- to short-term decisions (Janssen et al., 2016), considerably less articles in network (re)design have considered food quality deterioration at a strategic decision level (Esteso et al., 2021; Jonkman et al., 2019).

In articles where quality deterioration has been considered in network design models, typically a fixed shelf life of products is assumed (Esteso et al., 2021; Govindan et al., 2014; Patidar & Agrawal, 2020a, 2020b; Yakavenka et al., 2020). This means that there is an exact time point at which product quality drops to expiration (Lejarza & Baldea, 2022). Consequently, the sojourn time is fixed. However, a fixed shelf life neglects the gradual nature of quality deterioration, thereby overlooking the potential to extend shelf life by slowing down the deterioration process in alternative supply chain designs.

Product deterioration can be considered as a gradual and dynamic process that can be influenced by factors, such as the sojourn time, temperature, humidity, and (pre-)processing treatments during the supply chain (Janssen et al., 2016; Soto-Silva et al., 2016; Yadav et al., 2022). Although some FSC

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studies have considered gradual quality deterioration in medium- and short-term planning problems, such as Lejarza and Baldea (2022); Rong et al. (2011), the gradual process of quality deterioration has rarely been addressed in strategic network (re)design. Some examples are Khazaeli et al. (2024), Li and Zhang (2024), Esteso et al. (2022), and Musavi and Bozorgi-Amiri (2017), who use sojourn time or age as the primary influencing factor to model quality deterioration. Though other critical factors, such as environmental conditions (Han et al., 2021; Orjuela-Castro et al., 2017) and processing treatments (Jonkman et al., 2019; Nourbakhsh et al., 2016), also have substantial impacts on quality deterioration, they are not covered in network design models yet.

Moreover, due to variations across products and regions, these studies that include perishability in strategic network design assume fixed network configurations, making it challenging to apply existing models to other cases (e.g., Esteso, Alemany, Ortiz, & Iannacone, 2024; Biza et al., 2024; Shakuri and Barzinpour, 2024; Alemany et al., 2021). While a generic modelling framework can accommodate supply chain diversity and enhance cross-case applicability (Jonkman et al., 2019), this remains an unaddressed gap in the literature.

Food processing is a crucial stage in supply chain design to slow down product quality deterioration and to valorize product flows (Annapure et al., 2022; Ghoshal, 2018). Commonly, processing consists of a sequence of various operations, such as sorting, washing, cooling, and packaging (Annapure et al., 2022; Ghoshal, 2018). In order to exploit economies of scale, these operations are often performed in large-scale centralized facilities (Almena, Fryer, et al., 2019). However, according to Jonkman et al. (2019); Bruins and Sanders (2012), some preprocessing steps can already be conducted upstream in supply chains, for instance close to farmer's, which may help to maintain high initial product quality or decrease quality losses during downstream transportation and storage. However, as decentralized processing may compromise the advantages of centralized processing, the extent of decentralization should be carefully considered.

This article explores the impact of product-dependent quality deterioration on the design of FSC networks. Existing studies often assume a fixed shelf life, which fails to capture the gradual and dynamic nature of quality deterioration. Moreover, none of the existing studies have considered other influencing factors of the product deterioration process beyond time. To address this gap, this article introduces a generic modelling framework that integrates gradual quality deterioration processes into FSC network (re)design. It allows for product-dependent deterioration modelling by incorporating variable deterioration rates influenced by factors beyond time, such as storage environment and processing methods. Furthermore, it is applicable to different supply chain configurations with the possibility of redesigning supply chain networks. The applicability of the approach is demonstrated from a real-life case in a citrus supply chain network where the impact of decentralized processing on network design is assessed.

The article is organized as follows. Section 2 presents the related literature. Section 3 introduces a generic network (re)design model to address product-dependent quality deterioration. To demonstrate the approach, the model is applied to a case study with decentralized processing in Section 4. Section 5 provides a common discussion on the model and Section 6 draws conclusions.

2. Literature review

Section 2.1 provides an overview of current network design models that have considered perishability. Then, the variation of perishable FSC considered in existing studies is reviewed in Section 2.2. In addition, the literature on decentralization of food processing is reviewed in Section 2.3.

2.1. Modelling perishability in FSC network design

In FSC models, mixed-integer (non-)linear programming (MILP) plays a dominant role (Paam et al., 2016; Soto-Silva et al., 2016; Yadav et al., 2022). Modelling perishability of product flows in these models is typically included in two ways: 1) using a fixed shelf life or 2) considering a gradual deterioration process (Jonkman et al., 2019; Lejarza & Baldea, 2022; Patidar & Agrawal, 2020b).

In fixed shelf-life approaches, product quality is considered to be constant during a fixed time period without any change and becomes unsuitable for consumption immediately after that time period. Many studies use shelf-life constraints to restrict the sojourn time of the product in the supply chain or at a specific stage. For instance, Yakavenka et al. (2020) introduce an upper bound at transportation time to model perishability and optimize a sustainable supply chain network for perishable food. Similarly, Govindan et al. (2014) use a maximum storage time. Alemany et al. (2021), Esteso et al. (2021), and Patidar and Agrawal (2020a, 2020b) propose discrete-time MILP models with fixed shelf life parameters and assume immediate expiration incurring penalty costs after the shelf life. Biuki et al. (2020) incorporate the maximum storage time for inventories at manufacturing and distribution centres in a location-routing-inventory problem in the sustainable supply chain network design for perishable products. Shakuri and Barzinpour (2024) restrict the sojourn time of products to no longer than the shelf life to evaluate a risk-averse strategy for the perishable FSC. Hajimirzajan et al. (2021) integrate perishability in a supply chain planning model that considers sustainable climate-smart crop planning and complementary markets by restricting the time that products remain in the cold store.

However, fixed shelf life approaches overlook the fact that products deteriorate gradually over time in the supply chain, even within the estimated fixed shelf life (Janssen et al., 2016). Some studies reflect product perishability by modelling the increase in product quantity loss over time. For instance, Yu and Nagurney (2013) use an exponential function to describe product quantity losses depending on the sojourn time but ignoring quality deterioration. Nourbakhsh et al. (2016) introduce a quantity loss ratio representing product loss per time period and assumes a constant travel time for each path to calculate the product quantity loss throughout the supply chain. The product value depreciation (quality loss) during the processing stage is calculated as well using the same method. Similarly, Biza et al. (2024) introduce a deterioration rate to calculate the quantity loss of product per time period.

Only a few studies use a continuous function to model quality deterioration in FSC network design. Bortolini et al. (2016) and Musavi and Bozorgi-Amiri (2017) describe continuous quality deterioration over time in multi-objective MILP models, of which one objective is to maximize the quality of sold products. Both model the quality deterioration of products using a market purchase probability function, assuming that the probability of market purchases of food declines linearly with transportation time. Li and Zhang (2024) incorporate gradual deterioration by assuming that the freshness of perishable foods declines linearly from one to zero during the shelf life. Khazaeli et al. (2024) consider time-dependent quality, where time depends on transportation distance and speed to measure costs related to quality loss in a supply chain network design model of vegetables.

Other studies use discrete-time models to model quality deterioration in FSC network design. They introduce discrete quality levels as indexes of product flow variables and use changes in these quality indexes to represent product quality. Bolívar et al. (2025) use a selling price that depends on product quality to incorporate product perishability into a network design model. Esteso et al. (2022) use the remaining shelf life as an index of product flows to indicate product freshness in a multi-objective MILP model, of which one objective is to maximize the total profits. The remaining shelf life decreases over days, and the prices of products decrease accordingly. Based on the last study, Esteso, Alemany, and Ortiz (2024), Esteso, Alemany, Ortiz, and Iannacone (2024) extend the model into a multi-objective one considering sustainability, and Esteso, Alemany, and Ortiz (2024), Esteso, Alemany, Ortiz, and Iannacone (2024) further extend the multi-objective model by adding a minimum quality requirement. Similarly, Jonkman et al. (2019) use a quality index which can represent different quality indicators (such as age) depending on the specific case, but always decreases linearly over time in the entire chain. Additionally, price parameters varying with quality levels and penalty costs for discarded products are incorporated to maximize the total gross margin.

Other real-world factors than time that can influence the deterioration of product flows, such as changes of environmental conditions in supply chains or processing treatments that products undergo throughout the supply chain, are hardly considered. Han et al. (2021) confirm that the post-harvest loss is highly dependent on the time, environmental conditions, and supply chain stages. However, to reduce the complexity, they assume an ideal environmental condition in a production and distribution planning model. Nourbakhsh et al. (2016) calculate quantity loss and value loss of grains in the supply chain by considering different loss ratios during transportation, pre-processing, and processing stages in a network design problem. Orjuela-Castro et al. (2017) follow a comparable approach by considering loss ratios due to changing temperatures and humidity during transportation in a location problem. To the best of the author's knowledge, no study takes, besides sojourn time, other influencing factors of product perishability into account in discrete-time models for FSC network design.

2.2. Variety in perishable food supply chains

The geographical regions and perishable FSC types covered in existing FSC network design studies are various, as summarized in Table 1. Most of these studies present case-based models except for Esteso et al. (2022) and Biuki et al. (2020). Many recent research focus on case studies from developing countries in a wide range of regions, including Latin America (Argentina (Esteso, Alemany, & Ortiz, 2024; Esteso, Alemany, Ortiz, & Iannacone, 2024; Alemany et al., 2021; Esteso et al., 2021), Colombia (Bolívar et al., 2025)), South Asia (India (Patidar &

Table 1. Comparison of supply chain stages and case study characteristics in existing models.

Articles	Farm	Pre-processing facilities	Primary processing factories	Manufacturing plants	Distribution centres	Separate storage	Market	Flexibility of adding new stages	Region	Product
Bolívar et al. (2025)	X		X(S)				X		Columbia	Fruits, vegetables
Esteso, Alemany, Ortiz, and Iannacone (2024)	X(S)		X		X		X		Argentina	Tomato
Biza et al. (2024)	X			X	X	X	X		Ethiopia	Tomato
Li and Zhang (2024)	X				X(S)		X		China	Fruit
Shakuri and Barzinpour (2024)	X			X(S)	X(S)		X		Iran	Beef hamburger, Chicken sausage
Khazaeli et al. (2024)	X		X		X(S)		X		Iran	Vegetable
Esteso, Alemany, Ortiz, and Iannacone (2024)	X(S,P)						X		Argentina	Tomato
Esteso et al. (2022)	X(S)						X		N	N
Alemany et al. (2021)	X(S,P)						X		Argentina	Tomato
Hajimirzajan et al. (2021)	X					X	X		Iran	Tomato
Han et al. (2021)	X				X(S)		X		China	Tomato
Esteso et al. (2021)	X				X(S)	X(P)	X		Argentina	N
Biuki et al. (2020)	X			X(S)	X(S)		X		N	N
Yakavenka et al. (2020)					X(M)		X		Eastern Europe	Fruit
Patidar and Agrawal (2020b)	X				X(M)		X(S)		India	Vegetable
Patidar and Agrawal (2020a)	X				X		X(S)		India	Vegetable
Jonkman et al. (2019)	X(S)			X(S)			X		Netherlands	Sugar beet
Bortolini et al. (2016)	X				X(M)		X		Europe	Tomato, apple, orange, pear and potato.
This article	X	X(S)	X	X(S)		X	X	X	China	Orange

S: with storage; P: with packing; M: multiple levels of distribution centre; N: not specified

Agrawal, 2020a, 2020b)), East Asia (China (Li & Zhang, 2024; Han et al., 2021)), Sub-Saharan Africa (Ethiopia (Biza et al., 2024)), and the Middle East (Iran (Shakuri & Barzinpour, 2024; Khazaeli et al., 2024; Hajimirzajan et al., 2021)). A few studies focus on case studies from Europe (Bortolini et al., 2016; Jonkman et al., 2019; Yakavenka et al., 2020). There has been no case study focusing on North America or Australia yet. Most studies focus on single-product supply chains, typically involving fruits or vegetables. Shakuri and Barzinpour (2024) is the only study that examines a supply chain for meat products (beef burgers and chicken sausages). While the majority of these studies consider primary agri-food products, only Shakuri and Barzinpour (2024) and Jonkman et al. (2019) specify products requiring manufacturing processes.

Given the variation among supply chains for different products and regions, the supply chain stages considered in existing studies are diverse. Additionally, the functions assigned to each supply chain stage differ across studies, as highlighted in Table 1. For instance, distribution centres are commonly included in network design studies. However, the storage function of distribution centres is only considered in Li and Zhang (2024), Shakuri and Barzinpour (2024), Khazaeli et al. (2024), Han et al. (2021), Esteso et al. (2021), and Biuki et al. (2020). Moreover, only Yakavenka et al. (2020), Patidar and Agrawal (2020b), and Bortolini et al. (2016) account for distribution centres with multiple regional levels. Another example is that only a few studies consider primary processing factories, manufacturing plants, or separate storage facilities in the models, and none combine all three stages. Notably, no existing study considers the inclusion of pre-processing facilities.

Remarkably, no existing study has addressed the flexibility of redesigning an existing supply chain by adding new stages or adjusting the functions of existing stages. This gap may originate from the fact that supply chain configurations are often case-specific, highly influenced by geographical and product-dependent conditions. A generic modelling framework could be valuable for capturing the fundamental considerations needed for network design, particularly taking product perishability into account. Such a framework could be especially useful for the redesign of a supply chain, providing essential insights before practical implementations.

A notable recent contribution in this area is Jonkman et al. (2019), who proposes a general MILP model that incorporates food perishability. This study focuses on integrating harvest decisions and processing pathways choices into supply chain network design. However, the model does not offer the possibility of adding new supply chain stages.

Thus, the question of how to generalize a flexible modelling framework for the FSC network redesign remains unresolved in literature.

2.3. Decentralization of food processing in network design

The location of (pre-)processing is a key issue in the design of FSC networks (Annapure et al., 2022; Ghoshal, 2018). Currently, most food products are processed in large, centralized facilities (Almena, Lopez-Quiroga, et al., 2019). While centralized processing offers high efficiency, it can lead to lengthy and rigid supply chains and cause product quality loss during transportation (Almena, Lopez-Quiroga, et al., 2019). To overcome these drawbacks, some studies have explored decentralized processing, where processing occurs on a smaller scale (Almena, Fryer, et al., 2019).

Several studies have highlighted the benefits of decentralized processing in food-related fields, particularly in terms of economic profitability and resource utilization. Almena, Fryer, et al. (2019), Almena, Lopez-Quiroga, et al. (2019), and Almena et al. (2020) have considered decentralized processing in food processing system design. Psathas et al. (2022), Kang et al. (2021), and Bruins and Sanders (2012) have included it in biomass (food waste) processing. They address the advantage of decentralized processing on resource utilization. Urra-Calfuñir et al. (2024) develop a MILP production planning model for olive oil supply chains using mobile olive oil mills to demonstrate the advantage of decentralized processing in terms of profitability.

Only a few studies consider the impact of decentralized processing on quality preservation. Nourbakhsh et al. (2016) add optional pre-processing nodes in the redesign of a grain supply chain, demonstrating that decentralized pre-processing can reduce post-harvest losses. The study accounts for product quantity losses by using loss rate parameters. The study does not consider the gradual decline of product quality. Jonkman et al. (2019) develop a multi-objective MILP, in which a product quality index changes over time. The authors introduce several processing components, which can replace the previous processing stage. The results of the case study highlight the economic and environmental benefits of decentralized processing in a sugar beet supply chain.

To conclude, the existing literature on FSC network (re)design highlights several important gaps that this study aims to address. First, the gradual quality deterioration of products is hardly considered in FSC network design. The few studies that have considered gradual product deterioration take solely time as the primary factor influencing quality deterioration, neglecting other critical factors such as environmental conditions and processing treatments. Second, current research considers predefined supply chain structures, making it difficult to apply the developed model to other cases with different supply chain echelons. There is no generic and flexible modelling framework available that enables adding new stages or adjusting the functions of existing stages for FSC network redesign yet. Third, the benefit of decentralized pre-processing for improving product quality preservation remains underexplored, with limited attention to its integration into supply chain network design models.

3. Network design model

In order to study a network for perishable items, we first describe a generic network by using a set of nodes N and a set of arcs $A \subseteq N \times N$. Commonly, nodes can be interpreted as physical entities at certain geographical locations, such as for instance production, storage, or processing facilities. The arcs in a network graph represent possible material flows between nodes. To enhance the applicability of the generic network model for product-specific supply chains, we introduce two modelling structures consisting of artificial nodes. These structures allow to split up a physical entity into multiple sub-nodes connected by arcs.

To model quality deterioration over time we consider a finite number of time periods T indexed by $t \in \{1, 2, ..., T\}$. All products are assumed to be of a specified quality level $q \in Q \subset \mathbb{N}$ that declines over time. To achieve this, a quality deterioration parameter $\delta(n)$ is introduced to describe how the quality of the products changes at node n in the network. Thus, a product of quality level $q + \delta(n)$ in time period $t - 1$ turns into quality level q in period t if stored at node n.

Note that $\delta(n)$ depends on the current location n, indicating that even within the same supply chain, the quality deterioration process may differ by location due to different environmental conditions per location. For example, the quality deterioration rate in a cold store may differ from that in a regular storage at ambient temperature.

Inventory levels for products of quality level q at each location $n \in N$ at the end of time period $t \in T$ are denoted by I_{ntq}. For every arc $(n, m) \in A$, a variable x_{nmtq} is introduced to describe the material flows for products of quality $q \in Q$ shipped from location $n \in N$ to location $m \in N$ at the end of time period t. The corresponding material flow losses (e.g., by waste) on an arc (n, m) are described by the factor ω_{nm}. Similarly, weight losses of inventory (e.g., due to evaporation during storage) at a node n

is included by σ_n. In addition, we define the set of predecessors of a node $n \in N$ by

$$P(n) := \{m \in N \mid (m,n) \in A\}$$

and for the set of successors, we put

$$S(n) := \{m \in N \mid (n,m) \in A\}.$$

Using this, the inventory levels from one time period to the next at each node n change according to the following equation, as illustrated in Figure 1.

$$I_{ntq} = \sigma_n I_{n(t-1)(q+\delta(n))} + \sum_{m \in P(n)} \omega_{mn} x_{mntq} - \sum_{m \in S(n)} \omega_{nm} x_{nmtq} \quad \forall t \in \{1,\dots,T\}, q \in Q, n \in N$$

For each node n, there are upper bounds $I_n^{\max}$ and lower bounds $I_n^{\min}$ for inventory levels. This can reflect real-world limits on the inventory capacity of node n. Analogously, network inflows are bounded by $F_n^{\max}$ and $F_n^{\min}$, which may represent processing capacity limits at node n. In order to include or exclude certain nodes, a binary variable y_n is introduced, which is set to one if location n is used and zero otherwise. If a node n is not used in the network, there must be no inventory level and no material flow. Otherwise, the aforementioned lower and upper bounds are enforced. This is expressed by the following equations:

$$F_n^{\min} y_n \le \sum_{m \in P(n)} \sum_{q \in Q} x_{mntq} \le F_n^{\max} y_n \quad \forall n \in N, t \in \{1,\dots,T\}$$

$$I_n^{\min} y_n \le \sum_{q \in Q} I_{ntq} \le I_n^{\max} y_n \quad \forall n \in N, t \in \{1,\dots,T\}$$

To conclude, together with objective coefficients operating costs c^x associated with product flows x_{mntq}, holding costs c^I associated with inventory levels I_{ntq} and opening costs c^y associated with binary variable y_n that indicates if facility n is opened, the aforementioned considerations lead to a generic model of the following network flow problem with perishability (NFPP), as outlined below in Equations (1)–(7).

$$\max \sum_{t \in \{1,\dots,T\}} \left(\sum_{m,n,t,q} c^x_{mntq} x_{mntq} - \sum_{n,t,q} c^I_{ntq} I_{ntq} - \sum_{n} c^y_n y_n \right) \tag{1}$$

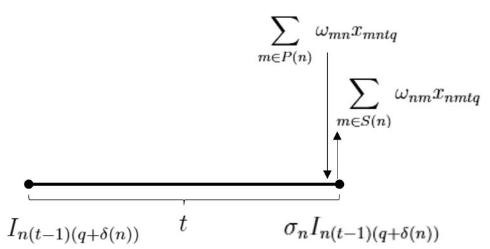


Figure 1. Schematic diagram of changes in inventory levels over time.

s.t.

$$I_{ntq} = \sigma_n I_{n(t-1)(q+\delta(n))} + \sum_{m \in P(n)} \omega_{mn} x_{mntq} - \sum_{m \in S(n)} \omega_{nm} x_{nmtq} \quad \forall t \in \{1,\dots,T\}, q \in Q, n \in N \tag{2}$$

$$F_n^{\min} y_n \le \sum_{m \in P(n)} \sum_{q \in Q} x_{mntq} \le F_n^{\max} y_n \quad \forall n \in N, t \in \{1,\dots,T\} \tag{3}$$

$$I_n^{\min} y_n \le \sum_{q \in Q} I_{ntq} \le I_n^{\max} y_n \quad \forall n \in N, t \in \{1,\dots,T\} \tag{4}$$

$$x_{nmtq} \ge 0 \quad \forall (n,m) \in A, t \in \{1,\dots,T\}, q \in Q \tag{5}$$

$$I_{ntq} \ge 0 \quad \forall n \in N, t \in \{1,\dots,T\}, q \in Q \tag{6}$$

$$y_n \in \{0,1\} \quad \forall n \in N \tag{7}$$

Equation (1) expresses that the model's objective is to maximize the total profit of the supply chain. Equations (2)–(4) are the formulas described in the former text, describing the process of product quality deterioration over time, facility inventory capacity constraints, and facility processing capacity constraints, respectively. Equations (5) and (6) are the non-negativity conditions. The binary variables are defined in Equation (7).

A key advantage of the way the proposed NFPP model has been formulated is that it allows for adding artificial nodes, either in a serial manner or in parallel. In order to incorporate multiple processing steps within a single facility, we can split a node k into multiple artificial serial nodes $k_1,\dots,k_K$. Each of these artificial nodes represents a single processing step, despite the fact that they may be performed at the same geographical location. Then, every in-flow to node k, arc $(n,k) \in A$, is replaced by a new arc (n,k_1). Analogously, every out-flow arc (k,m) is replaced by (k_K,m). Moreover, we connect every single processing step by adding the arcs $(k_1,k_2),\dots,(k_{K-1},k_K)$. In this way, different rates of quality deterioration during various processing steps can be described by setting suitable deterioration parameters $\delta(k_1),\dots,\delta(k_K)$. The required network changes are depicted in Figure 2.

As an example of parallel artificial nodes, we consider the case of a cold store that can operate at different temperatures in different compartments, leading to different quality deterioration processes. This can be described by replacing a node k with multiple nodes $k_1,\dots,k_K$ in parallel, each representing different temperatures in the same cold store. More precisely, each in-flow arc $(n,k) \in A$ is replaced by multiple arcs $(n,k_1),\dots,(n,k_K)$, and each our-flow arc $(k,m) \in A$ is replaced by

$(k_1, m), \ldots, (k_K, m)$. The required changes are depicted in Figure 3.

In this way, different quality deterioration rates $\delta(k_i)$ may be imposed for each artificial node k_i with $i \in \{1, \ldots, K\}$. The objective vectors c_x, c_I and c_y are adapted accordingly to account for different energy costs at different temperatures. To ensure

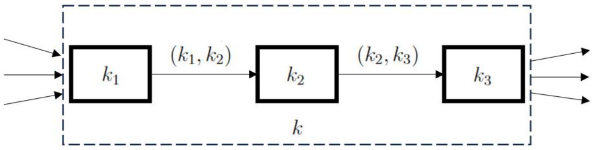


Figure 2. Adding an artificial node in a serial setting.

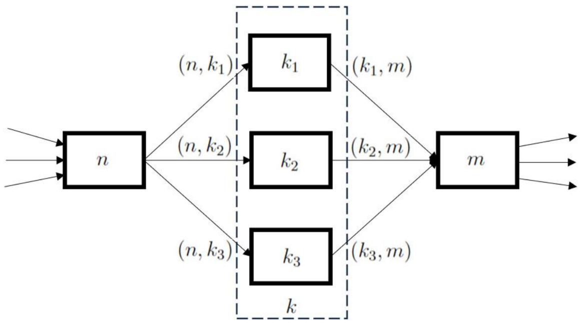


Figure 3. Adding an artificial node in a parallel setting.

unique conditions at a certain geographical location (e.g., the entire cold store is operated at the same temperature), the following constraints should be added:

$$\sum_{i=1,\ldots,K} y_{k_i} = 1$$

$$y_{k_i} \qquad i = 1, \ldots, K$$

4. Illustrative application

In Section 4.1, the basic NFPP model is utilized for a base scenario to demonstrate its applicability in a specific, practical context. In Section 4.2, the serial and parallel ways of adding artificial nodes and their combination are applied to three redesigned scenarios of the same network. Finally, in Section 4.3, the results of these different scenarios are compared to demonstrate that decentralized (pre-)processing may be a vehicle to better performance of FSCs because the unavoidable aging of product flows can be slowed down.

The case study refers to a Chinese orange supply chain that has been visited onsite. Citrus fruits, particularly oranges, are among the most produced and consumed fruits globally (Spreen et al., 2020; Strano et al., 2022). China is one of the leading producers of

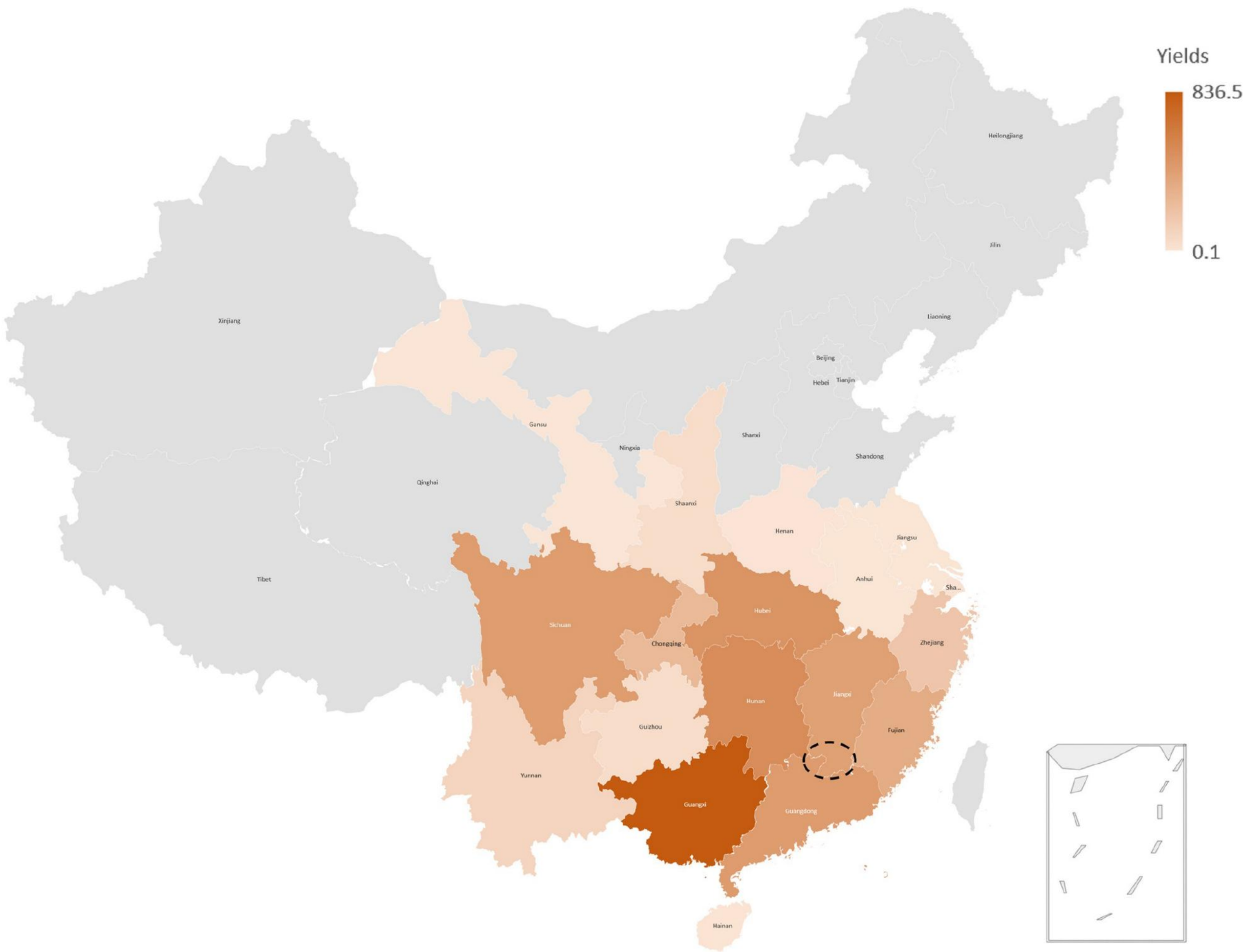


Figure 4. Location of the studied Gannan area in the heat map of annual citrus yields (million tons/year) in China.

citrus fruits and oranges (Spreen et al., 2020). The supply chain studied is located in the Gannan area (see Figure 4), which is renowned for its navel orange production (Hu et al., 2014). Case study data were collected through in-person interviews with stakeholders during on-site visits, supplemented by local government statistics. The interviewed stakeholders included small to large-scale farmers, processors at various stages of processing, transporters, and government officials.

4.1. Base scenario

The existing network involves 354 facilities, including production areas, primary processing factories, storage facilities, and intensive manufacturing plants. Two final nodes represent: 1) the market for fresh high-quality oranges and 2) the market for processed products of lower-quality oranges (e.g., juice production).

Products are harvested at production areas (nodes 1–151) and mostly delivered to primary processing factories (nodes 152–189). At these factories, products undergo several activities (e.g., washing, sorting, or packaging) before being sold to the fresh market (nodes 355) or stored in the factory. When the factory storage capacity is insufficient, the remaining products are transported to and stored at separate storage facilities (nodes 190–349), which are commonly in the mountain area. By doing so, oranges can be stored at lower temperatures using natural cooling without a cold store. When needed, these products are retrieved from mountain storage, transported back to factories, reprocessed, and sold.

In addition to products destined for the fresh market, it is crucial to note the existence of low-quality products that do not meet fresh consumption standards. From the production areas or primary processing factories, low-quality products that meet the minimum quality requirement can be sold to intensive manufacturing plants (nodes 350–354). In these plants, products are further processed into food products like juice or candies and sold to the processed product market (node 356) or stored in the plants. The complete stakeholder network, encompassing all mentioned segments, is visualized in Figure 5.

All nodes are subject to constraints regarding processing capacity or storage limitations if they are in use. Processing capacity limits are imposed by setting total inflow quantities of products to a node. Storage limitations restrict the inventory level. Relevant parameters therefore include lower and upper bounds for processing capacity ($F_n^{\min}$ and $F_n^{\max}$) and storage capacity ($I_n^{\min}$ and $I_n^{\max}$). Table 2 outlines all nodes.

Regarding quality deterioration, certain parameters related to quality index q are introduced, including the initial quality of a product flow (q_0), and the quality deterioration rates (Δq_n) at different node $n \in N$. We use titratable acidity (TA) content as index q in this orange supply chain, as it is one of the orange characteristics that significantly affect the organoleptic quality of oranges (Caixeta-Filho, 2006; Zhang et al., 2022). According to research of Gao et al. (2019) on the quality deterioration of Gannan navel oranges, we assume that the initial quality level q_0 is at most 65. In each time period, product quality decreases from q to $q - \Delta q_n$, with Δq_n varying in each n. To link quality with the objective function, prices of products sold to fresh markets are assumed to be a linear function of q. Appendix 1 summarizes the values of objective coefficients used in the case study, foremost derived from stakeholders' input or site visits.

The time period is denoted as discrete values t from 1 to 6, corresponding to a one-month duration. This aligns with the six-month harvesting and selling season of the considered supply chain.

4.2. Alternative network configurations

Based on insights gained from on-site interviews, the economic performance is identified as the most

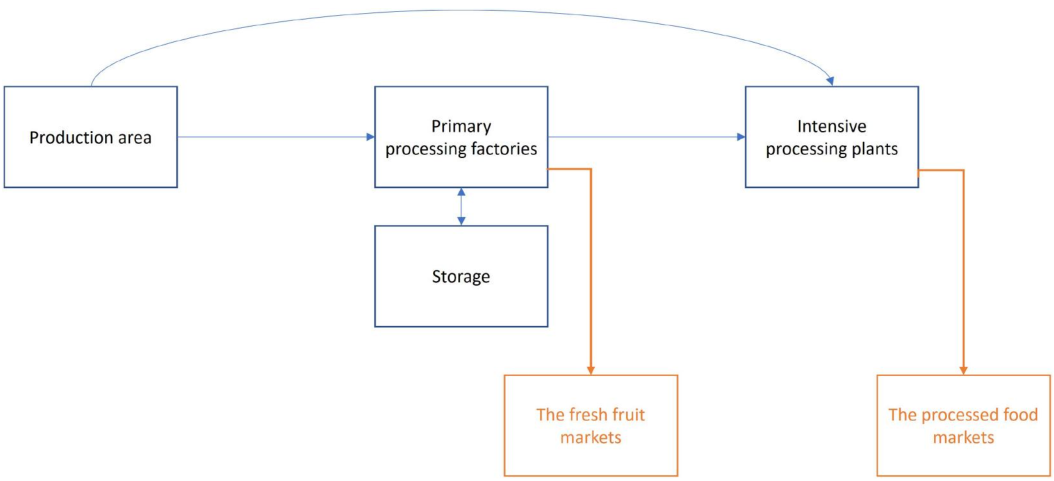


Figure 5. The network configuration in the base scenario.

critical optimization goal by local stakeholders. The overall profit of this navel orange supply chain can be increased by better maintaining product quality throughout the network. Post-harvest pre-processing is essential for mitigating quality deterioration and reducing product quality losses (Aked, 2002). Additionally, developing more suitable storage conditions with novel preservation technology is another typical approach. Therefore, we examine three scenarios for redesigning the network to mitigate quality deterioration and achieve a higher total profit: Scenario 1 considers decentralized pre-processing and storage, Scenario 2 explores different storage conditions for existing storage facilities, and Scenario 3 combines both approaches.

4.2.1. Scenario 1: Sorting by serial design (sorting, serial)

In Scenario 1, decentralized pre-processing spots are introduced using the serial artificial node structure in Figure 2. This new type of facility includes the opportunity to perform the first two sequential post-harvest operations (pre-sorting and local storage) immediately after harvest near the orchards in the mountain region at low temperatures. Decentralized pre-processing spots enable farmers to carry out decentralized pre-processing themselves. In this way, farmers can classify oranges immediately after harvest, and sell homogeneous high-quality oranges to the fresh market or store them at favourable storage temperatures in the mountains. The alternative network flows are illustrated in Figure 6. A total of 152 options are offered for the placement of these decentralized pre-processing spots: 151 near each production area in the mountain region, and one at the geographical centre of all production areas.

Table 2. List of nodes.

Nodes No.	Represent
1–151	Production areas
152–189	Primary processing factories
190–349	Storage facilities
350–354	Intensive manufacturing plants
355	Fresh market
356	Processed market

4.2.2. Scenario 2: Cold store by parallel design (cold-store, parallel)

In Scenario 2, different conditions in the storage facilities are introduced by using the parallel artificial node approach in Figure 3. The existing storage condition from the base scenario is maintained as condition b. Two additional conditions are introduced: condition a, with higher holding costs and a lower quality deterioration rate, and condition c, with lower holding costs but a higher quality deterioration rate, as illustrated in Figure 7.

4.2.3. Scenario 3: Combined serial and parallel design (sorting and cold-store, combined)

Scenario 3 exemplifies the combined application of both serial and parallel artificial nodes. In this scenario, decentralized pre-processing spots from Scenario 1 can be opened, and one storage condition among conditions a, b, and c can be selected for each storage facility, as in Scenario 2. The

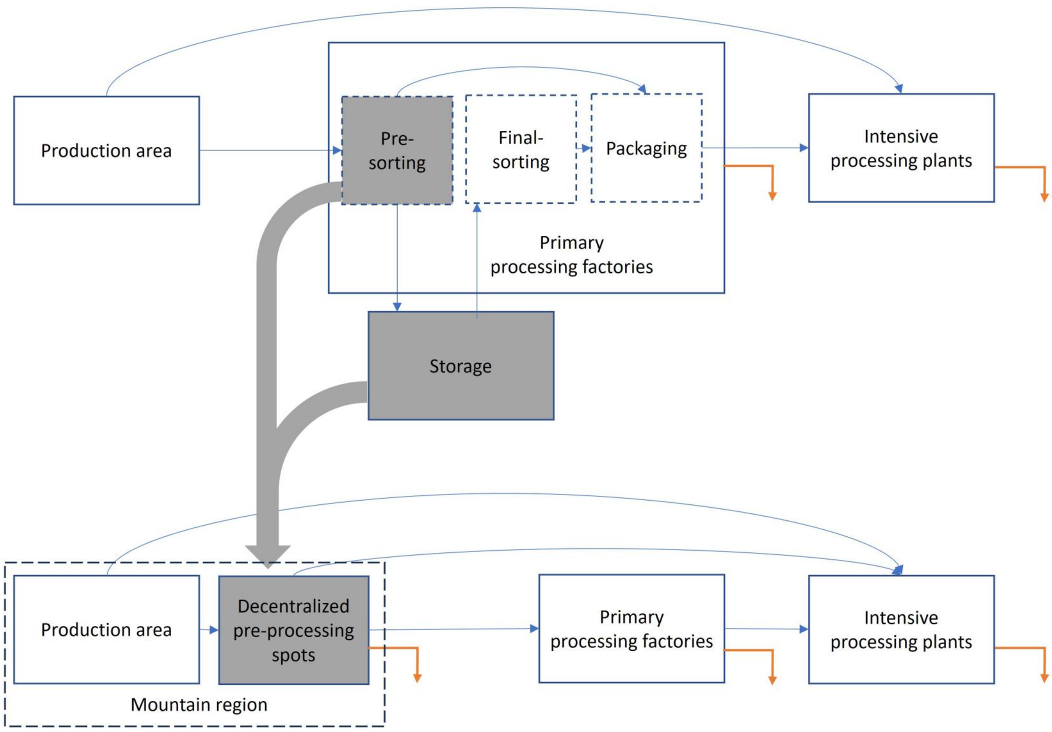


Figure 6. Adding decentralized pre-processing spots by the serial artificial node structure of the NFPP model.

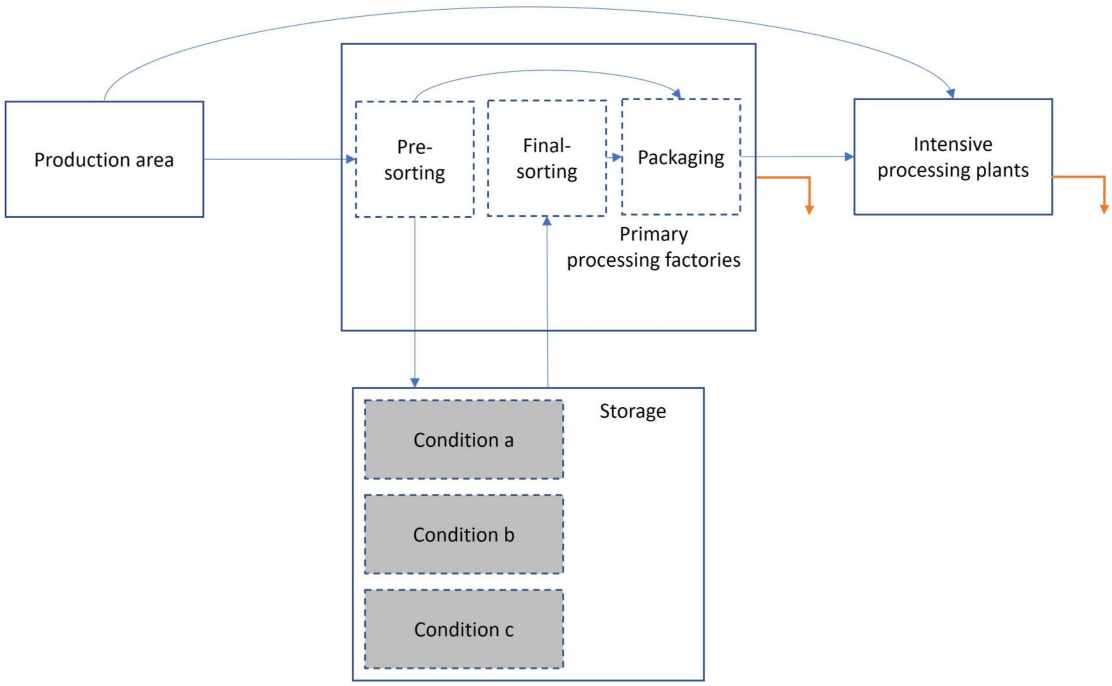


Figure 7. Adding different storage conditions by the parallel artificial node structure of the NFPP model.

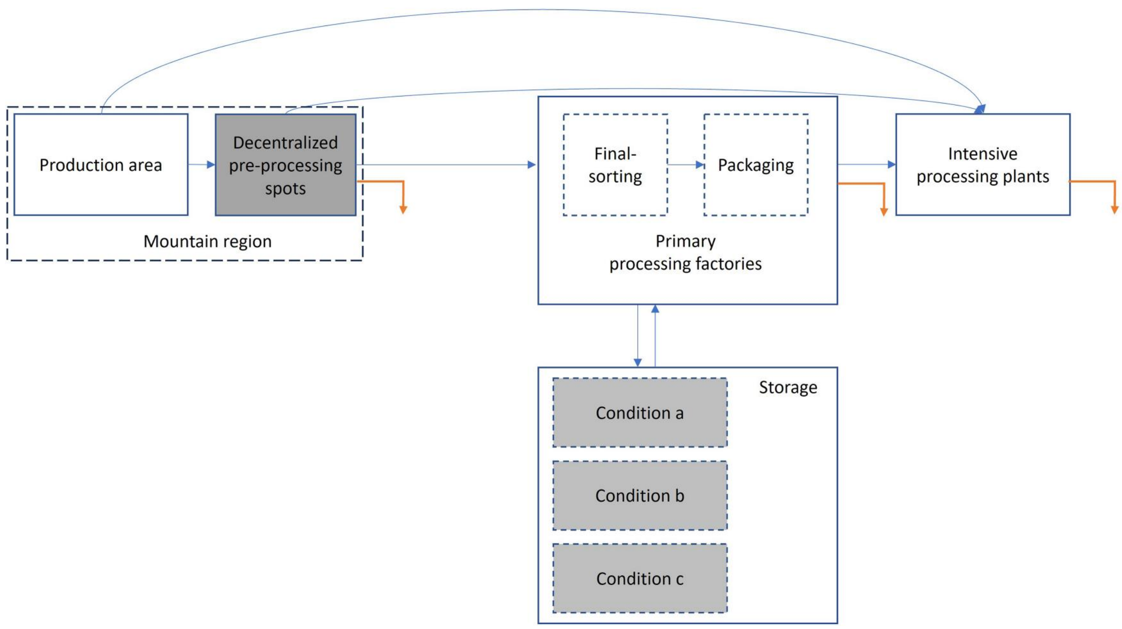


Figure 8. Adding decentralized pre-processing spots and different storage conditions by the combined serial and parallel artificial node structures of NFPP model.

combined network configuration is illustrated in Figure 8.

4.3. Results of different scenarios

This section presents and compares the results of different scenarios. The aim is to maximize total profit, calculated as the difference between revenue and several costs, including operational costs, transportation costs, holding costs, disposal costs, and raw product costs.

The model is implemented in PYTHON version 3.9 (Wilmington, DE, USA), using PYOMO to formulate the mathematical model. GUROBI version 10.01 (Beaverton, OR, USA) is used to solve the problem. The results are presented from five perspectives: the optimal network configuration, the economic performance of the supply chain, the quality distribution of products sold to the fresh market, environmental impacts, and social equity.

4.3.1. The optimal network configuration

The optimal network configurations in different scenarios are different. Figure 9 presents the network configuration of the base case in Section 4.1. Figures 10–12 show the network configurations in the

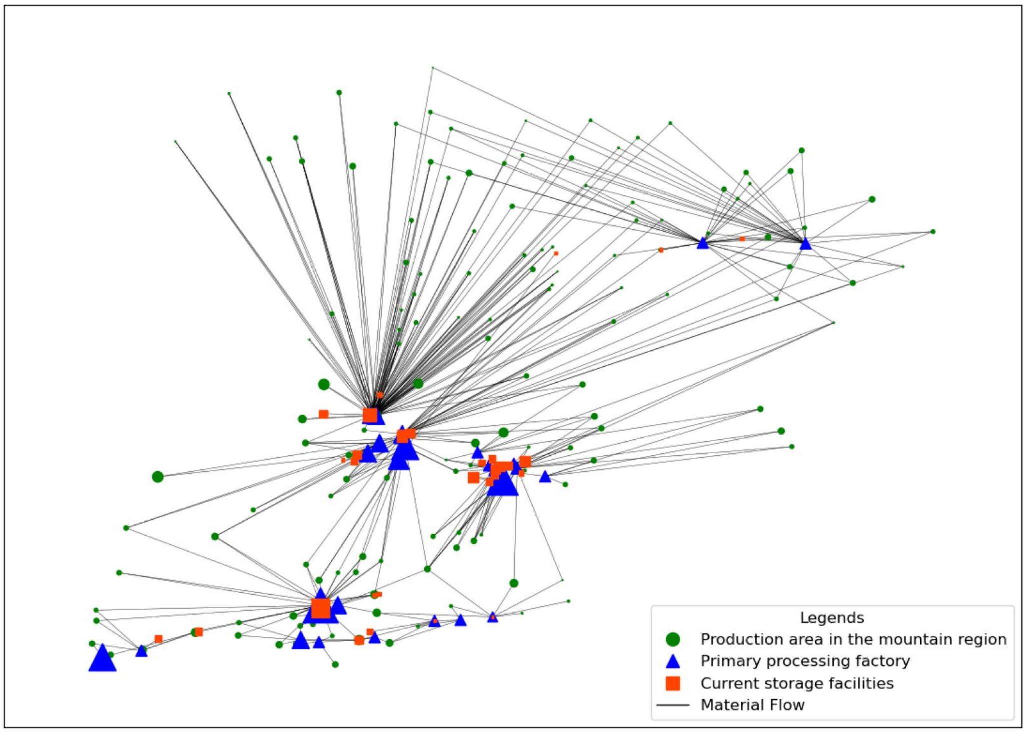
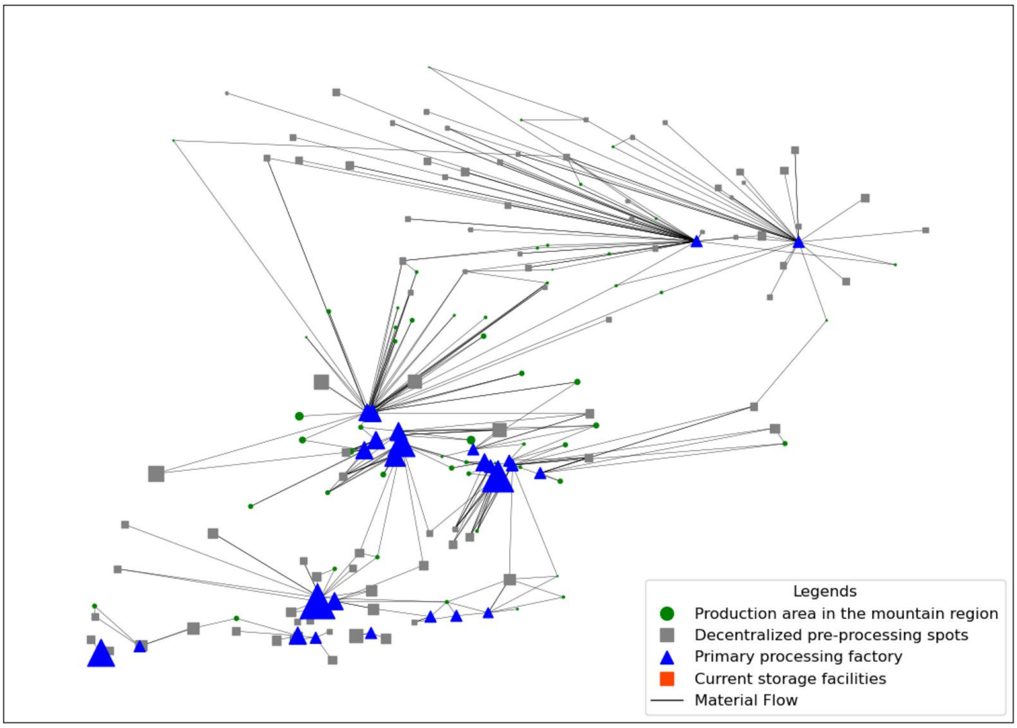


Figure 9. The optimal network configuration in the base scenario.

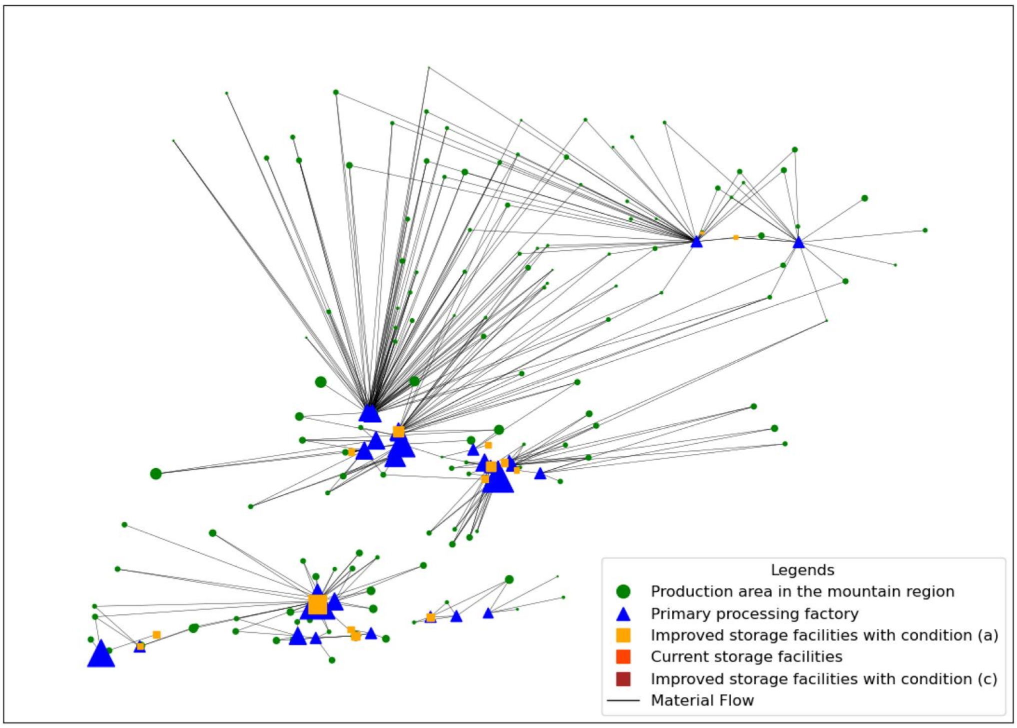


(1) Decentralized pre-processing spots are added.

Figure 10. The optimal network configuration in Scenario 1 (pre-sorting and serial).

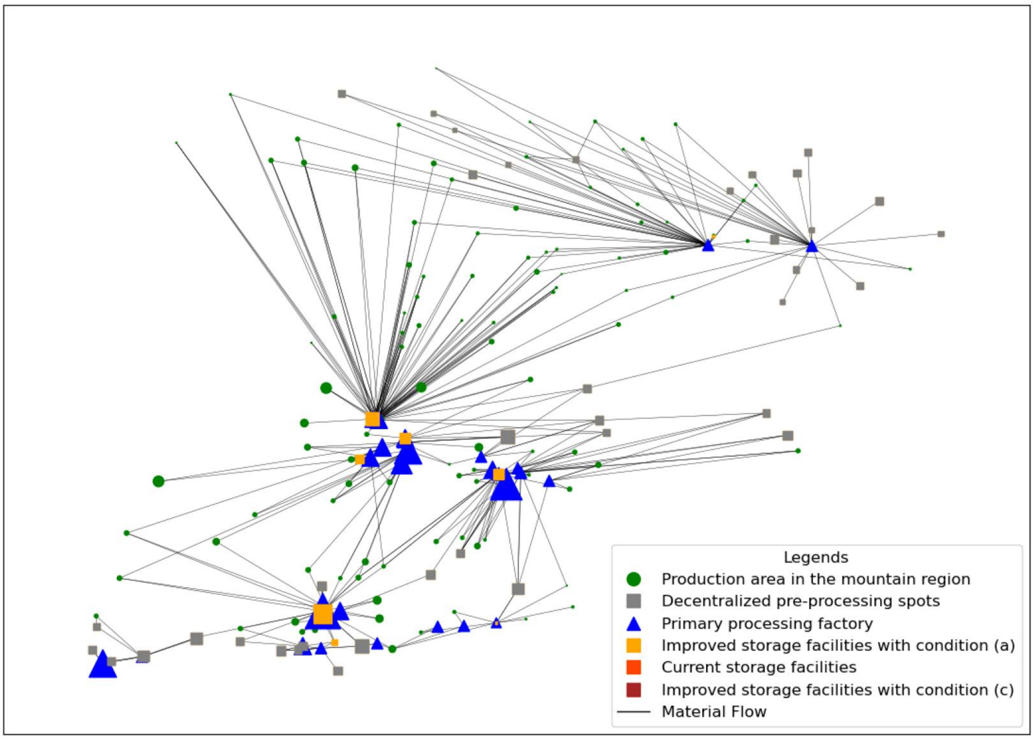
redesigned Scenarios 1–3 as described in Section 4.2. In the network configuration figures, nodes in different shapes and colours represent various types of facilities, and their sizes reflect the yield of production areas (green circles) or the capacity of processing plants (blue triangles) and storage facilities (orange-red squares). The arcs between the nodes represent the material flows in the network configuration.

In the base scenario, the network configuration consists of 37 primary processing factories, 46 storage facilities associated with primary processing factories, and two intensive manufacturing plants that are not shown in the figure due to distance. All 151 production areas are activated in all scenarios. As depicted in Figure 9, most product flows from production areas are centralized in several primary



(1) Improved storage conditions (a) and (c) of current storage facilities are added.

Figure 11. The optimal network configuration in Scenario 2 (improved storage and parallel).



(1) Decentralized pre-processing spots are added.

(2) Improved storage conditions (a) and (c) of current storage facilities are added.

Figure 12. The optimal network configuration in Scenario 3 (pre-sorting and improved storage, combined).

processing factories in the centre of the studied district.

For Scenario 1, the optimal network configuration with decentralized pre-processing spots (grey squares in the figure) is depicted in Figure 10. In this scenario, all storage facilities associated with primary processing factories are closed, while 91 decentralized pre-processing spots are opened. Compared to the base scenario, the most noticeable difference is the decentralization of product flows and processing places. Flows entering the primary processing factories at the centre of the studied district are reduced, while other factories become more pivotal as local centres. This shift is particularly evident when comparing the middle and upper right parts of Figures 9 with 10. The cause of this difference is that decentralized pre-processing spots enable farmers to add value to their product flows by sorting the harvested products locally and sell the products directly to the fresh market at higher price levels than in the case scenario.

For Scenario 2, the optimal network configuration with slower-deterioration (yellow squares) and faster-deterioration (brown squares) storage conditions is depicted in Figure 11. Compared with the base scenario, less storage facilities are used (26 in Scenario 2 *vs.* 46 in the base scenario). All utilized storage facilities opt for condition (a), which has a slower quality deterioration rate but higher holding costs. This demonstrates the importance of mitigating quality deterioration in achieving higher economic profits. Furthermore, the links between primary processing factories and storage facilities are more clustered around primary processing factories, as observed in the lower parts of Figures 9 and 11. The reason is that when the quality deterioration is mitigated and the holding costs increase, transportation costs are considered more important than in the base scenario, so the model searches for less storage facilities in shorter total transportation distances.

The optimal network configuration of Scenario 3, which combines decentralized pre-processing spots (grey squares) and different storage conditions (yellow, orange-red and brown squares) in the network redesign, is depicted in Figure 12. Compared with Scenario 1, fewer decentralized pre-processing spots (38 *vs.* 91) are opened in Scenario 3. Noticeably, all used decentralized pre-processing spots are located far from the central cluster of primary processing factories, mainly at the edges of this network, as observed in the lower and upper right parts of Figure 12. Compared to Scenario 2, the number of used storage facilities is further reduced to 12 in Scenario 3. This result indicates that adding decentralizing pre-processing spots is more beneficial for production areas far from central processing factories, while optimizing storage conditions is more important for centralized facilities storing large quantities of products.

4.3.2. Economic performance

The objective function value, representing the total profit, is the highest in Scenario 3. Compared to the base scenario, the total profit is 4.6% higher in Scenario 1, 6.7% higher in Scenario 2, and 7.2% in Scenario 3. The economic indicator values in all scenarios are summarized in Table 3.

When comparing the economic indicators in Scenario 1 with the base scenario, the revenue is 5.5% less but the total profit is 4.6% higher. This increase is mainly due to a 9.0% reduction in operational costs, as some products are pre-processed at decentralized pre-processing spots, which have lower operational costs compared to primary processing facilities due to cheaper labour. Additionally, raw product costs are 19.1% lower, because products pre-processed by farmers do not incur additional raw costs. Furthermore, transportation costs are reduced by 12.5% and holding costs are reduced by 1.7%, but these have few impacts on the objective value, as the amounts are relatively small in all costs. To conclude, this increase in profit suggests that it is beneficial to use the NFPP model with its sequential extensions to consider decentralized pre-processing in network redesign, as this can significantly reduce operational costs and raw material costs.

In Scenario 2, both the profit and revenue increase significantly, by 6.7% and 4.0% separately, compared to the base scenario. Most costs remain similar except holding cost, which increases by 213.8% due to maintaining improved storage conditions. The increase in profit and revenue shows that it is beneficial to consider alternative storage conditions in storage facilities using the NFPP model with its parallel extensions, suggesting that suitable investment in storage technology can enhance overall economic benefits.

Scenario 3 shows the best economic performance among all scenarios, offering the advantages of both decentralized pre-processing spots and improved storage conditions. Compared to the base scenario, the total profit is 7.2% higher. Compared to Scenario 1, the total revenue increases by 7.5% and all costs are reduced, increasing total profit by 2.5%. Compared to Scenario 2, the total revenue decreases by 2.3% while all costs are also reduced, so the total profit still increases by 0.5%. These results show that in this case, it is more beneficial to invest in storage condition improvement to enhance total profit. However, farmers cannot gain profit from this improvement. The best option is to consider the combination of decentralized pre-processing

Table 3. Economic indicator values (in millions RMB) in different scenarios.

Scenario	Profit	Revenue	Operational cost	Transportation cost	Disposal cost	Holding cost	Raw product cost
Base	1180.7	2610.7	728.6	2.4	0.6	11.6	686.8
1	1235.3	2468.4	663.3	2.1	0.6	11.4	555.7
2	1259.4	2715.5	729.9	2.4	0.6	36.4	686.8
3	1265.9	2653.5	709.9	2.2	0.6	33.2	641.8

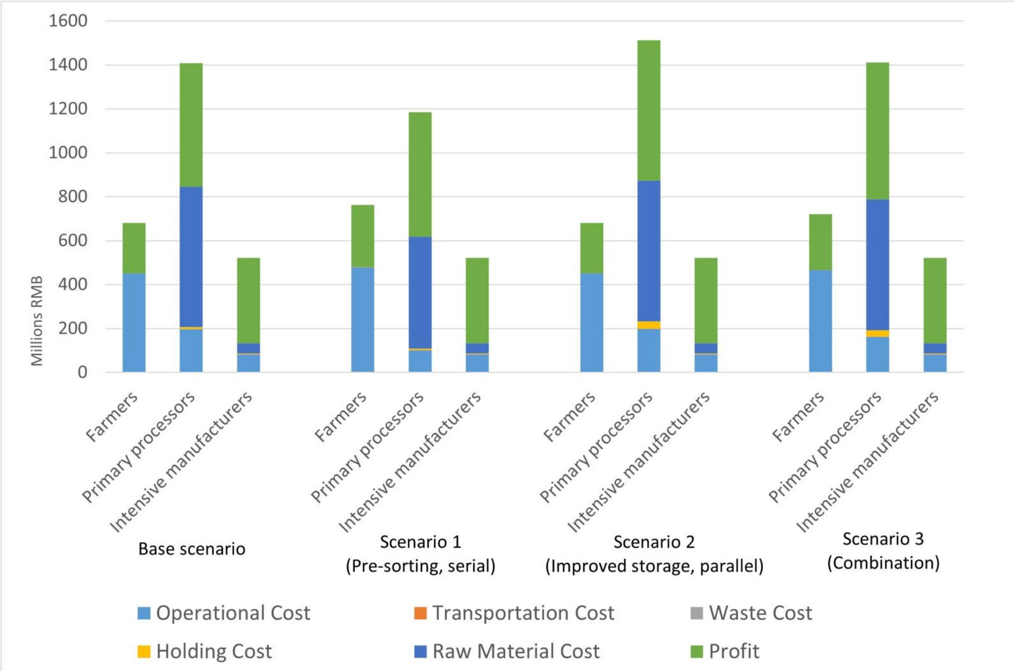


Figure 13. Costs and profits of all stakeholders in different scenarios.

spots and improved storage conditions to optimize both the economic performance of the entire chain and farmers' interests.

Figure 13 presents the costs and profits of all stakeholders in different scenarios in more details. Each bar in the chart illustrates the composition of costs and profits in the revenue for different stakeholders in the supply chain (farmers, primary processors, and intensive manufacturers) under one of the four scenarios. As can be seen from the figure, in Scenario 1, farmers' profits increase by 21.6% compared to the base scenario due to the decentralized pre-processing spots, while the operating, holding, and discarding costs are increased by 7%. Surprisingly, the increase in farmers' profits does not affect primary processors' profits, the later even increases slightly (0.8%) because all types of costs of primary processors are reduced, especially the raw material costs. In Scenario 2, primary processors are able to reach a (14.0%) higher profit than in the base scenario due to the improved storage. Their holding costs increase remarkably compared to the base scenario. However, these costs still remain a small portion (2.2%) of the total revenue. In Scenario 3, both farmers and primary processors gain higher profits (10.0% and 11.1%). The costs and profits of intensive manufacturers remain almost the same across all scenarios, as the quantity of intensively processed products is limited by the same processing capacity.

4.3.3. Quality distribution of products sold to fresh market

Besides economic performance, the network redesign also affects the quality of the final products, particularly those sold to the fresh market. The weighted average quality level of all products sold to the fresh market is 47.2 in the base scenario and Scenario 1 but increases by 4.6% to 49.5 in Scenario 2 and by 4.4% to 49.3 in Scenario 3. In more detail, the distributions of product quantity of different quality levels in different scenarios are shown in Figure 14.

As shown in the figure, in all scenarios, most products are sold immediately after harvest at the highest quality level $q = 65$, with the remaining products distributed across various quality levels. This proves the impact of product quality on the chain's profitability. The second most products are sold at various quality levels in different scenarios, with $q = 22$ (13.6%) in the base scenario, which improves to $q = 23$ (18.9%) in Scenario 1, $q = 38$ (12.3%) in Scenario 2, and $q = 33$ (13.9%) in Scenario 3. Additionally, the worst quality level of sold products is optimized in redesigned scenarios, which is $q = 22$ with 13.6% of sold products in the base scenario, remained as $q = 22$ but with only 1.9% of sold products in Scenario 1, developed to $q = 28$ (10.4% of sold products) in Scenario 2 and 3.

These improvements in product quality levels confirm that both decentralized pre-processing spots and improved storage conditions can improve the quality levels of sold products and thereby the total profit of the supply chain, demonstrating the necessity and importance of considering the product quality deterioration in the network (re)design. However, Scenario 2 rather than Scenario 1 or 3 performs the best regarding product quality levels,

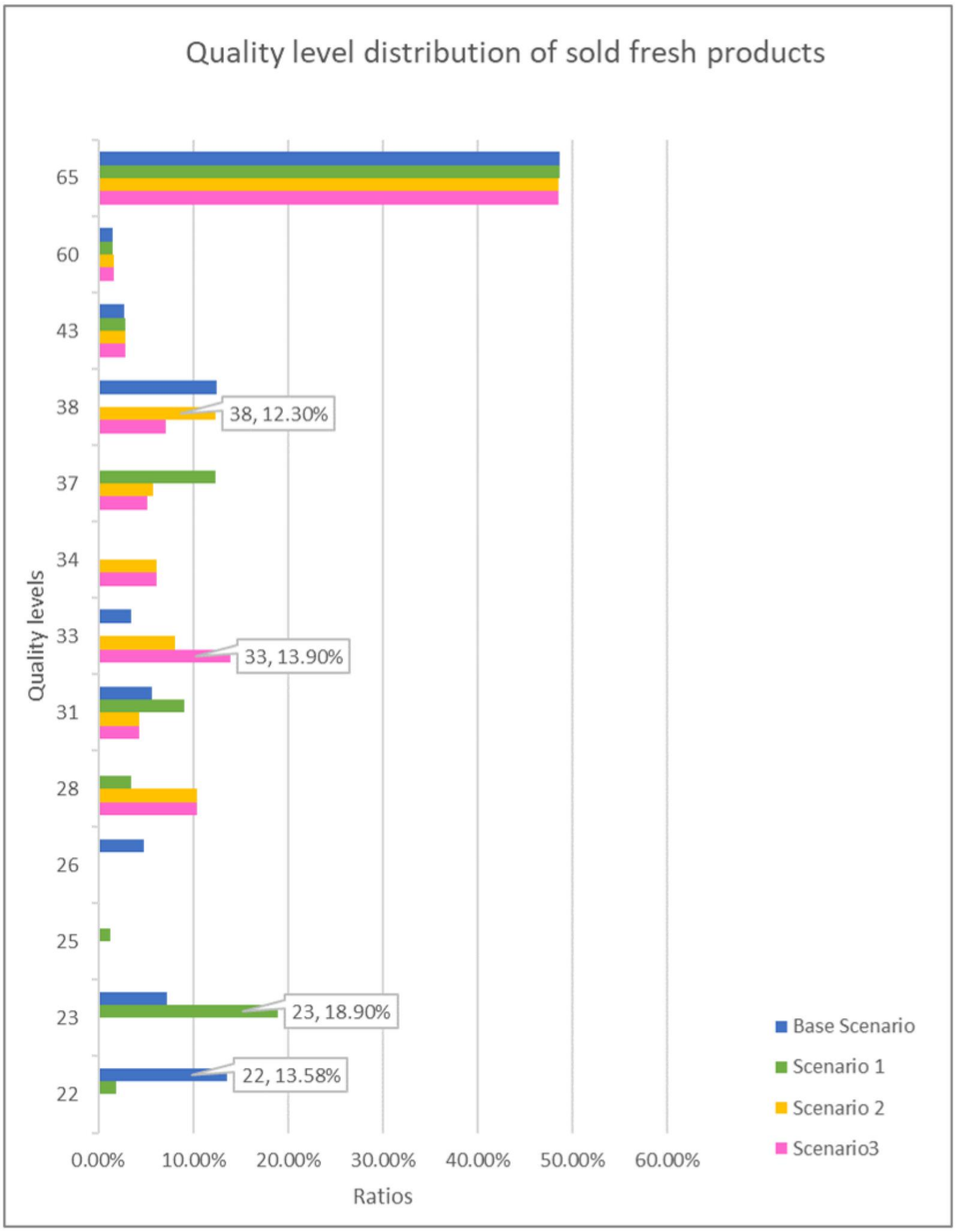


Figure 14. Quality level distributions in different scenarios.

suggesting that improved storage conditions are more effective in optimizing product quality levels than decentralized pre-processing spots. Moreover, the total profit in Scenario 2 is lower than in Scenario 3, suggesting that to optimize total profit of the supply chain, it is critical to not only mitigate product quality deterioration by improving storage conditions but also decrease costs by redesigning the network configuration.

4.3.4. Environmental impacts

The estimated energy usage varies across scenarios, highlighting the impact of network redesign on supply chain energy efficiency and therefore, on the environment. Specifically, Scenario 1 (decentralized pre-processing) and Scenario 3 (combination of decentralized pre-processing and improved storage) appear to reduce the total diesel usage while maintaining a comparable level of electricity consumption compared to the base scenario. This suggests that optimizing (decentralized) handling processes can contribute to substantial fuel savings without increasing electricity demand.

Figure 15 illustrates the total diesel (left vertical axis) and electricity usage (right vertical axis) under different supply chain scenarios (horizontal axis). The total diesel consumption (10^3 L) is depicted using blue bars, while the total electricity consumption (10^6 kWh) is represented by green bars.

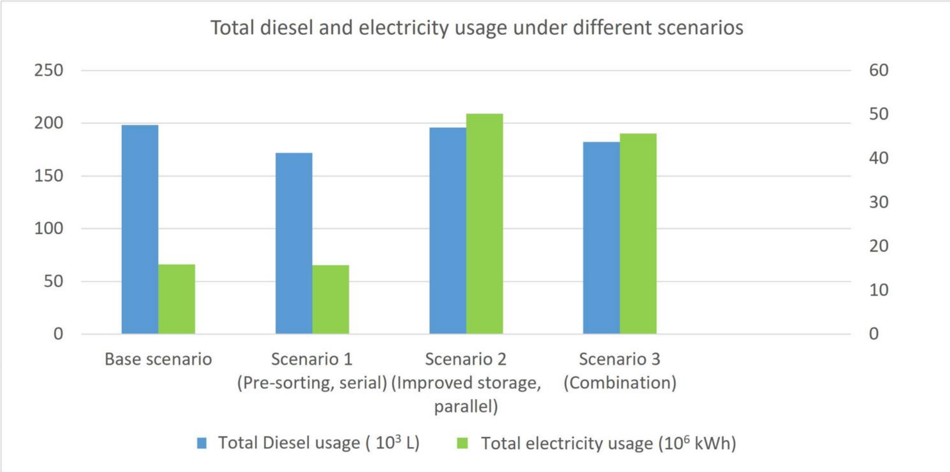


Figure 15. Total diesel and electricity usage under different scenarios.

Table 4. Profit distribution ratios among different stakeholders and changes from the base scenario.

Scenario (S)	Farmers	Primary processors	Intensive manufacturers
Base scenario	19.52	47.55	32.93
S1 (decentralized pre-processing)	22.69 (↑ 16.25%)	45.84 (↓ 3.61%)	31.47 (↓ 4.41%)
S2 (improved storage)	18.30 (↓ 6.25%)	50.83 (↑ 6.89%)	30.87 (↓ 6.25%)
S3 (combination)	20.03 (↑ 2.61%)	49.26 (↑ 3.58%)	30.71 (↓ 6.72%)

4.3.5. Social equity

In terms of social equity, Table 4 illustrates the impact of supply chain redesign on the profit distribution among farmers, primary processors, and intensive manufacturers. In the three redesigned scenarios, profit distribution shows a notable shift. In Scenario 1, where decentralized pre-processing is implemented, farmers experience the highest increase in their profit share, rising by 16.25%. Scenario 3 also yields a positive but smaller increase in the profit share of farmers.

While the profit distribution ratios of primary processors and intensive manufacturers decline in Scenario 1, it is crucial to take the absolute values for the profits (in Figure 13) into account. The results in Figure 13 show that instead of decreasing, the absolute profits of primary processors are increased. The decline in their relative share of the total profit is mainly due to the redistribution in favour of farmers, rather than an actual loss of income.

5. Discussion

5.1. Gradual quality deterioration in network design

This article introduces a generic modelling framework for the (re)design of Network Flow Problems with Perishability (NFPP). The framework is designed to optimize supply chain networks for a wide range of products, addressing a critical gap in the literature that network (re)design (such as done by Esteso et al. (2018)) and product perishability (such as addressed by Soler et al. (2021), Chen and Chen (2021), and Fu et al. (2019)) are often treated in isolation in the field of supply chain management (Yadav et al., 2022). The developed NFPP model integrates both dimensions, enabling flexible adjustments to product-specific deterioration processes and network configurations.

This study shows that considering quality deterioration in the (re)design of supply chains is essential, which is evidenced by the improved supply chain performance in the redesigned scenarios. When quality deterioration processes are different, the optimal network configuration and performance of the same chain will change accordingly. If this already holds for products like oranges with a high natural protection mechanism of peels, it should also be important for highly perishable products like soft fruits, dairy products, or meat. To further investigate this, more research is needed using the NFPP model and integrating it with knowledge from biological sciences on product deterioration (e.g., due to product-dependent respiratory, microbial, fungal, or enzymatic deterioration processes).

The model incorporates the impact of gradual quality deterioration on network design, considering deterioration-influencing factors beyond time, such as storage conditions and processing treatments. The illustrative case study on the Chinese orange supply chain uses unique deterioration rates of products under different storage conditions from Gao et al. (2019), demonstrating how the model accommodates the role of storage conditions in mitigating quality deterioration – a factor that is often oversimplified in network design models (Zhang et al., 2022). This finding aligns with Soto-Silva et al. (2016), who emphasize the need for tailored models in fresh (fruit) supply chains.

5.2. Model applicability

The proposed structures of artificial nodes (including the combination) can be used to model other supply chain situations than illustrated in the case study, thus enhancing the model's validity in different cases. For example, many existing studies, such as Li and Zhang (2024) and Shakuri and Barzinpour (2024), assume homogeneous environmental conditions within storage facilities, which may not accurately represent real-world variability. The serial artificial nodes can be used to model the changing environmental conditions in the supply chain. And the parallel artificial nodes enable the partitioning of facility compartments that operate under different environmental conditions.

The redesign option in the illustrative case study is decentralized pre-processing and improved storage condition, which can be replaced based on the product or technology. For example, highly perishable products like soft fruits may need better-controlled storage conditions to maintain their quality (Rong et al., 2011; Soto-Silva et al., 2016). In contrast, less perishable products, such as grains, may enable more centralized network designs to capitalize on economies of scale (Nourbakhsh et al., 2016). It is also valuable to extend the model with other redesign options, such as real-time adjustable storage conditions using the radio frequency identification technology (Fu et al., 2019) and other pre-processing treatments like pre-cooling (Lin et al., 2023).

In addition to the current monetary indicator, other key performance indicators from an environmental or social perspective can be used to define alternative objective functions. Moreover, the NFPP model can be extended by introducing a multi-objective approach. To increase awareness of decision-makers regarding trade-offs between different (conflicting) objectives, the set of efficient solutions can, for instance, be calculated using the ϵ-constraint method (Ehrgott, 2005) after incorporating corresponding parameters, such as done by Biswas et al. (2025) and Sharifi et al. (2023).

5.3. Decentralized pre-processing

The analysis reveals a trade-off between decentralized pre-processing and improved storage conditions, both of which impact supply chain performance in different ways. In terms of environmental impacts, decentralized pre-processing reduces both diesel and electricity consumption by shortening transportation distances and classifying raw materials before transit. In contrast, improved storage conditions rely heavily on energy-intensive refrigeration, leading to more than double the electricity use compared to the base scenario while maintaining a similar level of diesel consumption. These results align with previous studies, confirming the advantages of localized interventions in perishable food networks (Almena, Fryer, et al., 2019; Biuki et al., 2020; Urra-Calfuñir et al., 2024). However, improving storage conditions is more advantageous from an economic perspective, as it can increase sales of high-quality products and ultimately improve overall profitability. This confirms the positive impacts of upgrading preservation technology on extending product shelf lives and reducing waste found in other studies (Bolívar et al., 2025; Iqbal et al., 2024).

The trade-off extends to social equity along the supply chain, which is reflected by profit distribution ratios. Decentralized pre-processing increases the profit share of farmers. Conversely, improved storage conditions mainly benefit primary processors. A notable insight in Scenario 1 is that although the profit-distribution ratio of primary processors decreases, their absolute profits increase due to an overall increase in total supply chain profitability. This finding challenges the perception that improving equity in profit distribution comes at the expense of incumbent stakeholders (Cao & Zhang, 2011; Giannoccaro & Pontrandolfo, 2004). In this case, the farmers' share of the total profit increases without harming the existing economic interests at the primary processing level. Instead, the overall growth in supply chain value ensures that all stakeholders benefit. This result suggests that enhancing social equity and ensuring greater farmer participation in valorization activities does not by definition come at the expense of other stakeholders in the supply chain. Strategies that enhance overall supply chain efficiency and valorization can promote both economic growth and social equity at the same time (Cachon & Lariviere, 2005). This finding is partly aligned with Esteso, Alemany, and Ortiz (2024), who use the economic injustice among farmers to indicate social equity. Their findings also confirm that it is possible to enhance social equity without causing great economic damage to the supply chain by comprehensive planning of perishable FSC networks.

This study follows previous studies such as Almena, Fryer, et al. (2019) and Almena, Lopez-Quiroga, et al. (2019), using the energy demand (the total diesel usage and electricity usage) to indicate environmental impacts. However, in practice, primary indicators used to calculate the environmental impacts differ among supply chain stages. For example, pesticide usage, land use, and water consumption are widely used in the agricultural production stage, while less used in the transportation stage. Future studies can explore more on how to quantify the environmental impacts throughout the supply chain.

5.4. Managerial insights

The implementation of decentralized pre-processing facilities and improved storage technologies requires targeted policy support to overcome challenges related to investment costs, energy efficiency, and stakeholder coordination.

Decentralized pre-processing may be beneficial for reducing energy consumption, but requires adequate support to ensure its viability for small-scale farmers. Policies that promote access to finance for mobile (Lin et al., 2023) or small-scale processing units (Jonkman et al., 2019) could enhance the feasibility of decentralized processing infrastructure. Furthermore, the implementation of cooperative models or shared processing hubs could help address the scalability challenges associated with decentralization.

One critical challenge associated with improved storage conditions is the significant increase in electricity consumption. To mitigate this, policies should promote the adoption of energy-efficient refrigeration systems, particularly in regions where electricity costs are high or access to reliable power is limited. This is especially essential for developing countries.

Beyond investments in infrastructure, effective supply chain governance mechanisms are essential to ensure that the benefits of network redesign are distributed fairly. The findings reinforce previous research highlighting the need for collaborative actions in supply chain management (Plà et al., 2014; Vilalta-Perdomo & Hingley, 2018). Policymakers should explore contractual frameworks that align incentives among stakeholders, such as revenue-sharing agreements or funding programmes between wholesalers and farmers as demonstrated by Esteso et al. (2022).

6. Conclusions

This article aims to study the impact of gradual quality deterioration on the strategic (re)design of FSC networks. To achieve this, a generic modelling framework and two additional modelling structures using artificial nodes are introduced. The proposed model is applied to an illustrative case study, where decentralized pre-processing is implemented to redesign the network.

The presented model considers next to time other deterioration-influencing factors, such as storage conditions and processing treatments, enabling the modelling of product-dependent deterioration processes. The model offers a generic structure that can be applied to different network configurations and allows for flexible network redesign such as adding supply chain echelons or adjusting facility functions. The applicability of the proposed model is demonstrated from a case study of an orange supply chain in China, confirming that incorporating decentralized pre-processing influences the optimal network configuration, having positive impacts on the overall supply chain performance. Notably, the findings suggest that improving social equity and increasing farmers' participation in valorization activities do not necessarily come at the expense of other supply chain stakeholders.

While this study provides valuable insights into FSC network design considering quality deterioration, several limitations should be acknowledged. First, the findings are based on an orange supply chain exploiting local conditions like cold storage in mountains. Applying the NFPP model to various high- or low-perishable products, such as soft fruits or grains, could provide additional insights into the impact of quality deterioration on supply chain network design under different levels of perishability. The findings, based on a citrus supply chain in China, may also have limited generalizability to other products and regions, necessitating further validation across diverse contexts. Additionally, the model does not consider uncertainty. Integrating real-time disruptions, such as unexpected production cuts or demand changes, into the modelling framework would help to evaluate its robustness and adaptability to dynamic conditions. Moreover, multi-objective decision-making models can be developed to address trade-offs between economic, environmental, and social objectives, offering a holistic approach to supply chain network design. Lastly, the model assumes cooperative decision-making among stakeholders, which may not fully reflect real-world challenges. Investigating stakeholders' conflicting interests and their cooperation mechanisms could shed light on collaborative strategies and policy guidance that promote both mutual benefit and individual incentives.

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Appendix 1: Objective coefficient values in the illustrative case study

The objective coefficient related to the material flow quantity x_{mntq} is c^x_{mntq}, which equals the revenue minus operational cost:

$$c^x_{mntq} = \sum_t p_{mnq} x_{mntq} - \sum_{t,q} OC_{mn} x_{mntq} \tag{8}$$

In this specific case, we assume that product prices p_{mnq} depend on the processor and successor nodes of material flow & the quality of material flows. Values of p_{mnq} are summarized in Table 5. Operational costs OC_m depend on the processor nodes of material flows. Values of OC_m are summarized in the first column of Table 6.

The objective coefficient related to the inventory level I_{ntq} is c^I_{ntq}, which equals the holding cost HC_n. Values of HC_n are summarized in the second column of Table 6. The objective coefficient related to the binary variable y_n is c^y_n. It can represent the fixed cost FC_n of opening a facility and is set as zero in this case because the local government may pay for this part of cost to develop this supply chain.

Table 5. Values of product prices p_{mnq} (RMB/kg).

m/q/n	Nodes 152–189 Primary processing	Node 350–354 Intensive manufacturing	Node 355 Fresh market	Node 356 Processed market
Nodes 1–151 Production areas	$\frac{q-21}{65-21} \times 5.15 + \frac{65-q}{65-21} \times 1.5$	1.5	$8 + \frac{(q-43)}{65-43} \times 6.5$	–
Nodes 152–189 Primary processing factories	–	1.5	$8.43 + \frac{(q-43)}{65-43} \times 6.93$	–
Node 350 Intensive manufacturing plants	–	–	–	9.87
Node 351 Intensive manufacturing plants	–	–	–	9.87
Node 352 Intensive manufacturing plants	–	–	–	20
Node 353 Intensive manufacturing plants	–	–	–	50
Node 354 Intensive manufacturing plants	–	–	–	413.7

Table 6. Values of cost parameters.

Node n	OC_n	HC_n
1–151	2.5	–
15–189	1	0.05
190–349	0.5	0.02
350	2.11	1
351	2.11	1
352	2	1
353	5.15	1
354	50	1