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Tactical Planning of a Region-Wide Procurement Network

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Authors
Aidin Parsakhoo, *Ph.D.*[1]
Sättar Ezzati, *Ph.D.*[1*]
Saba Pirov, *Ph.D.*[2]
Yadollah Rasouli Akerdi, *Ph.D.*[2]

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[1] Department of Forest Resource Management, Gorgan University of Agricultural Sciences and Natural Resources, GR. Iran.
[2] Department of Forestry, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran.

*** Correspondence**
Address: Department of Forest Resource Management, Gorgan University of Agricultural Sciences and Natural Resources, GR. Iran, 386.
P. Box: 49189-43464
Tell phone: +981732 330 091#177
Fax: +981732 330 091
E-mail: sattar.ezzati@gau.ac.ir

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ABSTRACT

Aims: Procuring a sustainable supply of raw materials is crucial for industrial logistics managers as it directly affects production line continuity and global market competitiveness. This study analyzes the existing procurement networks in northern Iran, where raw materials are sourced from various pathways, including terminals, private farms, and illegal timber sources. The objective is to propose competitive logistic scenarios that enhance inbound logistics decisions, encompassing inventory levels and optimizing on-road transportation efforts for delivering resources to manufacturing destinations.
Materials & Methods: Since 2017, a logging ban policy on commercial forests has created a wood supply crisis for many forest companies. Companies have resorted to purchasing logs from distant terminals (100-150 km) and lower-quality timber from private farms or illegal sources. This has disrupted transportation planning and increased unit delivery costs. We propose a linear programming model incorporating inventory and transportation planning to manage the demand-side or downstream wood supply chain network across a realistic region-wide case study (23,000 km^2) encompassing 172 companies in 20 northern Iranian cities. The model's sensitivity to changes in inbound logistics was assessed by simulating scenarios with reduced, increased, or eliminated illegal timber use.
Findings: Eliminating illegal timber from the supply chain network reduced total network costs by 18.25% (US$1.29 per ton of delivered wood from terminals). Transportation distances also decreased: 58.43 km in the base case (with illegal timber) compared to 55.22 km (-6%) in scenario 1 and 45.47 km (-22%) in scenario 3. Excluding illegal sources resulted in a cost reduction of $0.36 per ton of wood delivered to mills.
Conclusions: The model developed in this study can assist logistics managers in designing efficient wood supply-chain networks at the operational planning level.

Keywords: Wood Terminal; Forest Logistics; Inventory; Illegal Harvesting; Transportation; Optimization.

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Introduction

In a forest product supply chain network, as a system of distributed facilities/ organizations, forest fibers and/or raw materials flow from forests (usually harvested or collected by forest contractors) to various production facilities (e.g., lumber and pulp industry or value-added forest industry) for making several products as per customer demand [1]. However, procuring and transporting the required raw materials cost-effectively to production industries is challenging regarding transportation planning and unit delivery costs [2]. Commercially harvested timbers, after pre-processing, are carried out by logging trucks or trucks, either directly to mills or indirectly to woodyard terminals, before distributing among alternative industrial consumers [3]. The spatial divergence of wood fibers across the management area, the intrinsic variability of natural raw material characteristics, the high transportation cost, and the diversity of geographic conditions all affect the variability of the raw materials and the productivity of the wood-supply chain. On the other hand, demand and price paid for the final products have also risen due to prevailing market volatilities. The complexity of the supply-chain dynamics and transport logistics within forest operations at the operational level and the financial incentive of their decisions have motivated researchers on efficient modeling using computer-based planning tools for several decades [4].

Transportation is one of the most essential pillars of a wood supply chain, accounting for a large share of the overall cost of raw materials when evaluating the feasibility of wood supply chain network(s). It can be modeled using operations research (OR) models. Depending on the problem's size, the network's complexity, and the type of decision variables, various analytical methods and decision support systems have been proposed in the literature [5,6].

Linear programming (LP) models have been widely used in operations management, enabling optimal allocation of limited resources among competing activities to achieve cost reductions and productivity increases [7]. Within the context of forest operations, LP models have been effectively applied to various aspects, including timber harvesting [8], maximum allowable timber yield [9], spatial forest planning [10], supply chain networks, and transportation networks [11] across the globe. For example, Palander and Väätäinen [12] presented an LP model that minimized unloading travel distances using backhaul opportunities. Bredström and Rönnavist [13] developed a mixed integer programming model to address a complex combined distribution and ship scheduling problem involving multiple forest products and picks up/delivery points. Beaudoin et al. [14] focused on plan robustness assessment, considering supply availability and machine capacity uncertainties. Shabaev et al. [15] proposed optimizing wood harvesting and timber supply for the Russian forest product industry. Their model, solved using a decomposition algorithm combined with heuristics, achieved cost savings of 5-10% compared to the base-case scenario.

Our literature review shows that a significant amount of research has so far been conducted on the design of supply-chain management, including decisions on inventory management, facility location, and production process at the operational level without considering their interdependencies among decisions. In addition, less effort has been jointly devoted to inventory and transportation costs, mainly when raw materials originated from multiple sources and locations across the supply-chain network. This is because the forest supply chain is very complex to conquer [16]; in

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particular, when various sources of wood supply from different locations are included in the network, better knowledge of this area is necessary.

The forest industries of northern Iran face significant challenges, including a growing domestic demand for wood products, high transportation costs, and limited domestic resources [17]. This situation is further compounded by a steady rise in overall wood demand and a recent and significant decrease in authorized wood supply resources. Demand in industry is typically easy to access, but supply information of assortments is often challenging to collect. Some information is detailed, and some are just estimates. Accurate information about transportation costs and distances is also challenging to grasp. Typically, the demand for raw materials for forest industries in Iran is mainly provided through i) legal harvesting on public forest management units, ii) import sources (e.g., debarked roundwood sawlog, lumber, sleepers) from neighboring countries (mainly Russia (81% by value) followed by Azerbaijan (7.50% by value) and the United Arab Emirates (2.7% by value), iii) domestic short rotation plantations and iv) low-quality timbers and firewood, and v) farm-pruned woods on private orchards (e.g., branches of apple, cherry, and olive).

Since 1963, the Forestry and Range Organization (FARO) has prepared forestry plans in Iranian forests under the Ministry of Agriculture. Once approved, the FARO contracts with individual companies to harvest timbers, according to the annual allowable cut, construct forest roads and log terminals, and rehabilitate harvested blocks, including replanting. Until 1995, 1.4 Mm^3 of annual allowable cut (AAC)was legally harvested on public management units, while between 2010-2016, it declined 35% to 0.560 m^3.

In 2017, the Iranian government implemented a ten-year ban on legal harvesting in public forests as part of a forest management policy known as the “breathing plan.” This plan aimed to improve forest health and enhance resource protection. While the policy’s theoretical foundation was sound, its practical implementation has yet to achieve conservation and sustainable forest management goals. The ban has inadvertently triggered a rise in illegal logging and wood smuggling[18]. Additionally, it has caused significant job losses in the forestry sector. Because of its clandestine nature, no accurate information is available on the extent and quantity of timber illegal sources that have reached the market. Of course, this constitutes a significant proportion of the AAC volume. The market of unlawful wood is the main incentive for smuggling wood from public forests. While many efforts, such as reducing tariffs on woods import, forest border control actions, and timber certification schemes, have been established to curtail trade of illegally harvested timbers in these forests, there are still many small-scale sawmills or carpentries that buy and process raw materials from entrepreneurs that have been harvested outside the concession (i.e., \$50m^{-3} for harvested hardwoods [19] to operate at less than full capacity). The closure of forestry plans and the halt of legal harvesting on management units in northern Iran have significantly impacted large forest companies. This restriction on raw materials has limited their production capacity and forced them to re-evaluate their wood supply chain practices from a sustainable source aimed at reducing the total cost of the delivered products and increasing productivity while minimizing reliance on illegal materials. One approach involves developing a coordinated wood supply chain that integrates inventory

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management of multi-sourced raw materials with transportation planning. In this study, we addressed improving inbound logistics decisions of a region-wide supply chain network where the demands of multiple production mills are satisfied from different outsource pathways. To do so, we propose three optimized logistics scenarios based on the volume of wood obtained from different inbound channels. We developed a linear optimization model with continuous variables to manage this complex network. This model integrates data on flow scheduling, inventory levels, and transportation planning to optimize the supply chain. We implement this model in a real-case study for a one-year planning horizon within the central part of Hyrcanian forests in northern Iran.

Mathematical formulation

An optimization model with continuous decision variables was developed to analyze the interactions of a complex forest supply chain network. This model can be described as network flow variables in a multi-commodity network problem representing the flow of products from supply nodes to the mill industries. The model minimizes transport and inventory management costs. The following generic model presents the relationships for flowing various types of assortment a $\in A$ throughout a regional supply-chain system using potential network site of $n \in N$ from supplier $s \in S \subset N$ to woodyard terminals of $w \in W \subset N$ or mill industries of $o \in O \subset N$. The supply chain model consists of three agents: inbound logistics decisions upstream (e.g., warehousing of raw materials, wood fiber characteristics, and quality), intermediate logistics decisions (e.g., inventory management (holding and stock out), processing, and cost) and outbound logistics decisions at downstream (product demand fulfillment, unit delivery cost, and transportation cost). We first describe the sets, variables, and parameters, then follow the objective function and constraints.

The objective function minimizes the total transportation costs of the supply-chain network. It is formulated as the sum of six terms, capturing all cost elements involved in the problem (Eq.1). Transportation cost from supply sites directly to industries or for shipment (Eq. 2), transportation cost from supply sites to terminals (Eq. 3), transportation cost from terminals to industries (Eq. 4), inventory holding cost at supply sites (Eq. 5), inventory holding cost at terminal nodes (Eq. 6) and inventory holding cost at industries (Eq. 7).

$$\text{Minimize } z = C_1 + C_2 + C_3 + I_1 + I_2 + I_3 \qquad \text{Eq. (1)}$$

$$C_1 = \sum_{s\in S}\sum_{o\in O}\sum_{a\in A}\sum_{k\in K}\sum_{t\in T} c^{f}_{asok}\, x^{f}_{asokt} \qquad \text{Eq.(2)}$$

$$C_2 = \sum_{s\in S}\sum_{w\in W}\sum_{a\in A}\sum_{k\in K}\sum_{t\in T} c^{w}_{aswk}\, x^{w}_{aswkt} \qquad \text{Eq.(3)}$$

$$C_3 = \sum_{w\in W}\sum_{o\in O}\sum_{a\in A}\sum_{k\in K}\sum_{t\in T} c^{v}_{awok}\, x^{v}_{awokt} \qquad \text{Eq.(4)}$$

$$I_1 = \sum_{s\in S}\sum_{a\in A}\sum_{t\in T} c^{f}_{s} I^{f}_{sat} \qquad \text{Eq.(5)}$$

$$I_2 = \sum_{w\in W}\sum_{a\in A}\sum_{t\in T} c^{w}_{w} I^{w}_{wat} \qquad \text{Eq.(6)}$$

$$I_3 = \sum_{o\in O}\sum_{a\in A}\sum_{t\in T} c^{v}_{o} I^{v}_{oat} \qquad \text{Eq.(7)}$$

The primary constraints are as follows:

Eqs. (8)-(14) are the mathematical model's constraints. Eq. 8 shows conservation in supply sites ensures that the quantity of available assortments must be transported to the mill sites (i.e., direct transport) or woodyard terminals.

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$$I^{f}_{sat-1} + \sum q_{sa} - \sum_{o \in O} x^{f}_{asokt} - \sum_{w \in W} x^{w}_{aswkt} - I^{f}_{sat} = 0$$
$$\forall s \in S, a \in A, t \in T \qquad \text{Eq.(8)}$$

Eq. 9 guarantees that the supply procured is less than or equal to the total available in each supply unit.

$$\sum_{k \in K} \sum_{t \in T} x^{f}_{asokt} \leq q_{sa} \quad \forall s \in S, a \in A \qquad \text{Eq.(9)}$$

Eq. 10 describes flow balance constraints in woodyard terminals, where the amount of inbound flow plus the already available volume of assortments at terminals must equal the volume of assortments transported to the mill storages.

$$I^{w}_{wat-1} + p_{w} + \sum_{s \in S} x^{f}_{aswkt} - \sum_{o \in O} x^{v}_{awokt} - I^{w}_{wat} = 0$$
$$\forall w \in W, a \in A, t \in T \qquad \text{Eq.(10)}$$

The terminals have a limited storage capacity for assortments. Eq. 11 ensures that volumes stored at a terminal never exceed the terminal capacities.

$$\sum_{k \in K} \sum_{s \in S} x^{f}_{aswkt} + p_{w} \leq \sigma_{awt}$$
$$\forall w \in W, a \in A, t \in T \qquad \text{Eq.(11)}$$

Eq. 12 represents the balancing constraints for mill storages. The mill storage receives flows from the woodyard terminals, private farms, and illegal timbers (i.e., for small sawmills) and supplies the mill's production unit for multiple products.

$$I^{v}_{oat-1} + \sum_{s \in S} x^{f}_{asokt} + \sum_{w \in W} x^{w}_{awokt} - I^{v}_{oat} = 0$$
$$\forall o \in O, a \in A, t \in T \qquad \text{Eq.(12)}$$

Eq. 13 states that demand at mill sites is satisfied such that outflows from supply sites (direct transport) or woodyard terminals must meet demand at the mill sites.

$$\sum_{s \in S} \sum_{k \in K} x^{f}_{asokt} + \sum_{w \in W} \sum_{k \in K} x^{w}_{awokt} = d_{oat}$$
$$\forall o \in O, a \in A, t \in T \qquad \text{Eq.(13)}$$

Eq. 14 specifies the non-negativity restrictions respectively.

$$I^{f}_{sat}, I^{w}_{wat}, I^{v}_{oat}, x^{f}_{asokt}, x^{w}_{aswkt}, x^{v}_{awokt} \geq 0 \qquad \text{Eq.(14)}$$

Material & Methods

Case study

Building upon the mathematical model developed in the previous section, it aims to support industrial logistics by ensuring a secure and diverse supply flow that keeps production lines active and competitive in the market. To demonstrate the model's full potential, we apply it to a real-world case study in Mazandāran province, northern Iran. The area is situated on the north slopes of Alborz mountains between 36°40 to 36°56N latitude and 50°21to 54°0'52E longitude. The area covers an area of 23,000 km^2, which stretches across 20 cities along the southern coast of the Caspian Sea. The region has 7,940 km^2 of forest resources and 4,420 km^2 of various orchards. The following steps were carried out to develop this study. Step 1) compile input database, Step 2) network structure and model formulation, and Step 3) model solving and scenario analysis. In the first step, input dataset, such as spatial components of the logistic network, i.e., supply information in terminals, at private farms and from illegal sources, mill locations, demand information at industries, cost data (transportation and type of machinery), road database and assortment types were compiled and processes in a geographical information system (GIS). Next, a modified version of the shortest path algorithm was developed using the Haversine algorithm to calculate the distance between nodes within the network. Transportation costs were collected for hauling different assortments using different truck systems. A continuous linear programming model with continuous variables was formulated to integrate this information and manage various flow

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Sets and Indices

$n \in N$	the set of potential nodes/sites with the supply chain network
$s \in S \subset N$	the set of supply locations
$o \in O \subset N$	the set of mill sites
$w \in W \subset N$	the set of woodyard terminals
$a \in A$	the set of assortment types (our definition of assortments includes raw materials, low-quality timbers, Roundwood sawlog, farm pruned trees, and illegally sourced timbers
$t \in T$	the set of periods
$k \in K$	the set of available trucks used for transporting different types of assortments through the supply chain network

Decision variables

x^{f}_{asokt}	flow of assortments $a \in A$ using truck type k between nodes $s \in S$ and o $\in O$ during time period t
x^{w}_{aswkt}	flow of assortments $a \in A$ using truck type k between nodes $s \in S$ and w $\in W$ during time period t
x^{v}_{awokt}	flow of assortments $a \in A$ using truck type k between nodes $w \in W$ and $o \in O$ during time period t
I^{f}_{nat}	inventory level of assortments $a \in A$ node $n \in \{S \cup w \cup o\}$ at the end of time period t

Constants

q_{sa}	quantity of assortment (ton) of type $a \in A$ available for transport in supply site $s \in S$
P_{wa}	quantity of assortment (ton) of type $a \in A$ already available for transport at woodyard terminal w $\in W$
c^{f}_{asok}	cost ($. ton^{-1}) of transporting 1 ton of assortment $a \in A$ using truck type k between nodes $s \in S$ and $o \in O$. This cost includes the length between nodes.
c^{w}_{aswk}	cost ($. ton^{-1}) of transporting 1 ton of assortment $a \in A$ using truck type k between nodes $s \in S$ and $w \in W$. This cost includes the distance between nodes.
c^{v}_{awok}	cost ($. ton^{-1}) of transporting 1 ton of assortment $a \in A$ using truck type k between node $w \in W$ and $o \in O$. This cost includes the length between nodes.
c^{f}_{n}	inventory holding cost ($) in at node $n \in \{S \cup w \cup o\}$
d_{aot}	demand quantity (ton) of assortment type $a \in A$ in site $o \in O$ in period t
σ_{awt}	the total capacity of the woodyard terminal for assortment type $a \in A$ in a node in period t

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scheduling, inventory, and transportation planning decisions. Finally, a set of different scenarios were developed to evaluate model performance.

Procurement

The supply-side (upstream) supply chain consisted of 20 private orchards, 42 illegal sites, and two terminals that could supply raw materials to wood industries. The demand-side (downstream) supply chain network was characterized by 172 industries, such as seven large sawmills (annual production level >46,000 tons of wood; one pulp and paper mill, five plywood mills, and one veneer mill) and 120 small sawmills (av. demand = 110 tons) and the number of assortments and/or raw materials was 4 with one-year planning horizon. The demand of mill industries provides different types of assortments, often heterogenous in quality and type, that arrivals from other sources such as legal harvesting practices on short rotation plantations, low-quality timbers, and farm pruned sources (e.g., branches of apples, cherries, and olives) on private orchards. A spatial map of the region with the logistic network complexities, including the geographic location of mills, woodyard terminals, and illegally harvested units, can be observed in Figure 1.

The wood flow can be made directly at the supply location or terminal before being transported to a mill. Due to the inaccessibility of the transportation costs of roundwood sawlogs from custom ports or plantation sites before arriving at terminals, their transport parts were not included in the mathematical model. We, therefore, assume that these types of wood (roundwood sawlogs) are already available at the terminal and planning of transportation activities for these types of wood is considered as direct transportation from the terminal to mills (sawmills, pulp and paper mills, and plywood mills). Within the current supply-chain network, seven out of 172 sawmills consume only roundwood sawlogs, made variable at the terminal from plantations or import sources. In contrast, plywood and paper mills consume low-quality timbers with small diameters, such as cross-cut debris and rejected or small-diameter wood fibers. Large-scale sawmills do not consume illegally sourced timbers; small-sized sawmills and wood industries, e.g., local carpentries, often consume illegal wood from close or far distance wood smugglers instead of purchasing timbers from legal sources. All timbers (farm-pruned timbers, low-quality timbers, and sawlog roundwood), except illegally sourced timbers, must first enter woodyard terminals for inventory and store purposes before transporting alternative mill industries. Woodyard terminals are reached from supply locations by logging trucks or trucks. From each terminal, raw materials are transported to multi-facility industries according to their requirements. Illegal sourced timbers, harvested outside of concession boundaries, are often directly transported to small-scale sawmills (i.e., direct transport), depending on where smugglers find markets for selling out timbers. Given that the supply of raw materials to the industry is determined by demand at industries, the inventory exists at the supply sites, at the woodyard terminals, and as the storage of the production industry. Figure 2 illustrates the forest product supply chain network through which the raw materials and information flow in our case study area. The studied logistics network includes inbound logistics (supply sites), transport wood flow to different locations (i.e., woodyard terminals or forest companies), inventory control at three levels of the logistics network (private farms, woodyard terminals, and mill storages), and outbound logistics (sawmills).

The total capacity of mill industries is

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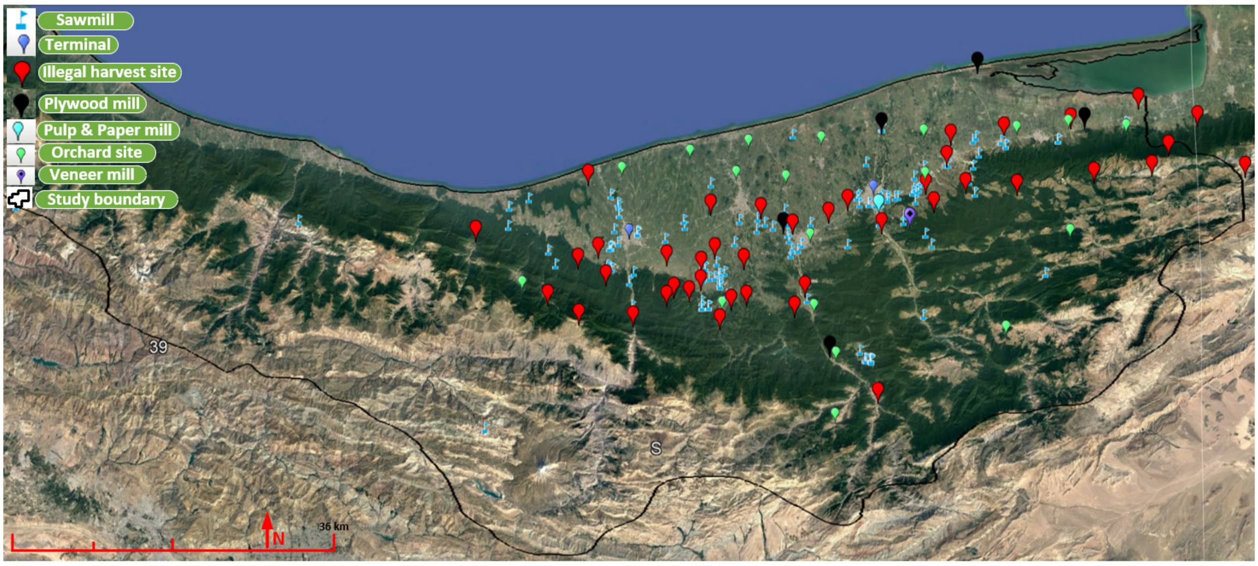

Figure 1) The geographical location of the study area with the logistic network complexities.

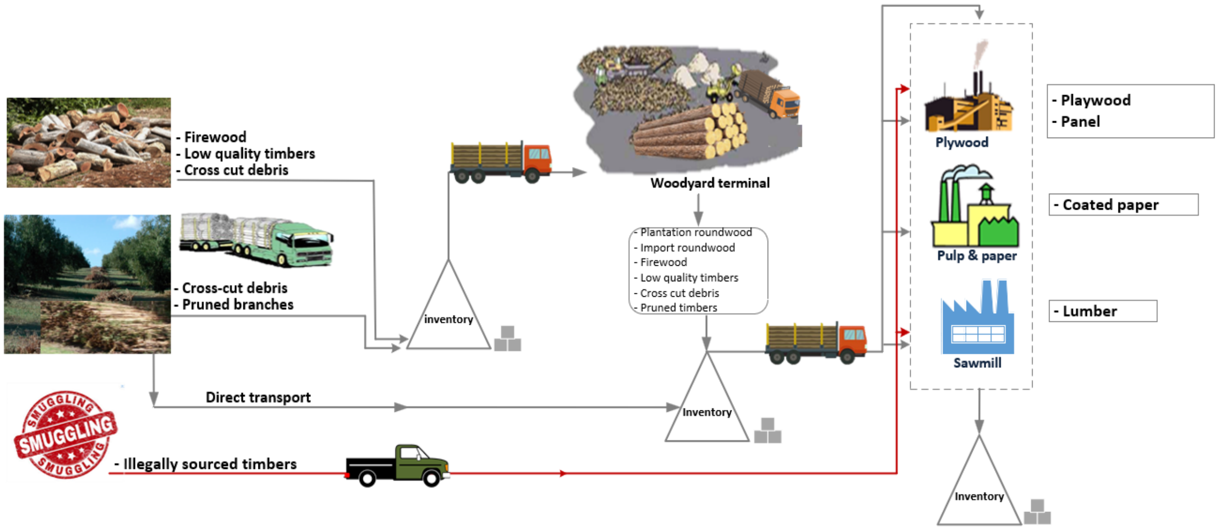

Figure 2) Forest product supply chain network under logging ban policy on forest management units.

865,000 tons, composed of 332,000 tons of sawlogs and 534,000 tons of low-quality timbers (e.g., firewood, rejected, and small-diameter wood fibers) over a one-year planning horizon. The majority of information required was obtained from the Ministry of Industries and Miners of Iran and scientific literature. Due to the lack of accurate statistics on input smuggled woods, we consulted reports provided by the police customs offices along the outlet routes in the study area (i.e., Mazāndāran province), which included information about the volume, species, type of products, and geographical locations where timber woods were illegally harvested. The smuggled woods are generally transported to the cities in the central and eastern sawmills, carpentry, or lumber mills with small capacities throughout the province. According to Nikooy et al. [19], most smugglers are forest dwellers or locals who illegally fell

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trees and transport their products to end-consumers by private or public vehicles. Under the circumstance of the breathing plan, the downstream supply chain and/or industries are not assured of receiving sufficient supply from the upstream supply chain and/or supply sources; therefore, the inclusion of inventory control management into the traditional supply chain network is required to ensure the product demand of mill industries is fulfilled.

Transportation

After establishing the availability of wood supply, the logistics network model is developed to distribute multiple flows among different industries. In a forest supply chain network, it is crucial to establish connections among supply fibers, woodyard terminals, and mill industries for the road network. Having more than 2,800 km of public roads, shipping woods has become emblematic of the resource region. The wood supply has several routing options throughout the network that significantly impact the transportation and unit delivery costs. Route search requires a valuable and accurate algorithm to find the shortest path routes between each one of the logistics nodes. To calculate the distance between nodes, we developed a modified version of the shortest path algorithm incorporating the Haversine algorithm. Provided with the geographic coordinates, our algorithm enables us to accurately calculate the distance between two nodes on the surface of a sphere, providing more reliability than existing distance estimators like Euclidean or Manhattan. An illustration of the distance calculator using the Haversine algorithm compared with the straight-line distance (straight distance) is illustrated in Figure 3. The pseudocode of the haversine algorithm is presented in Algorithm 1.

Different truck types are available to transport wood fibers between supply and demand sites, where each truck carries a single type of wood with a full load at a time. The cost varies with distance, volume, and type of products. The input parameters of the forest supply-chain network are given in Table 1.

Findings

The planning problem was formulated using a linear programming model and solved using Lingo 18.0 (Lindo Systems, Inc. 2018) modeling language with default settings. All experiments were conducted on a PC with an Intel core i7 GHz processor and 8 GB RAM. The model was easily computable, which required an average computational time of less than 5 minutes per scenario. The problem thus consisted of 17,807 variables

Table 1) Input parameters of the integrated supply-chain network. The input parameters were compiled from the Iranian Road and Transport Ministry.

Transport cost (\$ ton^{-1})	Timbers from private orchards to terminal (mini-truck)	0.185
	Illegally timbers to mills (typical 4-wheel vans)	0.72
	Timbers from terminals to mills (dump trucks)	0.122
	Transport other types of fiber (mini-truck)	0.124
Storage cost (\$ ton^{-1})	Private orchards	0.75
Woodyard terminals		1.25
Mills		1.00
Terminal capacity (ton)		600,000

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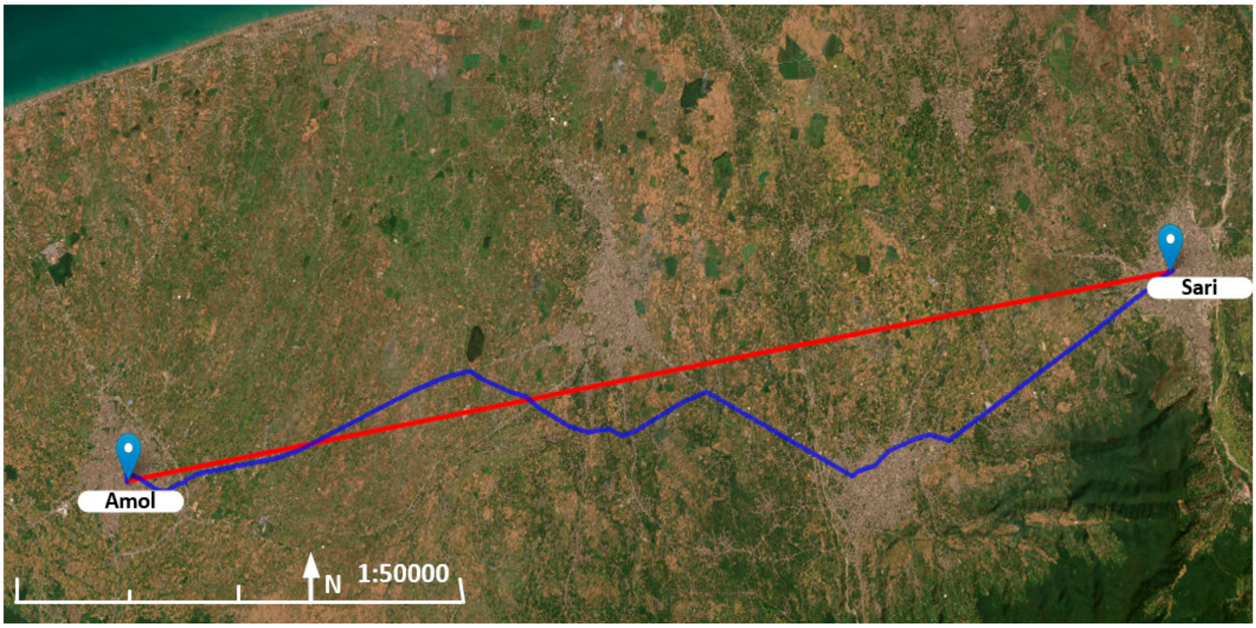

Figure 3) Comparison of the straight distance (red line) and Haversine distance (blue line) between two points.

Algorithm 1. Pseudocode of the haversine to calculate distance between nodes

//algorithm ***shortest path*** *based on haversine distance algorithm*

begins

input data

set ***s,d&r*** *//read spatial position of nodes from files (s: source node, d: end node, r: earth's radius)*

add *geographic coordinates of nodes in radian*

for *each i in the list of nodes*

do *//Call math import radians*

*find_*$\Delta long_{ij}$*_between_nodes* *// longitude of start and end node*

Calc.$a=\sin^2(\Delta\varphi_{ij}/2) + \cos(\varphi_i)\cos((\varphi_j)\ \sin^2(\Delta\varphi_{ij}/2)$ *// Square of straight-lie distance between pairs*

Calc. $\beta=2.atan^2(sqrt(a), sqrt(1-a))$ *//Great circle distance in radians*

Calc. $\lambda= r.\beta$ *//real distance in km*

end for

return λ *for each pair*

End

Note: φ_{ij} *represents the geographical coordination of nodes in radian*

and 1,563 constraints.

Since legally sourced timber from management units is the core pathway to the current supply-chain network, it is essential to determine *i*) how each mill fulfills its demand from multiple sources of assortments and *ii*) how these raw materials are transported to them while reducing transport and unit delivery costs. Table 2 shows the total cost of the status quo scenario (i.e., the current supply-chain network).

The analysis revealed a total network cost

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of $6,087,245 for the status quo scenario. Notably, transportation costs associated with illegal wood supply accounted for 22% of this total cost. Farm-pruned wood supply dominated transportation costs, representing 44% of wood directly delivered to mills and 20% of wood transported from terminals. In contrast, roundwood sawlog transportation from terminals to mills comprised a minor share (4%) of the total cost. Interestingly, a surplus of roundwood sawlogs at terminals resulted in an additional cost of $196,000 (3.21% of the total). The unit cost per ton of wood transported through the network was calculated to assess overall delivery efficiency. The results indicated a delivery cost of $7.09 per ton. Further analysis of the mill demand portfolio (Table 2) revealed that industries primarily relied on farm-pruned wood (63%), followed by illegally sourced timber (22%). Roundwood sawlogs (4%) and low-quality timbers (8%) obtained from terminals constituted a smaller portion of the total wood supply. Figure 4 illustrates a portion of the model's solution for routing different raw material types through the logistics network.

We assessed the model's sensitivity and the solution's efficiency to address this question: how do transport and total supply-chain costs change given variable proportions of illegal timbers within the existing supply-chain network? By adjusting the network configurations compared to the primary case and/or the status quo scenario, we generated a set of three other scenarios that represent various operational analyses that can be made: i) reduced the amount of illegal timber by 15%, thanks to strict enforcement of regulations, ii) increased the amount of illegal timber by 15%, due to the unexpected rise in demand and the increase in the price paid for the logs or timbers in the market, and iii) omit the supply of illegal timber from the current supply-chain network, as legal harvesting practices in public forests and the distribution of timber from woodyard terminal to industries are allowed. Table 3 summarizes the results of the examined logistics scenario by changing the quantity of illegal wood within the network.

The result showed that changing the policy of

Table 2) Logistics cost decomposition of the wood supply-chain network (status quo scenario).

Cost attributes		Transportation cost (US$)	Share of demand (%)
Illegally sourced timbers		1,304,597	21.43
Farm-pruned timbers	From farm to mills (direct transp.)	2,655,873	43.63
	From terminal to mills	1,212,973	19.93
Roundwood sawlogs from terminals		254,444	4.18
Low-quality timbers from terminals		463,673	7.62
Inventory in farms		0.00	0.00
Inventory at terminals		195,684	3.21
Inventory at mills		0.00	0.00
Total transportation costs		5,891,560	96.80
Total supply-chain		6,087,245	100.00
Unit delivery cost ($ ton^{-1})		7.09	-

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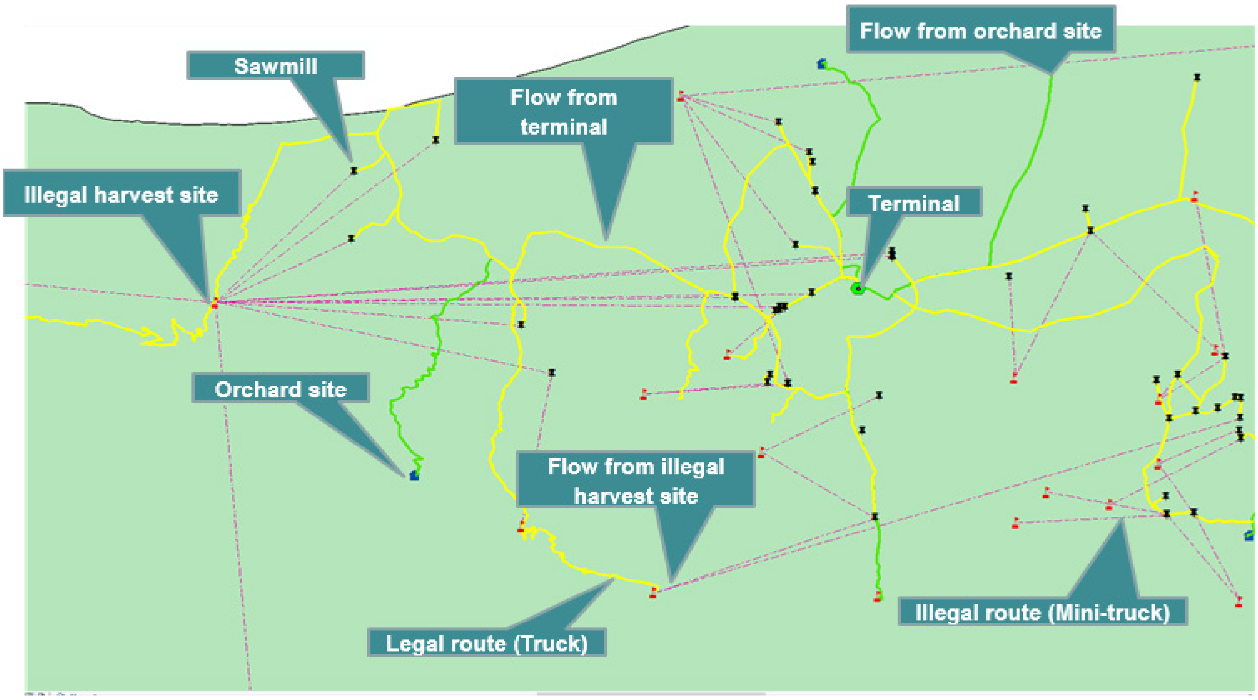

Figure 4) Mapping part of the solution generated by the optimization model.

Table 3) Cost decomposition for the total supply-chain cost subject to studied logistics scenarios

Item		**Transportation cost (US$)**		
		Scenario 1	**Scenario 2**	**Scenario 3**
Illegally sourced timbers		992,553	1,500,321	0.000
Farm-pruned timbers	From farm to mills (direct transp.)	2,655,873	2,655,873	2,655,873
	From terminal to mills	1,212,973	121,2973	1,212,973
Roundwood sawlogs from terminals		254,444	254,444	254,444
Low-quality timbers from terminals		46,3673	410,272	657,297
Inventory in farms		0.000	0.000	0.000
Inventory at terminals		195,684	203,846	195,688
Inventory at mills		0.000	0.000	0.000
Total transportation cost		5,579,517	6,033,883	4,780,588
Total supply-chain		5,775,202	6,237,730	4,976,277
Unit delivery cost ($ ton^{-1})		6.73	7.27	5.80

Scenario 1 (reduce smuggles of wood by 15%); Scenario 2 (increase smuggles of wood by 15%); Scenario 3 (eliminate smuggling wood from the network)

supplying wood to the network significantly changed the total cost of the procurement network. The cost of transporting illegally sourced timber from smuggled areas to the mills was $1,304,000 (i.e., status quo scenario: see Table 2) while reducing the

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proportion of illegal timber by 15% decreased its share by 24 or to $992,000. An increase in the share of illegally sourced timber in the supply-chain network (i.e., scenario 2) incurred the cost of transportation by 15% compared to the status quo management scenario 1 and by 51% compared to scenario 1. In the case of removing illegal timber from the procurement network, which means the demand of mills satisfied with the supply materials from terminals, the total cost of the network was reduced by 18.25% compared to the status quo scenario (Table 3). With the reduced share of illegal timber, the unit delivered cost reached \$6.73 ton^{-1}, 5% lower than the status quo scenario. However, when smuggled wood is completely removed from the network, and wood supply emanates from woodyard terminals to mill locations, the unit delivery cost reaches 5.80 or 18.20% lower than the status quo scenario.

Discussion

Understanding the origin of raw materials through correctly optimizing inbound logistics decisions and their supply-chain network is critical for a procurement manager to ensure the sustainability and legality of their supply chain and promote responsible sourcing practices. The outcome of this decision can significantly impact the cost of deliveries and the price paid for final products. In this study, we proposed an integrated LP-based inventory and transportation model to manage the current procurement network in which raw materials at inbound logistics come from multiple sources. Transportation and logistics managers can use the generic model as an operational decision tool to analyze and plan the wood supply-chain network. The original problem (i.e., status quo scenario) showed that smuggled wood contributed to 22% of the demand portfolio for the current in-operation supply-chain network in the region. Purchasing smuggled wood (mainly hardwoods, due to the high value) increased the total cost and, therefore, the unit delivery cost of the network to \$7.09 ton^{-1}. The results generally match the findings of [20], who indicated that hardwood sawlogs are the main species to smuggle rather than softwood due to their premium price and high-value products. Using the scenario analysis conducted in this study, we found that the share of illegally harvested timber can be reduced or eliminated from the current supply chain given that the management policy changes or demand of mill industries fulfilled either from plantation sites or increase the share of wood imports through the use of woodyard terminals. However, according to several technical reports, forest industries in northern Iran need to catch up with many other industries in terms of transportation and logistics operations. As a result of the present study, it was confirmed that eliminating illegal timbers or using woodyard-sourced timbers to meet mill demands resulted in a decrease of 18.25% in the cost of delivering timber compared to the baseline scenario. This scenario assumes eliminating smuggled timber in the current network and providing all timber available from the terminals before transporting it to meet the demand of the mill industries. The results agree with [21] that woodyard terminals within the forest supply-chain network allow trucks with greater hauling capacity between terminals and mill locations and lower transportation costs. The benefit generated by using intermediate terminals to satisfy mills' demand directly varied economically regarding transportation and unit delivery costs [4,21] and environmentally regarding GHG emissions. However, some studies, for example, [1], did not show financial gains for a terminal in Ontario that served as a buffer to face demand uncertainty. Zhang

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et al. [22] conducted an empirical analysis to assess the economic costs of eliminating illegal timber from wood production. Their findings suggest that removing illegal timber products from the market could offer a more economical solution. Specifically, their analysis revealed that eliminating illegal timber consumption would only decrease the global forest sector's added value by 3.37%, compared to a scenario where all illicit consumption of timber and production are eliminated. Woodyard terminals are always needed to balance seasonal fluctuations in supply and demand and allow quality raw materials to reach the correct destinations [4]. In our study, using a woodyard terminal within the procurement network reduced the overall supply-chain cost and declined the share of smuggled wood in the supply-chain network. Our analysis revealed significant reductions in total transportation costs (excluding inventory holding costs) across the three scenarios. Scenario 1, which reduces smuggled wood by 15%, yielded a 5% decrease in transportation costs. This improvement is further amplified in Scenario 3 (eliminating smuggled wood and utilizing woodyard terminals), achieving an 18.86% cost reduction. The use of a terminal allows for prompt sharing of information, improved cutting and sorting of logs in a more controlled environment, physical transformation of logs, and synchronization in the supply chain while reducing empty truck transportation by using backhauling opportunities (i.e., a truck carries a load when returning from a destination to the area of the origin of the first load) depends on the geographical location of mills and harvest units. These findings align with the research of Zhang et al. [22], who highlight the economic benefits of eliminating illegal logging and implementing centralized processing facilities [22].

On average, the transportation distances were 58.43 km in the base-case scenario (where illegal timbers were consumed in the network). In comparison, it decreased to -6% (55.22 km) in scenario 1 and -22% (45.47 km) in scenario 3, respectively. This analysis showed that using a woodyard terminal in the current supply chain is more profitable because it reduces the delivery cost and average transport length by breaking deliveries between supply and demand sites. In addition, using woodyard terminals eliminated the share of illegal wood sources from the network. Excluding smuggled wood from the market can potentially encourage smugglers to seek alternative income-generating options from the social point of view and ensure supply chain managers provide their supply from legal and sustainable sources.

Conclusions

In this paper, we propose a linear optimization model that enables integral operational planning between inventory management and planning of transportation activities in a demand-driven multi-facility environment to manage the current supply-chain network in which raw materials are outsourced from multiple sources and locations. Due to the closure of forest plans in northern Iran, forest companies have been plagued by structure instability and increased illegal harvesting operations in public forest management units. Our model makes it possible to evaluate the impact of removing illegal sources of timbers from the current procurement network and global network benefits. The result indicates that deducting illegally sourced timbers from the current supply-chain network reduced the total cost of the network by 18.25% or led to a lower US$1.29 per ton delivery of wood from terminals to satisfy demand at production industries. This study demonstrates the economic viability of excluding illegal timber from the wood supply network. Our analysis revealed a cost reduction of $0.36 per ton of wood delivered to mills when illegal sources are eliminated from the model. The most economically beneficial scenario involves sourcing wood from legitimate sources and/or woodyard terminals. This approach leverages high-capacity trucks for transporting timber from terminals to mills, reducing overall transportation distances and costs. Optimizing distribution routes and transport systems can minimize transportation costs and improve delivered wood quality, discouraging unauthorized harvesting activities. It is essential to acknowledge that real-world implementation requires adjusting the input data to reflect practical conditions. Moreover, the model can be used as a decision support tool for operational planning to analyze the effects on the current supply chain network in response to multiple sources of timbers. Since there are numerous delivers and terminals with the current logistics network and distance between these locations (60 km on average), the use of backhauling routes could significantly minimize empty travel and gain more value to the transportation subproblem, identified by [21], which is left as an extension of the current model for future study.

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