Operational Planning Of Optimal Wood Supply-Chain Network With Focus On Inbound Logistics Constraints

Aidin Parsakhoo (Parsakhoo@gau.ac.ir)
Gorgan University of Agricultural Sciences and Natural Resources
Sattar Ezzati
Gorgan University of Agricultural Sciences and Natural Resources
Saba Pirov
Sari Agricultural Sciences and Natural Resources University
Yadollah Rasouli Akerdi
Sari Agricultural Sciences and Natural Resources University

Research Article

Keywords: Wood supply chain, forest logistics, transportation, optimization, inventory control

Posted Date: March 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1444409/v1

Abstract

Procuring enough raw materials is an important decision faced with industries' logistic managers to sustain production lines and improve the competitiveness of an industry within the global market. Since 2017 a large numbers of forest companies in northern Iran have struggling with providing enough wood supply to retain their production-line demands as a result of the logging ban policy over commercial forests. Therefore, they have to buy commercial logs from far-distance domestic plantation and low-quality timbers, either from legitimate or illegitimate sources. This will negatively affect transportation and unit delivery cost of raw materials. The current study is aimed to provide an integrated modeling approach to analyze the current supply-chain network and propose possible logistic scenarios to improve inbound logistics. The model was applied to a realistic wood supply-chain network of 23,000 km² with 172 forest companies which stretch across 20 cities in Mazandaran province, located in northern Iran. To do so, supply sites, demand locations, cost data (transport, loading and unloading type of machine, etc.) and assortment types were collected. Then, an optimization model with in inventory management was formulated to integrate this information and provide an optimal solution. The results showed that the demand portfolio of the studied logistic network consisted of sawlogs (38%), low-quality timbers (15%) and farm-tree pruning woods (45%). Illegitimated timbers provided 22% of the small-sized mill's demands, while the rest came from legal sources and/or wood yard terminals. The use of wood-yard terminal instead of purchasing woods from illegitimate wood dealers led to a saving of US$1.29 of available tonnes of wood fibers. We assessed the sensitivity of the solution, such as changing in the policy of illegitimate woods, which shows a significant effect on the total cost of network.

Introduction

In a forest product supply chain, forest fibers (commercial and low-quality woods) are practically needed to produce forest products. However, procuring and transporting the required fibers in the most cost-effective way is challenging in terms of transportation cost and unit delivery cost (Anderson and Nelson 2004; Contreras et al. 2008; Alzaqebah et al. 2018). Harvested timbers, after pre-processing operations, are often carried by trucks; either directly or indirectly to wood-yard terminals before distributing them among supply consumers (Augustynczik et al. 2016; George and Binu 2018). Spatial dispersal and a reduction in the amount of wood fibers available for harvest, a high transportation costs, an environmental concern regarding ecological paradigms and an increasing price of final products persuaded researchers to search for an optimal wood supply-chain network in forest product industries (Taskhiri et al. 2015; Chen et al. 2017). Nowadays, the development of an optimal logistic network becomes one of the significant aspects of supply-chain planning, and even a slight improvement in transportation efficiency can significantly reduce the total cost of operations (Chung et al. 2008; Chen et al. 2017). In the wood industry, given that transportation phase is the major cost of a wood supply-chain network, using an appropriate logistic network planning it is possible to minimize the overall distance, cost of the network and finally the unit delivery cost (Beaudoin et al. 2007; Chauhan et al. 2009). Such a planning approach must meet the needs of all demand centers, while using the full capacity of suppliers (Carlsson and Rönnqvist 2007; Beed et al. 2020). Forest transportation planning, both off-road and on-road, is one of the most expensive activities in wood supply-chain network which can be modeled through mathematical modeling approaches. Depending on the size of the problem, complexity of the network and the type of decisions various solution algorithms, e.g., exact solutions, heuristics and evolutionary algorithms, have so far been proposed in the literature for solving complex and challenging transportation problems (Chung and Session 2000; Aruga 2005; Gracia et al. 2014; Zamora-Cristales et al. 2015; Charkhgard et al. 2018; Jamhuri et al. 2021).

Linear programming (LP) model, as the most common operations research method, is one of the most popular and widely used to allocate limited resources optimally among competing activities, quality improvements, cost reductions and productivity increases (Macmillan and Fairweather 1988; Acuna 2018). In the context of forestry, LP has been successfully applied to timber harvesting (Öhman et al. 2011), maximum allowable timber yield (Rijal et al. 2018), spatial forest planning (McDillet al. 2016), supply chain network (Daya and Nourelfath 2018) and transportation planning (Hosseini et al., 2018) across the world. Palander and Väätäinen (2005) presented an optimization model based on linear programming scheme in which they used backhaul opportunities to minimize unloading travel distance throughout the entire wood supply-chain network. Bredström and Rönnavist (2006) used a mixed integer programming model for a difficult combined distribution and ship scheduling problem. The problem includes several forest products and multiple pick up and deliveries. Beaudoin et al. (2007) address plan robustness assessment taking into account multiple sources of uncertainties related mainly to supply availability and machine capacity. Chauhan et al. (2009) demonstrated a good performance level of the heuristic approach for a small-scale wood supply-chain problem, and of the branch-and-price approach for large scale problems. Zamora-Cristales et al. (2015) used ant-colony (ACO) evolutionary algorithm for the biomass supply-chain network, i.e., procurement and logistics. Their study appraised lower cost than the usual to plan the optimum network design from forest sites to wood yard terminals. Acuna (2018) developed an integrated optimization model for handling decisions on wood flow scheduling, and routing when both commercial timbers and biomass residues needed to be transported from forest coups to the mill yards from the perspective of the Australian forest industry. Shabaev et al. (2020) proposed an approach to the optimal planning of wood harvesting and timber supply from the perspective of Russian forest product industries. They used decomposition algorithm combined with heuristics for solving their operational problem. The results showed that a saving of between 5 and 10% in the total supply chain cost compared to the base-case scenario. Jamhuri et al. (2021) developed an optimization approach for routing problem in order to reduce the total cost of network by reducing the truck fleet, eliminating overtime, and increasing the efficiency of the transportation network. The real-time supply chain planning and inventory management of each potential and existing node within the network of wood supply chain is governed by product delivery prices and operations management efficiencies of each unit throughout the entire network (Shahi 2016). This will result in improving the competitiveness of industries within the global market. Azizi et al. (2008) estimated demand of wood panels by the year of 2012 in Iran and reported the consumptions of particleboard, fiberboard and mid-density fiberboard will increase by 33%, 72% and 107%, respectively. A few years later, Mohammadi Limaei et al. (2011) based on 30-year time series analysis (1979–2009) estimated that wood export is expected to be 21,000 tons per to cover the demand of forest industry across the country.

Increasing wood demands at the global level, high transportation costs and limiting domestic wood suppliers for providing industries' raw materials are some of the practical challenges faced with major forest companies in northern Iran (Rafighi et al. 2006; Norizah et al. 2014). Parallel to this, the general demand of wood is growing from year to year, while the amount of legitimate and/or authorized wood supply productions has been intensely decreased in recent years (Rafighi et al. 2006). So, according to country's dependence on imported woods from neighboring countries (e.g., Russia (81% by value), United Arab Emirates (2.7% by value), Azerbaijan (7.50% by value) and the rest 8.8% from other countries such as south Korea, Armenia, China, Malaysia, Turkey, etc.), it is necessary to specify the optimal wood supply chain network. Menhaj (2007) concluded given decreasing and/or remove the government's tariff on imported woods, the social benefits and wood smugglers caused by illegitimated harvesting would decrease. In addition, since 2017 the government prohibited any commercial exploitations of Iranian natural forests for a period of ten years, due to the recent forest management policies called "breathing plan "aimed at improving forest health and protecting these resources as much as possible. Deploying this policy not only was successful, but also led to extensive illegal smuggling of logs as 10–15% higher than ever before (Sotoudeh foumani et al. 2021). This policy may put increasing pressures on forest industries to re-think of their current wood supply-chain network and practices leading to reduce total cost of the delivered products and increase productivity while reducing a surge in companies demand for illegitimate supply materials.

Because of the supply shortage, uncertainty in inbound logistics (raw materials) and avoid high transportation cost, some forest companies, mainly small-scale sawmills, are purchasing woods from illegitimate sources instead of importing timbers or supplying woods from remote afforestation regions to keep production lines active and reduce their unit production cost. Illegitimate activity not only has significantly affected forest resources, but this could help spur timber and timber market change. Therefore, in order to remain competitiveness in the global market, it is necessary for forest industries to find ways to manage supply shortages and inventories of raw materials at different locations of the supply chain network (such as source, wood-yard and production plans). This therefore, helps sawmill supply team to reduce operational costs and avoid interruptions in mill's production lines while reducing the cost of deliver products and increasing its competitiveness. For this reason, we studied the current supply chain network and analyze three set of logistic scenarios by integrating inventory management and production planning with traditional supply chain management decision models aiming to achieve lower operation costs while decreasing illegitimate harvesting from these forests. In this study, we developed an integrated solutions based on the spatial analysis and mathematical optimization to identify the optimal logistics network of a wood supply-chain network. Spatial analysis tailored to preprocess the spatial database while a production supply chain management with inventory management formulated to improve the quality of solutions. We analyzed a few logistics scenarios to explore the sensitivity of the model while removing illegitimate harvesting and integrations in the inbound logistics (supply side) for a short-term operational problem of a case study in Mazandaran's forest industry in northern Iran.

Materials And Method

Case study

The mathematical model developed in previous section is intended to help industrial logistic managers by securing enough supply from various sources to keep their production lines active and remain competitive in the market. To use and push the developed decision tool to the limit of its capacity, a realistic case study has applied to the region of Mazandaran province in northern Iran. The area is situated on the northern slopes of Alborz mountains between36°40 to 36°56N latitude and 50°21to 54°0'52E longitude. The area covers an area of 23,000 km² which stretch across 20 cities along southern coast of the Caspian Sea. The region has 7940 km^2 of forest resources and 4420 km^2 of various types of orchards. The geographical location of study area with the logistic network complexities is illustrated in Fig. 1. The area has high diversity of physiographic and topographic features, experiencing the mild climate of the Caspian region with an elevation extend from sea level up to 2,800 meters. Figure 2 presents the flowchart of the study.

Figure 1

Figure 2

Mathematical Formulation

An optimization model was developed to analyze the interactions of a complex forest supply chain network. The model minimizes the transport and inventory control costs. The following generic model presents the relationships throughout a regional supply chain system using potential network site $s \in S \subset N$ from supplier to $o \in O \subset N$mill in order to allocate effectively assortment a $\in A$. The supply chain model consists of three agents: inbound logistics includes upstream supply or potential wood-yard terminals $w \in W \subset N$, as midstream processing centers, and outbound logistics (downstream mill demands). The indexes, sets, parameters, and decision variables required are presented below.

Sets	
$n \in N$	the set of potential nodes with the supply chain network
$s \in S \subset N$	the set of supplier sites
$o \in O \subset N$	the set of mill sites
$w \in W \subset N$	the set of wood-yard terminals
$a \in A$	the set of assortment types
$t \in T$	the set of time periods
$k \in K$	the set of available trucks used for transporting different types of assortments through the supply chain network

Parameters	
q_{sa}	amount of assortment (tone) of type $a \in A$available for transportation in supply sites$s \in S$
P_{wa}	amount of assortment (tone) of type $a \in A$ already available for transportation in wood-yard terminal w $\in W$
c^{f}_{asok}	cost (\$. tone^{-1}) of transporting 1 tone of assortment $a \in A$ using truck type k between nodes $s \in S$ and $o \in O$. This cost includes length between nodes.
c^{w}_{aswk}	cost (\$. tone^{-1}) of transporting 1 tone of assortment $a \in A$ using truck type k between nodes $s \in S$ and $w \in W$. This cost includes length between nodes.
c^{v}_{awok}	cost (\$. tone^{-1}) of transporting 1 tone of assortment $a \in A$ using truck type k between node $w \in W$ and $o \in O$. This cost includes length between nodes.
c^{f}_{s}	unit cost (\$) of inventory in forest site $s \in S$
c^{w}_{w}	unit cost (\$) of inventory at terminal node $w \in W$
c^{v}_{o}	unit cost (\$) of inventory in industry node $o \in O$
d_{aot}	demand (tone) of assortment type$a \in A$ in node $o \in O$ in time period$t$
σ_{awt}	the total capacity of wood-yard terminal for assortment type $a \in A$ in node in time period$t$
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}_{sat}	inventory level of assortments $a \in A$at node $s \in S$ at the end of time period t
I^{w}_{wat}	inventory level of assortments$a \in A$ at node $w \in W$ at the end of time period t
I^{v}_{oat}	inventory level of assortments $a \in A$at node o $\in O$at the end of time period t

The objective function minimizes total transportation cost of the supply chain network including from forest to industries and/or direct shipment (Eq. 2), from forest to terminals (Eq. 3), from terminals to mills (Eq. 4), inventory cost in supply sites (Eq. 5), in terminal nodes (Eq. 6), and in mill sites (Eq. 7), respectively. The cost is sum of the following six terms which accumulate all cost elements involved in the problem.

$$\text{Minimize } z = C^{f} + C^{t} + C^{m} + I^{f} + I^{w} + I^{m} \quad (1)$$

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

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

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

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

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

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

Main constraints as follows:

$I^{f}_{sat-1} + \sum q_{sa} - \sum_{o\in O} x^{f}_{asokt} - \sum_{w\in W} x^{w}_{aswkt} - I^{f}_{sat} = 0$	$\forall s\in S, a\in A, t\in T$	(8)
$\sum_{k\in K}\sum_{t\in T} x^{f}_{asokt} \leqslant q_{sa}$	$\forall s\in S,a\in A$	(9)
$I_{{wat - 1}}^{w}+{p_w}+\sum\limits_{{s \in S}} {x_{{aswkt}}^{f}} - \sum\limits_{{o \in O}} {x_{{awokt}}^{v}} - I_{{wat}}^{w}=0$	$\forall w\in W, a\in A,t\in T$	(10)
$\sum\limits_{{k \in K}} {\sum\limits_{{s \in S}} {x_{{aswkt}}^{f}} } +{p_w} \leqslant {\sigma _{awt}}$	$\forall w\in W, a\in A,t\in T$	(11)
$I_{{oat - 1}}^{v}+\sum\limits_{{s \in S}} {x_{{asokt}}^{f}} +\sum\limits_{{w \in W}} {x_{{awokt}}^{w}} - I_{{oat}}^{v}=0$	$\forall o\in O,a\in A,t\in T$	(12)
$\sum\limits_{{s \in S}} {\sum\limits_{{k \in K}} {x_{{asokt}}^{f}} } +\sum\limits_{{w \in W}} {\sum\limits_{{k \in K}} {x_{{awokt}}^{w}} } ={d_{oat}}$	$\forall o\in O,a\in A,t\in T$	(13)
${I}_{sat}^{\text{f}},{I}_{wat}^{\text{w}},{I}_{oat}^{\text{v}},{x}_{asokt}^{\text{f}},{x}_{aswkt}^{w},{x}_{awokt}^{\text{v}}\ge 0$		(14)

Eqs. (8)-(14) are the constraints of the mathematical model. Eq. 8 flow conservation in supply sites, ensure that quantity of available assortments must transport either to the mill sites or wood-yard terminal. Eq. 9 guarantees that the supply procured is less than or equal to the total available in each supply site. Eq. 10 presents flow balance constraints in wood-yard terminals such that the amount of inbound flow plus already available volume of assortments at terminals must be equal to the volume of assortments transported to the mill sites. The terminals have a limited storage capacity of assortments. Eq. 11 ensures that volumes soared at a terminal never exceed the terminal capacities. Eq. 12 represents the balancing constraints for mill sites. Eq. 13 states that demand at mill sites is satisfied such that outflows from supply sites (direct transport) or terminal locations must meet demand at the mill sites. Eq. 14 states the non-negativity restrictions, respectively.

Procurement

The downstream supply chain network was characterized by 172 sites with one-year planning horizon. Demand of the industries assume to be fulfilled with different types of assortments (e.g., commercial logs, low-quality timbers and farm-tree pruning) transported either directly from source nodes or from wood yard terminals. In the present forest product supply chain, the large-scale sawmill (7 out of 172) consumes sawlogs (either from forest plantation or imported woods), while and plywood and paper mills consume low-quality timbers such as cross-cut debris, rejected or small-diameter wood fibers. In addition to sawlogs, small-scale sawmills consume illegitimate wood fibers from close-distance wood dealers instead of purchasing fibers from legitimate sources. Forest product industries supply chain network in our study area can be described by Fig. 3. The total demand of industries is 865,000 tones, composed of 332,000 tones of sawlogs and 534,000tones of low-quality timbers (e.g., firewood, rejected, small-diameter wood fiber, etc.) over a one-year planning horizon. Since 1963's commercial harvesting operations have been conducted by the Iranian forest service with an annual allowable cut of 2M m^{-3} annually. Due to the forest logging ban policy imposed by the bureau of forests, procuring this source of supply can no longer provide legitimate wood fibers for the forest industry companies, however, smuggle-wood dealers sometime violate this policy and harvest a significant quantity of woods, which they transport and sell out to some small-scale sawmills. The volume of smuggled wood fiber was identified through general police custom offices in the outlets of the study area. In addition to smuggled timbers, other sources of supply include legitimate timbers from domestic plantation, commercial and low-quality timbers, wood imports, and farm-tree pruning woods from private orchards (e.g., branches of apple, cherry, olive, etc.) that can be consumed by industrial mills. Regardless of illegitimate woods that are directly shipped to the forest companies, all available timbers (i.e., authorized wood supply) are often transported to wood-yard terminals before distributing them among forest industry consumers.

Figure 3

Under this condition, downstream directions of forest supply chain are not assured of wood fibers from upstream directions therefore we inclusion of inventory control management into the traditional supply chain network is required to meet demand requirements of mill sites.

Within the current network, a large proportion of sawlogs (approx. 98%) flows either from forest plantation or imported woods, this supply volume are already available in wood-yard terminals before distributing among industrial mills. The information (shipment flow) starts from the upstream direction (i.e., supply) towards the downstream direction (demand) either directly or after passing wood-yard terminals transported to mill locations, considering mills' demand requirements. The network includes inbound logistics (raw materials), transportation of wood fibers as raw materials to forest companies, inventory control management at three levels of the logistics network (farm-tree pruning woods, wood-yard terminals and mill storages), outbound logistics (sawmills). The input parameters were compiled from the Iranian road and transport ministry (RMTO 2020). The input parameters of the forest supply chain network described in Table 1.

Table 1

Transportation

After defining wood fiber availability, the next step is the development of logistics network within which the fibers will be brought to the mills based on their requirement. Accordingly, the two major elements that have to be defined are 1) how the mills acquire the fiber and 2) how fiber is conveyed to them. In the forest supply chain network, it is imperative the connection among supply fibres, wood-yard terminals and mills have to be established in relation to the road network. Having more than 2857 kilometres of public roads, the shipment of wood becomes emblematic of the resource region. Flowing in various forms across the region, the fiber has several routing options which have a direct influence on the transportation costs from supply sources such as the road types, speed limits, road curvature, etc. Route search requires a useful and accurate algorithm to calculate the distance between each one of logistic nodes. Here, we developed a version of the shortest path algorithm by imbedding the Haversine algorithms (Chopde and Nichat 2013). This algorithm provides a considerable circle distance between two locations on a non-flat surface, which is more accurate than other distance estimators such as Euclidean, Manhattan, etc. Provided with the geographic coordination of nodes, it can determine real-distance between two nodes on the surface of a sphere. An illustration of the distance calculator using the Haversine algorithm compared with the straight-line distance (crow fly) is illustrated in Fig. 4. The pseudo code of Haversine algorithm is presented as Algorithm shortest path:

// 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 nodesin radian*	
for *each i in list of nodes*	
do	*//Call math import radians*
find_$\Delta long_{ij}$_between_nodes	*// longitude of start and end node*
$Calc.a = sin^2(\Delta{\phi }_{ij}/2) + cost({\phi }_{i})cos(({\phi }_{j})sin^2(\Delta{\phi }_{ij}/2)$	*// 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: {\phi }_{ij} *represents geographical coordination of nodes in radian*

Results

The planning problem was formulated using linear programming techniques and solved using Lingo 18.0 (Lindo Systems, Inc. 2018) modeling language without adjusting default settings. All experiments were conducted on a PC with an Intel core i7 GHz processor and 8 GB of RAM. The model was ease of computation, which required an average computational time of less than 5 minutes per scenario. The problem thus consisted of 17,807 variables and 1,563 constraints.

Considering that providing supply from authorized sources is the core constituents of the forest supply chain in the region, it is essential to determine how the available supply can be distributed among industries while reducing transportation and unit delivery costs. The total cost of status quo scenario (i.e., the current supply-chain network) is shown in Table 2. The total cost of the network was 6.087,000 $ for the status quo scenario, of which the transportcost of Illegitimate wood fibers accounted for 22% of the total cost. Transportation cost of farm-tree pruning woods accounted for a large share of the cost, either directly to mills (44%) or distributed from terminal to mills (20%). Transportation of sawlogs from terminal to mills constituted a small share (4%) of the total supply-chain cost. Because of the surplus supply of sawlogs at terminals the model incurred an extra cost of inventory (3.21%) at terminals. If the total cost of the network is divided by the total transported wood through the logistics network, it is possible to see the unit delivery cost per one tone of wood fiber. The wood fiber can be delivered at a cost of US$ 7.09 available tonne-1. The results showed that the demand portfolio of mills consisted of legitimate wood fiber such as sawlogs (4%), low-quality timbers (8%) and farm-tree pruning woods (63%). Illegitimate wood fibers, however, provided 22% of the demand of industries (Table 2).

Table 2

We assessed the sensitivity of the solution aiming to exclude smuggle wood fibers from the existing supply-chain network. By changing the network configurations, through changing the volume of illegitimate fibers, we generated a set of three scenarios: i) reduced by 15%, increasing by 15% of illegitimate wood fibers and omitting from the current wood supply-chain network and asses their impacts on the total cost of supply-chain network. Table 3 illustrates the results of examined logistics scenario by changing the volume of illegitimate wood fibers.

Table 3.

The results showed that changing the policy of wood procurement significantly changed the total cost of wood supply-chain network. Reducing the illegitimate wood from the network, reduced the total cost of the network by 5.13% compared to the status quo scenario, while increasing it led to increase the total cost as 2.47%. Total cost of network significantly reduced by 18.25% compared to the status quo scenario in which mill supplies provided from the terminal instead of illegitimate wood fibers in the network (Table 3). Reducing the share of illegitimate wood from the network led to a gain of US$0.36/tones, while increasing its share caused an extra cost of US$0.18/tones. The best-case scenario optimistically led to a gain of US$1.29/tones for the entire supply-chain network. A part of the solution generated by the model for flowing different types of wood fibers (from private orchards, terminals and illegitimate wood dealers) through the logistic network is illustrated in Fig. 5.

Discussion

Although, supply-chain management design problems for an operational planning have been studied extensively in recent years, most of the models consider traditional decision elements separately, such as flow scheduling, facility location, production processes, while less effort focused on integrating inventory control decisions into the context of supply-chain problems within the forest logistics domains. Therefore, there is a need for an efficient planning system that integrates supply-chain network design model with inventory management and under shortage of supply sources. We proposed a modeling framework that can be used as decision support tool for operational analysis and tactical planning of wood supply chain. The modeling approach is generic and it could be possible to evaluate a number of operational scenarios. We have analyzed a real-world forest supply-chain problem in which supply sources are coming from different sources that make the operational logistics network challenging and the delivery cost of raw materials expensive to sawmill. In addition, due to recent forest management policy of prohibiting harvesting activities from the natural forests trading illegitimate wood fibers has increased (Sotoudeh Foumani et al. 2021), which significantly increased pressure on forest product industries to review their logistic practices from a sustainable and authorized source, while reducing a surge in companies demand for illegitimate supply. The original problem showed that at the moment 22% of the demand portfolio is supplied from the illegitimate wood fibers. Purchasing wood fibers from the illegitimate sources increased the delivery cost of raw materials and also the total cost of the network. Using the scenario analysis, we found that this proportion (i.e., illegitimate source of wood fiber) can by reduced or taken away provided that policy is changed or sawmills supplied raw materials from authorized sources such as wood yard terminals (Chan et al. 2009; Sarrazin et al. 2018a). Sarrazin et al. (2018b) reported that the use of wood-yard terminals, oversized trucks and backhauling opportunities between terminals and mill locations could procure a profit of US$0.68/available m3 to the forest products supply chain considered in eastern Canada. The use of wood yard terminal is not generalized well in the forest product industry and a few studies considered its potential to reduce the overall transportation cost and sort timbers before distributing them among mill industries. Results of current analysis with this study suggested that lower transportation and delivery costs were the most important variables in making a wood yard terminal profitable. The results are in line with findings of Epstein et al. (2007), reported that the use of terminal allows for backhauling opportunities (i.e., truck carries a load when returning from a destination to the area of the origin of the first load: (Zhang et al. 2017), which led to saving of industries up to 20% in a case study of Chilian forest product industries. Averaged, the transportation distances were 58.43 km in base scenario (in which illegitimate wood fibers provided supply to mills), 55.22 km for scenario two and three (changing the share of illegitimate wood fibers) and 45.47 km for scenario three (the use of wood yard terminals to send materials to mills). This analysis showed that it is more profitable to use wood yard terminal in the supply-chain network, while it can reduce share of illegitimate wood fibers from the forest and save more forests for the case in practice. This result is in accordance with findings of Sarrazin et al. (2021), reported that the use of wood-yard terminal led to increase the profit by US$0.0.70 for each cubic meter of wood available for harvesting.

Conclusions

The present model can produce more flexible solutions if the illegitimate wood fibers are removed from the network. Our analysis showed that by neglecting this scenario led to a gain of US$0.36/tones for the delivered raw materials to the mill gates. Perhaps the most optimistic or economic scenario is to provide mills with the materials from legitimate source and/or wood-yard terminal. The reason is attributed to the use of high loading capacity trucks to transport timbers from terminals to mill locations and reduce transportation distance. Therefore, with determining optimal distribution paths and transportation system it is possible to send woods from supply centers to demand centers with lower price and higher quality and this lead to decrease unallowable harvesting from forest.

Declarations

Acknowledgment

We gratefully acknowledge Gorgan University of Agricultural Sciences and Natural Resources for the financial support of this work (Research plan No: 99-430-68). We would also like to thank anonymous reviewers whose comments and suggestions helped improve the manuscript.

Authors' contributions A. Parsakhoo and S. Ezzatti performed the analysis and took the lead in writing the manuscript. S. Pirov and Y. Rasouli Akerdi helped with the interpretation. All authors contributed to the manuscript and read and approved of its final version.

Funding The project was funded by the Gorgan University of Agricultural Sciences and Natural Resources (GAU).

Data availability Data used and produced in this study may be available on request (Parsakhoo@gau.ac.ir).

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. Azizi A, Ghorbannezhad P, Hatefnia H (2008) Estimation of demand for wood panels in Iran by the year of 2012. J For Res 20: 179–182. https://www.academia.edu/2101594/Estimation_of_demand_for_wood_panels_in_Iran_by_the_year_of_2012
2. Acuna M (2018) Frontiers in wood and biomass supply chain optimization. 51st edition of the international symposium of forest mechanization 24–28 September 2018. Madrid, Spain. https://www.formec.org/images/proceedings/2018/Proceedings2018.PDF
3. Alzaqebah M, Jawarneh S, Sarim HM, Abdullah S (2018) Bees algorithm for vehicle routing problems with time windows. Int J Mach Learn Comput. 8: 236–240. https://doi.org/10.18178/ijmlc.2018.8.3.693
4. Anderson AE, Nelson J (2004) Projecting vector-based road networks with a shortest path algorithm. Can J for Res 34: 1444–1457. https://doi.org/10.1139/x04-030
5. Aruga K (2005) Tabu search optimization of horizontal and vertical alignments of forest roads. J For Res 10: 275–284. https://doi.org/10.1007/s10310-004-0136-5
6. Augustynczik ALD, Arce JE, Silva ACL (2016) Aggregating forest harvesting activities in forest plantations through integer linear programming and goal programming. J For Econ 24: 72–81. https://doi.org/10.1016/j.jfe.2016.06.002
7. Beed R, Roy A, Sarkar S, Bhattacharya D (2020) A hybrid multi-objective tour route optimization algorithm based on particle swarm optimization and artificial bee colony optimization. Comput Intell 36: 884–909. https://doi.org/10.1111/coin.12276
8. Beaudoin D, LeBel L, Frayret JM (2007) Tactical supply chain planning in the forest products industry through optimization and scenario-based analysis. Can J For Res 37: 128–140. https://doi.org/10.1139/x06-223
9. Chauhan SS, Frayret JM, LeBel L (2009) Multi-commodity supply network planning in the forest supply chain. Euro J Ope Res 196: 688–696. https://doi.org/10.1016/j.ejor.2008.03.024
10. Carlsson D, Ronnqvist M (2005) Supply chain management in forestry–case studies at Sodra Cell AB. Euro J Ope Res 163: 589–616. https://doi.org/10.1016/j.ejor.2004.02.001
11. Carlsson D, Rönnqvist M (2007) Backhauling in forest transportation: models, methods, and practical usage. Can J for Res 37: 2612–2623. https://doi.org/10.1139/X07-106
12. Charkhgard H, Savelsbergh M, Talebian M (2018) A linear programming-based algorithm to solve a class of optimization problems with a multi-linear objective function and affine constraints. Comput Oper Res 89: 17–30. https://doi.org/10.1016/j.cor.2017.07.015
13. Chen CX, Pierobon F, Zamora-Cristales R, Ganguly I, Sessions J, Eastin I (2017) Modeling the processing and transportation logistics of forest residues using life cycle assessment. J For 115: 86–94. https://doi.org/10.5849/jof.2016-027
14. Chung W, Session J (2000) Network 2000, a program for optinizing large fixed and variable cost transportation problems. Syst Anal For Resour 22: 109–120. https://doi.org/10.1007/978-94-017-0307-9_12
15. Chung W, Stückelberger J, Aruga K, Cundy TW (2008) Forest road network design using a trade-off analysis between skidding and road construction costs. Can J for Res 38: 439–448. https://doi.org/10.1139/X07-170

16. Contreras MA, Chung W, Jones G (2008) Applying ant colony optimization metaheuristic to solve forest transportation planning problems with side constraints. Can J for Res 38: 2896–2910. https://doi.org/10.1139/X08-126
17. Chan T, Cordeau J-F, Laporte G (2009) Locating satellite yards in forestry operations. INFOR. 47, 223–234. https://doi.org/10.3138/infor.47.3.223
18. Chopde NR, Nichat M (2013) Landmark based shortest path detection by using A* and Haversine formula. Int J Innov Res Comp Comm Eng 1: 298-302. https://doi.org/10.17762/ijritcc.v6i7.1690
19. Dai R, Contreras MA, Zhang J (2017) Combining ant colony optimization with 1-opt local search method for solving constrained forest transportation planning problems. Arti. Intel Res 6: 27-33. https://doi.org/10.5430/air.v6n2p27
20. Ebeniro ST, Osho JSA (2018) A linear programming approach for sustainable harvesting schedule for Tectona grandis Linn F. in Omo Forest Reserve. J Res For Wildlife Environ 10: 63–73. https://www.ajol.info/index.php/jrfwe/article/view/170233
21. Epstein R, Mikael R, Sophie D, Weintraub A (2007) Forest Transportation. USA: Springer. Chapter 20, Handbook of Operations Research in Natural Resources; p. 391–403. https://doi.org/10.1007/978-0-387-71815-6_20
22. Frayret JM, Amours SD, Rousseau A, Harvey S, Gaudreault J (2007) Agent-based supply-chain planning in the forest products industry. Int J Flex Manuf Syst 19: 358–391. https://doi.org/10.1007/s10696-008-9034-z
23. George S, Binu S (2018) Vehicle route optimisation using artificial bees colony algorithm and cuckoo search algorithm-a comparative study. Int J Appl Eng Res 13: 953–959. https://www.ripublication.com/ijaer18/ijaerv13n2_20.pdf
24. Gracia C, Velázquez-Martí B, Estornell J (2014) An application of the vehicle routing problem to biomass transportation. Biosyst Eng 124: 40–52. https://doi.org/10.1016/j.biosystemseng.2014.06.009
25. Haridass K, Valenzuela J, Yucekaya AD, Mcdonald T (2014) Scheduling a log transport system using simulated annealing. Inf Sci 264: 302–316. https://doi.org/10.1016/j.ins.2013.12.005
26. Iqbal S, Kaykobad M, Rahman MS (2015) Solving the multi-objective vehicle routing problem with soft time windows with the help of bees. Swarm Evol Comput 24: 50–64. https://doi.org/10.1016/j.swevo.2015.06.001
27. Jamhuri J, Norizah K, MohdHasmadi I, Azfanizam AS (2021) Bees algorithm for Forest transportation planning optimization in Malaysia. For Sci Tech 17: 15-22. https://doi.org/10.1080/21580103.2021.1925597
28. Lin P, Dai R, Contreras MA, Zhang J. (2017) Combining ant colony optimization with 1-opt local search method for solving constrained forest transportation planning problems. Artif Intell Res 6: 27–38. https://doi.org/10.5430/air.v6n2p27
29. Limaei SM, Heybatian R, Vaezin SMH, Torkman J (2011) Wood import and export and its relation to major macroeconomics variables in Iran. For Pol Econ 13: 303-307. https://doi.org/10.1016/j.forpol.2011.03.001
30. Macmillan DC, Fairweather SE (1988) An application of linear programming for short-term harvest scheduling. North J Appl For 5(2): 145-148.
31. Norizah K, MohdHasmadi I, Kamaruzaman JK (2014) Quantification of least cost path analysis for best forest road planning. Malaysian For 77(2): 101–110. https://www.researchgate.net/publication/286212644_Quantification_of_least_cost_path_analysis_for_best_forest_road_planning
32. Peyrov S, Lotfalian M, Adeli K, Pentek T (2020) Optimization of wood distribution and transportation network with emphasis on rail transport. J For Res Dev 7: 427-441. https://doi.org/10.30466/JFRD.2021.121097
33. Palander T, Väätäinen J (2005) Impacts of interenterprise collaboration andbackhauling on wood procurement in Finland. Scand. J. For. Res. 20: 177-183. https://doi.org/10.1080/02827580510008301
34. Rafighi A, Amiri S, Enayati AA, Faezipour MM (2006) A research on the existing obstacles in the way of developing paper products, supply and demand and the guidelines to solving the problem. Iranian J Nat Res 58(4): 199–208. https://www.sid.ir/en/journal/ViewPaper.aspx?id=68566
35. Sotoudeh Foumani B, Kolahi M, Mohammadi Limaei S, Fisher J, Rostami Shahraji T (2021) Multiple streams framework and logging policy change in the Hyrcanian forests of Iran. Austr For 84(4): 191-199. https://doi.org/10.1080/00049158.2021.1989848
36. Shahi SK (2016) Supply chain management of the Canadian Forest Products industry under supply and demand uncertainties: a simulation-based optimization approach, Ph.D thesis, Lakehead University, 160 p. https://knowledgecommons.lakeheadu.ca/bitstream/handle/2453/828/ShahiS2016d-2b.pdf?sequence=1&isAllowed=y
37. Szeto WY, Jiang Y, Wang DZW, Sumalee A (2015) A sustainable road network design problem with land use transportation interaction over time. Netw Spat Econ 15(3): 791–822. https://doi.org/10.1007/S11067-013-9191-9
38. Shabaev A, Sokolov A, Urban A, Pyatin D (2020) Optimal planning of wood harvesting and timber supply in Russian conditions. Forests 11(662): 1-16. https://doi.org/10.3390/f11060662
39. Taskhiri MS, Garbs M, Geldermann J (2016) Sustainable logistics network for wood flow considering cascade utilisation. J Clean Pro 110: 25-39. https://doi.org/10.1016/j.jclepro.2015.09.098
40. Zamora-Cristales R, Sessions J, Boston K, Murphy G (2015) Economic optimization of forest biomass processing and transport in the Pacific Northwest USA. For Sci 61(2): 220–234. https://doi.org/10.5849/forsci.13-158
41. Zamora-Cristales R, Sessions J, Marrs G (2017) Economic implications of grinding, transporting, and pretreating fresh versus aged forest residues for biofuel production. Can J for Res 47(2): 269–276. https://doi.org/10.1139/cjfr-2016-0221
42. Zhang D, Cai S, Ye F, Si YW, Nguyen TT (2017) A hybrid algorithm for a vehicle routing problem with realistic constraints. Inf Sci 394: 167–182. https://doi.org/10.1016/j.ins.2017.02.028

Tables

Table 1 Input parameters of the integrated inventory management sawlogs supply chain simulation model with a merchandizing yard.

Inbound logistics (supply)	Private orchards		20.00
	Illegitimate wood dealers		42.00
Wood-yard terminal			2.00
Outbound logistics (demand)	Large-scale mills (av. demand 46000 tone^{-1})	Pulp & paper mill	1.00
		Plywood mill	5.00
		Veneer mill	1.00
	Small scale mills (av. demand = 110 m^3)		120.00
Assortment types			4.00
Transport cost (US$/tonne^{-1})	From private orchards to terminal (mini-truck)		0.185
	Illegitimate sources to mills (Typical vans)		0.72
	Transport logs from terminals to mills (dump trucks)		0.122
	Transport other types of fiber (mini-truck)		
Storage cost (US$/tonne^{-1})		Private orchard	0.75
		Wood-yard terminal	1.25
		Mill	1.00
Terminal capacity (tone)			600,000

Table 2. Separation of the total logistics cost of the wood supply-chain network (status quo scenario)

Cost attributes		Transportation cost (US$)	Share of demand (%)
Illegitimate wood		1,304,597	21.43
farm-tree pruning wood	From wood-dealers to mills	2,655,873	43.63
	From terminal to mills	1,212,973	19.93
Sawlogs from terminal		254,444.50	4.18
Low-quality wood		463,673	7.62
Inventory in forest		0.00	0.00
Inventory at terminal		195,684.40	3.21
Inventory at mills		0.00	0.00
Total supply-chain		6,087,245	100.00
Unit transportation cost ($/tonne^{-1})		7.09	

Table 3. Cost decomposition for the total supply-chain cost subject to multiple logistics scenarios

Item	Transportation cost (US$)			
		Scenario 1	Scenario 2	Scenario 3
Wood smuggling		992,553.90	1,500,321.	0.000
farm-tree pruning woods	From province cities to demand centers	2,655,873.	2,655,873	2,655,873
	From terminal to demand centers	1,212,973.	121,2973	1,212,973
Sawlogs from terminal		254,444.5	254,444.5	254,444.5
Low-quality timbers from terminal		46,3673.4	410,272.4	657,297.5
Inventory in forest		0.000	0.000	0.000
Inventory at terminal		195,684.4	203,846.5	195,688.80
Inventory at mills		0.000	0.000	0.000
Total supply-chain		5,775,202.00	6,237,730.00	4,976,277.00
Unit transportation cost ($/tonne^{-1})		6.73	7.27	5.80

Figures

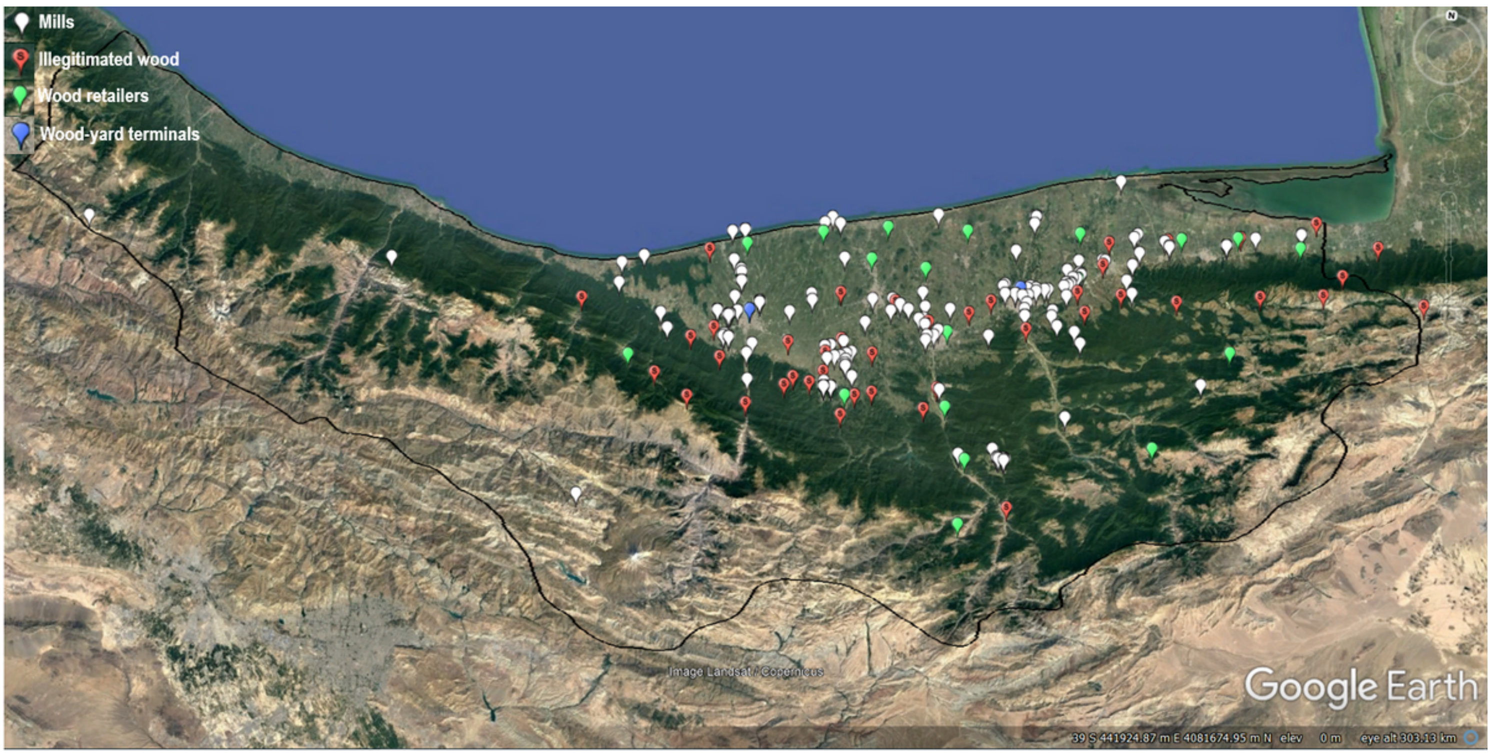

Figure 1

The geographical location of study area with the logistic network complexities

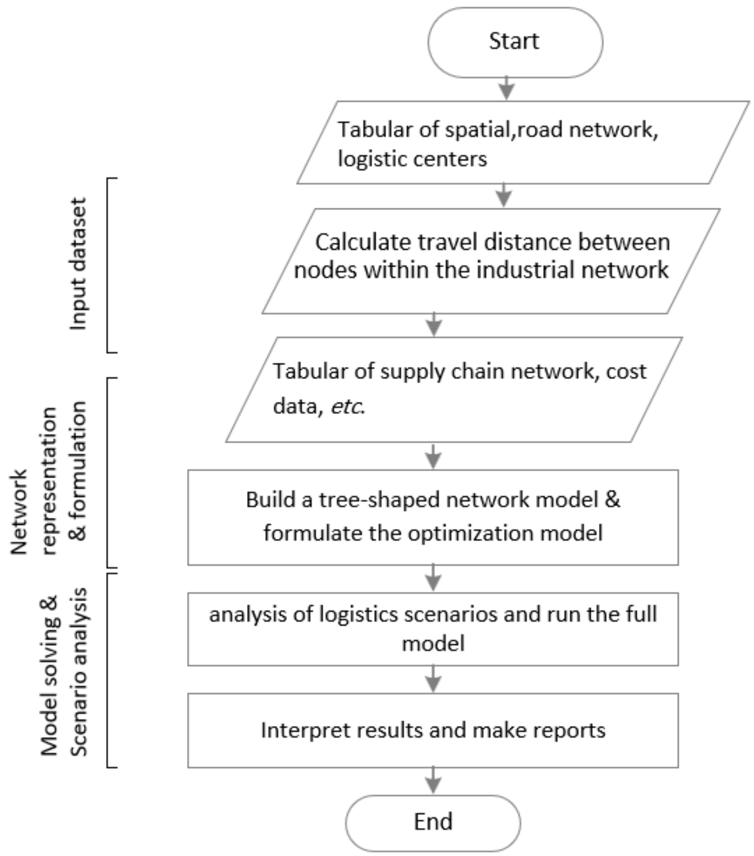

Figure 2

Flowchart of the study

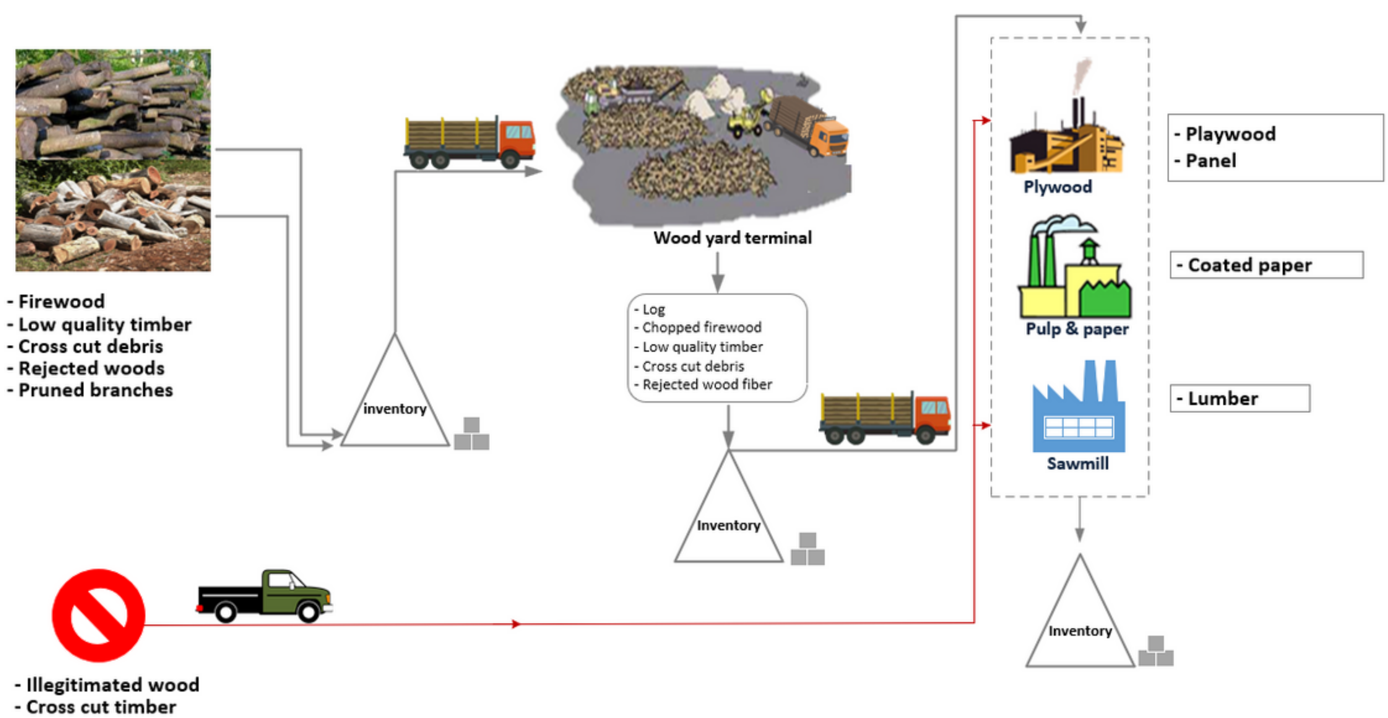

Figure 3

Forest product industries supply chain network

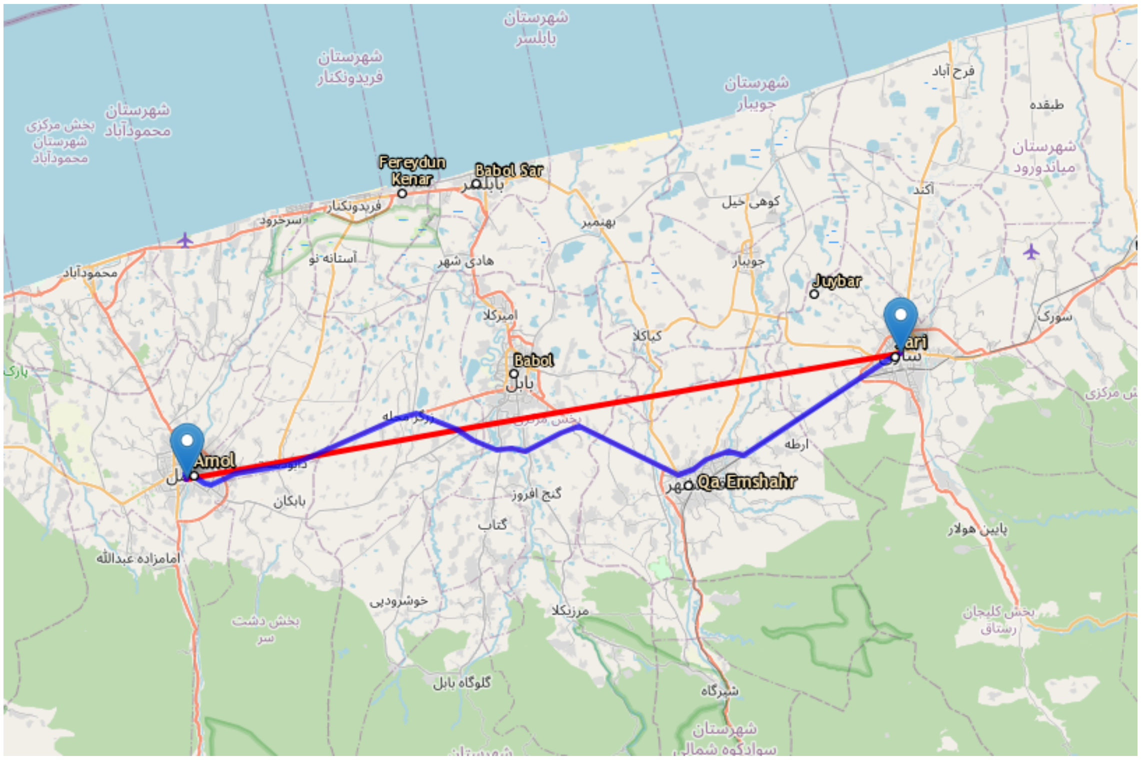

Figure 4

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

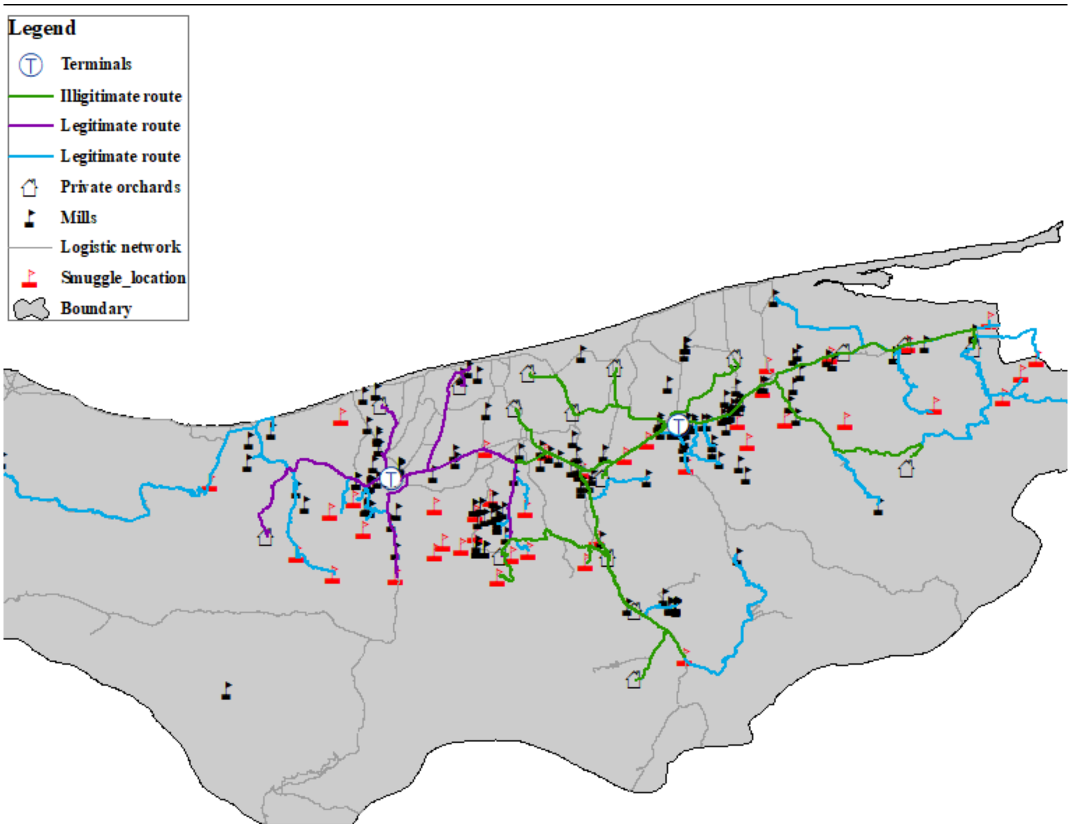

Figure 5

mapping part of the solution generated by the optimization model