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Modelling and optimization of material flows in the wood pellet supply chain

Ignacio Vitale [a], Rodolfo G. Dondo [a], Matías González [b], Mariana E. Cóccola [c,*]

[a] INTEC (Universidad Nacional del Litoral – CONICET), Güemes 3450, (3000) Santa Fe, Santa Fe, Argentina
[b] UTN-FRCU, Ing. Pereyra 676, (3260) Concepción del Uruguay, Entre Ríos, Argentina
[c] UTN-FRCU, CONICET, Ing. Pereyra 676, (3260) Concepción del Uruguay, Entre Ríos, Argentina

HIGHLIGHTS

- An algorithm for the short-term planning of wood pellet supply chains is developed.
- Both inbound and outbound logistics are mathematically represented in detail.
- The Column Generation method is used to compute the set of transportation routes.
- The integrated logistics problem is mathematically represented through a MILP model.
- The procedure is applied to the case of a pellet producer in Argentina.

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ABSTRACT

To reduce the use of fossil fuels, forest-based biomass appears as an engaging source of energy. Nevertheless, logistics costs represent one of the main barriers in the use of forestry residues and wood waste for bioenergy and biofuels production. The relatively low energy density of biomass contributes to a higher transportation cost per unit of energy content compared with fossil fuels. Other issues, such as raw material availability, seasonality, production and storage capacity constraints, and transportation distances for product distribution also are critical in the management of biomass supply chain. The interconnectedness of these factors directly impacts into the movement of materials along the logistics chain. In this way, this paper researches the alternative of using forest residues and wood waste as raw material sources for wood pellet production through the modelling and optimization of all logistics activities performed in the supply chain. The objective is the minimization of the total operative cost, which in turn allows determining the minimum profitable selling price of produced pellets. Besides production and inventory decisions, the proposal determines the more profitable routes for biomass collection and pellets distribution. A standard decomposition technique, consisting in designing routes first and later computing products and raw material flows, is employed to solve the optimization problem. The proposal is tested on a large-size case study designed with real data from the forest industry in the Argentinean Mesopotamia. Due to the close interaction between all logistics decisions in the supply chain, several scenarios are assessed to estimate the impact on the solutions of some changes in the problem configuration.

1. Introduction

Depletion of natural resources, increased pollution, climate change, and scarcity of natural resources are major global challenges [1]. In the light of this situation, resource recovery from wastes and residues is becoming important for a sustainable economy, conservation of the ecosystem as well as for reducing the dependence on finite natural resources [2]. The valorization of available biomass through its conversion into solid, liquid, or gaseous fuels contributes to promote sustainable energy sources. Biomass is as a carbon neutral-based renewable resource, and fuels from biomass are more sustainable than petroleum-based fuels [3].

Wood pellets are a compact form of forest biomass made from harvest residues and by-products of wood processing facilities. During the

* Corresponding author.
E-mail address: marcoccola@santafe-conicet.gov.ar (M.E. Cóccola).

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Table 1
Overview of the literature on biomass logistics listed in this work (ordered from newest to oldest).

Authors	Decision Levels	Solution Approaches	Upstream logistics	Downstream logistics	Inventory Decisions	Vehicle routing	Multiple time-periods	Multi-objective
Our approach	• Operational	• Decomposition-based algorithm (Column Generation + MILP model)	•	•	•	•	•	
Baghizadeh et al. [7]	• Strategic • Tactical • Operational	• MINLP model • Lagrangian relaxation	•	•	•		•	•
Fernandez-Lacruz et al. [30]	• Operational	• Discrete-event simulation	•		•		•	
Akhtari and Sowlati [33]	• Strategic • Tactical • Operational	• MILP model • Discrete-event simulation	•	•	•		•	•
Malladi and Sowlati [38]	• Operational	• MILP model	•		•		•	•
Akhtari et al. [31]	• Operational	• Discrete-event simulation	•		•		•	•
Soares et al. [34]	• Operational	• MILP model • Matheuristic	•			•		
Campanella et al. [37]	• Strategic	• MILP model	•	•				
Zamar et al. [32]	• Operational	• Discrete-event simulation	•			•	•	
Boukherroub et al. [36]	• Strategic	• Spatially explicit optimization • Generic optimization model	•	•			•	
Memişoğlu and Üster [35]	• Strategic • Tactical	• Benders decomposition–based algorithm	•	•	•		•	
Mobini et al. [29]	• Operational	• Discrete-event simulation	•	•			•	•

past decade, trade of wood pellets has increased its share in the global bioenergy market. Wood pellets are an important solid biofuel commodity on the international market. Rapid increases in the production and consumption of wood pellets, and predictions of an increased demand in the future have formed a competitive global market. Europe is currently the major market for woody pellets. The statistical report published by Caferri [4] highlights that global pellet production showed a growth of 12% from 2018 to 2019, with countries in Europe, outside the EU28, and South America as the areas faster expanding with pellet production volume growth rates of 37% and 21%, respectively, in 2019 compared to 2018. On the other hand, Japan, Korea, and China appear as the new consumption countries.

Forest biomass is usually widely dispersed geographically and need to be transported to conversion plants in a cost-effective way. The biomass must be collected, transported, and stored for use over time, while maintaining technical qualities that allow its conversion to wood pellets. Therefore, it is essential the consideration of storage operations and lead times, almost similarly to those materials that have specific perish time [5]. Nowadays, there are still underutilized large quantities of residues in countries with intensive forestry management because the cost of collecting and transporting them is greater than the market value. Moreover, after the conversion process, the wood pellets must be delivered at a price that allows the energy produced from them to compete in the marketplace with other energy forms [6]. Therefore, the design and use of optimal transportation routes for both biomass collection and pellets distribution are of utmost importance. Pellet producers are forced to optimize the material flows along the whole supply chain (SC) to keep their products competitive against traditional energy sources. The SC concept is widely used as an effective approach in decision-making and planning for highly complex industries [7]. The efficient management of material flows across any SC allows performing sustainable operations and achieving economic benefits for all actors involved the value chain [8–10].

In the last years, manufacturing of wood pellets became a very active area of research and different SC approaches have been proposed to evaluate the environmental performance of wood pellet production [11,12] and to develop sustainable logistic processes [13]. Also, the development of cost optimization strategies has gained great interest to improve the profitability and hence, the viability of the industry. For instance, a reduction of SC costs could contribute to increased utilization of pellets [14].

Despite the high associated costs, the routing and scheduling of truck operations over a short-term period is a neglected area in the biomass SC management. Most available studies published in the literature simplify transportation activities by assuming fixed transportation orders to directly deliver forest biomass from its generation points to delivery facilities, without considering routing. The same assumption is generally made for end-product distribution. According to the review on biomass logistics published by Malladi and Sowlati [15], there are few models that deal with routing of trucks for transporting forest biomass and all of them are focused just on the upstream logistics (see Table 1). This review also highlights that the number of papers dealing with logistics-related decisions in biomass SCs is large, but the short-term planning of logistics operations is nascent, and a lot of research remains to be done, especially in the development of efficient solution techniques for real-life problems, which generally result in intractable and complex mathematical models [9]. In this way, the review leaves open a wide area for research.

To address the knowledge gap in the short-term planning of biomass SCs, this paper develops a two-stage decomposition procedure for optimizing raw material and pellet flows over multiple time-periods in a realistic wood pellet SC. The SC infrastructure is assumed to be fixed and known. The solution strategy explicitly includes the design of routes for both biomass collection and pellet distribution. To the best of our knowledge, our proposal is the first computational approach that allows optimizing, in a detailed way, all logistics activities performed in both the upstream and downstream sides of the wood pellet SC, including routing decisions. The first algorithmic stage identifies a set of profitable routes for biomass collection and pellet distribution. The procedure generates pickup routes that start at a factory, collect biomass from several suppliers, and finally return to the pellet mill to unload the collected biomass. Similarly, on a same delivery route, one or more distribution hubs can receive products from a factory. The second stage solves the integrated logistics problem, determining the number of trucks assigned to each pickup and delivery route and computing the remaining decisions variables related procurement, inventory, production, and distribution operations.

In summary, the contributions of this paper are threefold. First, it mathematically models all logistics activities involved in the flows of raw material and product along the whole wood pellet SC, designing and selecting the best profitable routes for biomass collection and pellet distribution. Second, it proposes a decomposition approach for solving

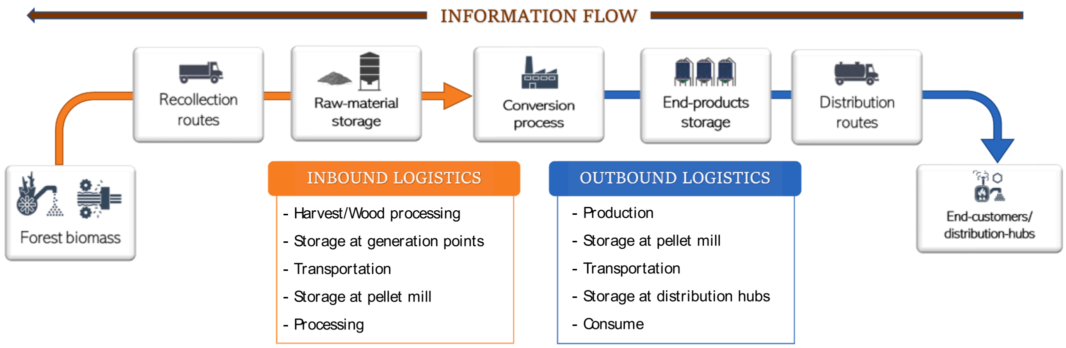

Fig. 1. Logistics activities in the wood pellet SC.

in reasonable computational times, large-sizes instances of the problem. The approach disengages routing decisions from the computation of raw materials and pellets flows by first generating banks of candidate raw-materials-pick-up-routes and pellets-delivery-routes and by later solving a problem that selects the more convenient routes while fixing raw materials and pellets flows along the SC. Third, it evaluates the effect of different replenishment strategies on the final cost of wood pellets at customer locations.

The proposal is first validated by solving several testing instances and by comparing the results with those found by an exact optimization model. Then, the optimization algorithm is used to solve a case study of a pellet producer located in the Argentinean Mesopotamia. This region of South America generates around 2.7 million tonnes of reachable harvest residues per year in addition to 3,129,360 tonne/year of biomass coming from solid waste generated by wood processing companies [16]. The proposed optimization procedure will not only allow to save time and money to the pellet producer but will also lead to more adequate decisions by simultaneously considering all factors involved in the supply chain, thereby significantly facilitating and enhancing the decision-making process.

1.1. The wood pellet supply chain

Fig. 1 shows a sketch of the typical wood pellet SC. The logistic network starts with the sources of forest biomass (forest sites and wood processing mills), to move them in the upstream side to conversion plants, continues and is complete at the downstream side when the products are delivered to regional distribution hubs, exportation harbors or end-consumers. In this way, the wood pellets-chain starts out as forest residues or wood waste and moves through logistics and production processes until reaching customers.

Residues from harvesting operations include thinning, pruning or any other leftover plant material after cutting, which can be chipped in the forest site and loaded directly into trucks. On the other hand, wood-waste is mostly the result of wood processing industries which may generate significant number of by-products, such as bark, sawdust, shavings, and offcuts. Generally, the milling industry is the main raw material source for pellet production [17]. The woody biomass is transported to a pelletizing mill by capacitated trucks. Due to the low bulk density and the high moisture content of forest residues, transportation of raw materials heavily contributes to the final cost of end-products. It is preferable to separate wet and dry materials for storage. Wet sawdust or chips can be stored outdoor but dry sawdust or shavings should be stored indoor, in covered storage areas or silos, to prevent the materials getting wet. In plants, these materials are transformed, via successive and intertwined process steps in pellets. The wet materials are dried before size reduction. The heat for the dryer can be supplied by any kind of fuel, even by biomass. Through a hammering operation, the dry materials are homogenized to an even-size so that they can pass by die holes of the wood pellet machines. The mixing of raw materials is also completed here. After a pelletizing operation, the pellets are hot and plastic and hence, they need to be cooled down to become hard and rigid. After cooling the pellets are screened and stored either in sheds or bagged for distribution. Wood pellets are bulk distributed or bagged and sent to consumers using several transportation modes, such as trucks, railcars, and vessels. As in any other SC, the wood pellet logistics involves three main activities: storage, transportation, and processing. Decisions related to each one of these activities are closely interlinked and affect each other. They are next briefly described.

Storage: Storage decisions include the quantity of raw materials and pellets to be inventoried at different locations of the supply chain during every period of the planning horizon. The main driver of storing biomass is to match raw materials supply and products demand during the entire planning period. Seasonal supply of raw materials, uncertainties, and unexpected disruptive events that are present in the supply chain make storage a crucial logistics operation to avoid any interruption in the pellet mill operations.

Transportation: Transportation deals with the movement of forest and wood residues and the movement of pellets between different locations of the supply chain. High recollection costs due to the low bulk density, the high moisture content of raw materials and long transportation distances for pellets distribution are important contributors to the high logistics cost of this industry.

Processing: A series of processing stages, depending on the technology and the type of raw material, is required for densification and hardening of biomass. Drying, size reduction, pelletizing, cooling, screening, and packaging processes are typically seen in pellet mills. A biomass boiler is the most used technology for generating the required heat for the drying process. Thereby, the raw material can be used for both heat generation and pellet production.

Many decisions-variables are involved in wood pellet production on an industrial scale at a competitive price and in a sustainable way; procurement, storage, transportation, and production decisions must be taken together in any realistic optimization model. This highlights the necessity of globally optimizing raw materials and products flows in the SC. In addition, storage of biomass is essential to maintain a consistent supply of raw material to production process, but biomass stored for long periods out in the open undergo decay and, as a result, it may not be useful for pellet production. On the other hand, timely pickup of wood waste must be performed because wood processing industries have dedicated storage areas with limited capacity for storing their residues. This is of utmost importance in a wood pellets SC where transport decisions, storing decisions, and production decisions are very intermingled. This, in turn, leads to a great complexity of any mathematical model aimed at optimizing the raw material and products flows along the whole SC. In summary, the following issues must be addressed by the planner to operate the SC at its optimum regime:

Transport decisions

- What quantity of raw materials must be collected during each period of the planning horizon from each visited supplier?
- When to resupply a given distribution hub and what quantity of bulk and bagged pellets must be supplied to each of them at any period?
- When to resupply a given plant with wood chips, shavings and/or sawdust and what quantity of these raw materials must be supplied to each plant at any period?
- When to move bagged pellets to exportation harbors and what tonnage move there?

Production decisions

- What quantity of pellets must be manufactured and what quantity must be bagged during each period of the planning horizon?
- What quantity of raw material is used for the drying process during each period of the planning horizon?

Storage decisions

- How must vary the inventory of raw materials (wood chips, shavings, and sawdust) and bulk/bagged pellets on sawmills, conversion plants, and distribution hubs as a function of transportation and production decisions while meeting maximum and minimum inventorying constraints?

Obviously, the high number of intermingled decisions involved in the problem leads to complex monolithic mathematical formulations which are not solvable in practical computation times when realistic case studies are tried to solve. Therefore, to find practical solutions providing answers to the above questions in reasonable computational times, a decomposition algorithm that partially disengages routing decisions from procurement, production, and inventory decisions is proposed in this paper.

The remainder of this paper is organized as follows: Section 2 presents a review of the literature on optimization of forestry SCs; the problem researched is formally stated in Section 3; the solution approach is presented in Sections 4 and 5. Numerical results are discussed in section 6 and finally, the conclusions are outlined in Section 7.

2. Literature review

Optimization of bioenergy and biofuel SCs is an active research area and several reviews have been published on biomass logistics. While some of these reviews focused only on forest-based biomass [18–20], another group focused on agriculture-based biomass [21,22]. A few articles reviewed the mathematical aspects of optimization models such as the objective function, decision variables, and the solution method used to solve the problems [23,24]. The review of de Meyer et al. [25] classified the studies on optimization models according to the solution method adopted to solve the problem at hand. Studies were classified into those dealing with mathematical programming models, heuristics, and multi criteria decision analysis. Ba et al. [23] classified mathematical models of biomass SCs into deterministic, stochastic, and multi-objective optimization models and analyzed issues such as the solver used, the number of variables, and constraints in each model. Another review presented on biomass logistics was published by Gold and Seuring [26], who reviewed 54 papers published between 2000 and 2009 and classified the literature based on biomass SC management and logistics issues for bioenergy production. Logistics decisions were categorized into harvesting and collection, storage, transportation, and pretreatment of biomass. Malladi and Sowlati [15] presented an extensive review focusing mainly on economic objectives while environmental concerns received less attention. The authors analyzed issues as particularities of biomass SCs and its associated logistics problems, the mathematical models developed to optimize them, seasonal availability and quality variation of biomass, storage, transportation activities, and finally the new trends in optimization of biomass SCs. Recently, Visser et al. [14] presented an overview of the cost structure of pellet SC, focusing on SCs design and analysing the impact of design variables, feedstock types, production location, technology, and plant size. These authors concluded that tailored optimization strategies must be developed because logistics costs are highly dependent on specific SC conditions. In the same line, Strandgard et al. [27] performed a literature review of overseas experience to identify the potential areas for cost-reductions in the Australian forest biomass SCs to further develop the industry in their country. Uasuf and Becker [28] developed a study for determining the wood pellet production costs and energy consumption under different framework conditions in the northeast of Argentina. This study was limited to the pelleting operation stage, considering just operating cost and energy consumption from the feedstock handling operation until the intermediate storage of wood pellets within the production plant.

One computational technique that has been widely used for representing and evaluating biomass logistics is discrete-event simulation. For instance, Mobini et al. [29] proposed a simulation model for representing the entire wood pellet SC from the sources of raw materials to end-customers. The simulation tool was used to perform different studios concerning the design and analysis of operations along the SC. Fernandez-Lacruz et al. [30] used a discrete-event simulation model for analysing the supply cost of chipped logging residues and small-diameter trees, from chipping at forest storage sites to delivery to two possible end-users: a combined heat and power plant or a biorefinery. The simulation tool was used to evaluate two alternative modes of operation: exclusive direct supply from the sites to the end-users or supply via a feed-in terminal. Akhtari et al. [31] used simulation modelling to evaluate and compare the performance of two inventory management systems (“order-up-to-level” and “fixed order quantity”) in a forest-based biomass SC including multiple number of conversion facilities that use different types of biomass. The authors highlight that efficient inventory management is of utmost of importance to balance the conflicting goals of increasing the demand fulfilment and decreasing the cost and emissions. However, inventory decisions are generally overlooked in the related literature [31]. Zamar et al. [32] developed a model to solve a stochastic vehicle routing problem, where the goal is to efficiently collect biomass residues from a set of sawmills and deliver them to a single depot. Even though simulation is a useful computational tool to analyse the behaviour of a system over time and to evaluate alternative operative scenarios, the solutions given by simulation runs are dependent of the heuristic rules defined by the users within the model for ordering the work-in-progress. To overcome this weakness, Akhtari and Sowlati [33] proposed a hybrid optimization-simulation approach for integrating strategic, tactical, and operational plans of forest-based biomass SCs considering the uncertainties arising in the operational level. The optimization model is used first to determine the strategic and tactical plans without considering variations at the operational level. Then, the resulting plans are taken as the input for the simulation model to evaluate those plans in terms of the net present value and demand fulfilment.

With regards to pure optimization approaches, several mathematical models and solution strategies have been proposed for the efficient management of forest SCs. Focusing just on the upstream side, Soares et al. [34] presented a MILP model together a matheuristic for the integrated route planning considering the synchronization of three types of vehicles (lorries, loaders and trucks) which need to perform interrelated operations with minimum logistics costs. Other studies have considered the optimization of the whole SC. Memişoğlu and Üster [35] proposed a Benders decomposition–based algorithm for the planning and design of a bioenergy SC along a multiperiod planning horizon. Both strategic and tactical-level decisions are considered in the upstream and downstream echelons of the SC with the goal of minimizing logistics

Table 2
Nomenclature.

Sets	
I	facilities in the supply chain
I^S	sources of forest residues
I^F	pellet mills
I^C	distribution hubs
K	end-products
M	raw materials
R^+	pickup routes
R^-	delivery routes
T	time-periods of the planning horizon
W	wet materials
Subscripts	
i,j	facilities in the supply chain
k	end-products
m	raw materials
r	routes
t,t'	time-periods of the planning horizon
Parameters	
$a_{i,r}$	determining if facility i is included in route r
$c^{res}_{i,m}$	price paid to supplier i for a tonne of residue m *(USD t^{-1})*
$c^{pen}_{i,m}$	penalty paid for those residues m not collected from supplier i *(USD t^{-1})*
$c^{pr}_{i,k}$	cost of producing a tonne of product k on plant i *(USD t^{-1})*
$c^{inv}_{i,k}$	cost of storing a tonne of product k at location i *(USD t^{-1})*
$c^{inv}_{i,m}$	cost of storing a tonne of raw-material m at location i *(USD t^{-1})*
$c^{stp}_{i,k}$	fixed cost for enabling fabrication of product k on plant i *(USD)*
c_r	cost of route r
cf_m	conversion factor from one tonne of raw material m to one tonne of pellets
$d_{i,j}$	distance between two locations i and j *(kms)*
$dem_{i,k,t}$	demand of product k by distribution hub i during period t *(t)*
dp	percentage of damaged pellets after cooling stage
hd	energy requirement per tonne of evaporated water *(kWh t^{-1})*
$i^0_{i,k}$	initial level of product k in plant or distribution hub i *(t)*
$i^0_{i,m}$	initial level of raw material m in plant i *(t)*
$i^{min}_{i,k}$	lower bound on the quantity of product k stored on location i *(t)*
$i^{max}_{i,k}$	upper bound on the quantity of product k stored on location i *(t)*
$i^{min}_{i,m}$	minimum storing capacity of raw material m at location i *(t)*
$i^{max}_{i,m}$	maximum storing capacity of raw material m at location i *(t)*
km_r	total length of route r *(km)*
lr	loading rate *(m^3 h^{-1})*
M_d, M_c	big-m values
$ncv^{sawdust}$	net calorific value of wet sawdust *(kWh t^{-1})*
$p^{min}_{i,k}$	lower bound on the quantity of product k to fabricate on plant i *(t)*
$p^{max}_{i,k}$	upper bound on the quantity of product k to fabricate on plant i *(t)*
q^M	weight capacity of trucks used for collecting raw materials from suppliers *(t)*
q^K	weight capacity of trucks used for distributing products *(t)*
rc^+	transportation cost for raw material recollection *(USD t^{-1} km^{-1})*
rc^-	transportation cost for product distribution *(USD t^{-1} km^{-1})*
st_i	fixed service-time in the facility i for each load/unload operation *(hours)*
$t_{i,j}$	travel-time between two locations i and j *(hours)*
$t_{i,j,t}$	travel-time between two locations i and j during period t *(hours)*
t^{max}	maximum duration for any travelled route *(hours)*
tr^{max}	maximum time agreed with the suppliers for collecting their woody residues (*time periods*).
ur	unloading rate *(m^3 h^{-1})*
v^M	volume capacity of trucks used for collecting raw materials from suppliers *(m^3)*
v^K	volume capacity of trucks used for distributing products *(m^3)*
$w_{i,m,t}$	quantity of residue m generated at location i during period t *(t)*
π_i	dual variables associated to location i in the reduced master problem
δ^{min}_m	minimum load of raw-material m paid to any used truck *(t)*
δ^{min}_k	minimum load of product k paid to any used truck *(t)*
δ_i	plant i from which the routes depart
γ_i	burner efficiency
∂_m	bulk density of raw material m *(t m^{-3})*
∂_k	bulk density of product k *(t m^{-3})*

Table 2 (*continued*)

Binary Variables	
$PR_{i,j}$	sequencing variable of locations i and j along a route
$P^+_{i,j,r,t}$	sequencing variable of locations i and j along pickup route r during period t
$P^-_{i,j,r,t}$	sequencing variable of locations i and j along delivery route r during period t
X_r	determining if route r is selected by the master problem
$XC^+_{r,m,t}$	determining if raw material m is transported by pickup route r during period t
$XC^-_{r,k,t}$	determining if product k is transported by delivery route r during period t
$XL^+_{i,r,t}$	determining if location i is visited by pickup route r during period t
$XL^-_{i,r,t}$	determining if location i is visited by delivery route r during period t
Y_i	determining if customer i is included in the route generated by the pricing problem
$Y^+_{r,t}$	determining if pickup route r is used during period t
$Y^-_{r,t}$	determining if delivery route r is used during period t
Integer Variables	
$X^+_{r,m,t}$	determining the number of vehicles allocated to pickup route r during period t for transporting raw material m
$X^-_{r,k,t}$	determining the number of vehicles allocated to delivery route r during period t for transporting product k
Continuous Variables	
$\Lambda^-_{i,k,r,t}$	quantity of product k loaded/unloaded by route r on plant/distribution hub i during period t *(t)*
$\Lambda^+_{i,m,r,t}$	quantity of raw material m loaded/unloaded by route r on supplier/plant i during period t *(t)*
$C^+_{m,r,t}$	cost of pickup route r used during period t for transporting raw material m *(USD)*
$C^-_{k,r,t}$	cost of delivery route r used during period t for transporting product k *(USD)*
D_i	distance travelled for reaching facility i *(km)*
DC	penalty costs for residues not collected *(USD)*
$EW_{i,t}$	mass of water evaporated from wet residues at plant i during period t *(t)*
FC	feedstock acquisition costs *(USD)*
$Heat_{i,t}$	requirement of heat at plant i during period t *(kWh)*
IC	total inventory cost *(USD)*
$I_{i,k,t}$	inventory of product k on location i during period t *(t)*
$I_{i,m,t}$	inventory of raw material m on location i during period t *(t)*
PC	total production cost *(USD)*
$P_{i,k,t}$	quantity of product k manufactured in plant i during period t *(t)*
$Q^{heat}_{i,m,t}$	quantity of raw material m consumed at plant i during period t for heat generation *(t)*
$Q^{pellet}_{i,m,t}$	quantity of raw material m consumed at plant i during period t for producing pellets *(t)*
RC^+	total raw materials pickup cost *(USD)*

costs. Boukherroub et al. [36] used spatially explicit optimization for designing a profitable wood pellet SC. Through a generic model, the authors determined the optimal operational conditions under which the wood pellet SC is profitable. The model decides about the best feedstock locations and determines the optimal supplied quantities as well as the optimal production capacity. Campanella et al. [37] developed a MILP model for the optimal design of a forest SC. The model aims at determining the location and size of each production facility with the goal of maximizing the total benefit. The movement of products and residues between facilities are also represented. Malladi and Sowlati [38] developed a bi-objective optimization model for determining the mix of wood residues, briquettes, and pellets to meet the daily demand of a biomass-fed district heating plant under different carbon price policies. The objective function includes the feedstock cost and the cost of emissions defined by three carbon pricing policies. Baghizadeh et al. [7] presented a multi-period and multi-product MINLP mathematical model for a forest SC. The proposal includes tactical, strategic, and operational decisions, as well as environmental and social aspects. The Lagrangian Relaxation method was used by the authors to efficiently deal with large-size instances of the problem.

The papers on biomass logistics listed in this review have been categorized in Table 1. The works are classified according to the decision level, the solution strategy, and main features of the problem addressed. In general, most models of the literature deal with biomass storage just in the upstream side of the SC, which includes biomass supply-sites, intermediate storage, and conversion facilities. Few models considered the inventory management at the downstream side. Moreover, vehicle routing decisions are generally neglected by those works considering the entire SC. To the best of our knowledge, there is not yet any optimization approach that deals with inventory and routing decisions at both sides of the value chain. To address this research gap, we propose a decomposition algorithm to optimize raw material and product flows along the whole wood pellet SC. The optimization procedure considers, in a detailed way, inbound logistics of raw materials, processing of raw materials into wood pellets, and outbound logistics to the end-customers. The proposal aims at minimizing the total operative cost. In addition, two alternative replenishment strategies are assessed to estimate the pellet cost at the last echelon of the SC. On one hand, replenishment activities may be triggered by a customer order, strategy known as "order-based-resupply" (OBR), wherein each order to the vendor specifies the desired quantity and the time window within which the delivery must be fulfilled. As another alternative, the inventory of products at customers/distribution-centers can be monitored by the vendor, which uses forecasting to replenish and to avoid inventories to fall under safety levels. In this strategy, known as vendor-managed inventory (VMI), demand and inventory information from the customers are shared with the supplier. The VMI is a collaborative strategy that allows smoothing the impact of demand variability to reduce production, inventory holding, and distribution costs. Such a strategy, used in many industries, integrates production planning, inventory management, and delivery scheduling decisions. The supplier acts as the central decision maker, monitoring the inventory on retailers to plan the replenishment policy. In general, the VMI policy shows a more efficient resources utilization than the traditional retailer managed inventory system [39]. For a forest products SC, alternative replenishment strategies have been assessed by Alayet et al. [40]. The results obtained by these authors confirm the ability of the VMI approach to reduce logistics costs for the overall SC. Since raw materials acquisition depends on the production and inventory decisions, the VMI also impacts on the raw materials procurement policy. So, this paper also considers the use of the VMI practice in the upstream side of the SC to globally optimize material flows along the whole SC.

3. Problem statement

Before mathematically defining the problem under study, Table 2 introduces the nomenclature used throughout the paper.

Let $I = \{I^S \cup I^F \cup I^C\}$ be the set of facilities, which stand respectively for forest biomass sources, pellet mills, and distribution hubs/harbours, and let the graph $G(I, A)$ represent the roads network where A is the set of minimum-distance arcs $a_{i,j}$ interconnecting facilities i and j. Arcs i-j correspond to road segments characterized by a length $d_{i,j}$ and a travel time $t_{i,j}$. As seasonality can affect road conditions, the speed of trucks can also vary as a function of both the time period and the road type and therefore, arcs travel times can be defined as $t_{i,j,t}$. The subscript $t \in T$ refers to each period of planning horizon, which is partitioned in weeks, i.e., each period t stands for a planning week. Let $K = \{bulk, bagged\}$ and $M = \{sawdust, shaving, wood\ chip\}$ be the sets of products and raw materials, respectively, moved along the SC. Every distribution-hub/harbour $i \in I^C$ requires a known quantity $dem_{i,k,t}$ of bulk or bagged pellets during time-period $t \in T$. Factories, denoted by the subset $I^F \subset I$, produce an unknown quantity $P_{i,k,t}$ of bulk and bagged pellets during each period $t \in T$. At each pellet mill $i \in I^F$, the production level should remain between a minimum and a maximum level $\left[p_{i,k}^{min}, p_{i,k}^{max}\right]$ determined by the operative limits of the pellet machine. A drum dryer is used for the drying process. The required heat is generated in a solid fuel burner using wet sawdust as fuel. After the cooling process, the pellets produced at any period $t \in T$ are sieved to separate the fine particles from the well-made product. The damaged pellets are re-entered to the pellet machine at the next period $t+1$ [41]. The transportation activities are outsourced to a trucking company. A fleet of trucks with volumetric capacity v^M and weight capacity q^M is available for collecting raw materials from wood processing mills and forest sites. No mixing of different raw materials along a pickup route is allowed. Another homogenous fleet of trucks with volumetric capacity v^K and weight capacity q^K is available for moving pellets to distribution hubs and exportation harbours. Each load/unload operation in any facility $i \in I$ consumes a fixed service-time st_i plus a variable time depending on the tonnage of raw material/pellets to be loaded/unloaded to/from the truck. The loading and unloading rates are assumed to be constant. Routing costs depend on both the route length and the total tonnage of raw material or products transported. Even if no cargo is transported by a mobilized truck, minimum capacities δ_m^{min} or δ_k^{min} must be paid, depending on the type of material transported. If the transported cargo exceeds such a threshold, a value proportional to the real cargo is paid. Pickup and distribution routes are considered feasible when the volumetric and weight capacity constraint are both satisfied, and the overall travelling time is lower than a maximum time-length t_{max}. The bulk density of materials ($t\,m^{-3}$) multiplied by the truck capacity (m^3) sets an upper bound to the tonnage that can be transported in every route.

Woody residues can be stored both in their sources $i \in I^S$ and factories $i \in I^F$ with the storing capacity defined by $\left[i_{i,m}^{min}, i_{i,m}^{max}\right]$, where $i_{i,m}^{max}$ is the maximum storing capacity and $i_{i,m}^{min}$ is the minimum operative capacity or safety stock. Due to the limited storing capacity at some suppliers and for preserving the adequate conditions of woody residues, the pellet producer agrees with the suppliers to collect their residues before tr^{max} periods after their generation. On the other hand, bulk and bagged pellets are stored in both plants and distribution hubs with stock levels ranging into a limited capacity defined by the interval $\left[i_{i,k}^{min}, i_{i,k}^{max}\right]$. At the start of the planning horizon, initial inventories of raw materials and products, $i_{i,m}^0$ and $i_{i,k}^0$, are available at different facilities of the SC. The total inventory holding cost is calculated by multiplying the cost of holding one unit in stock by the storage quantity at the end of each period. Costs incurred per tonne of produced pellets to satisfy products demand are the following:

(i) Raw material procurement costs, which are given by the sum of the quantity of each raw material m purchased from supplier $i \in I^S$ multiplied by the acquisition cost $c_{i,m}^{res}$.
(ii) Pick-up costs for transporting raw materials from harvesting sites or wood processing mills up to conversion plants.
(iii) Delivery costs, which are defined as the sum of costs of full truckload vehicles moving bagged and bulk pellets to harbours and distribution hubs.
(iv) Raw materials inventory costs associated to the quantities $I_{i,m,t}$ of raw material m stored at each time period t on suppliers and factories $i \in \{I^S \cup I^F\}$. Holding costs per tonne of raw material are given by parameter $c_{i,m}^{inv}$.
(v) Products inventory costs proportional to quantities $I_{i,k,t}$ of bagged/bulk pellets stored at each time-period t on factories and distribution-hubs/ports $i \in \{I^F \cup I^C\}$. Holding costs per tonne of product are given by parameter $c_{i,k}^{inv}$.
(vi) Production costs given by the summation of variable and fixed costs. Fixed costs $c_{i,k}^{stp}$ are the necessary expenses involved in operating factory i for producing bagged and bulk pellets during every period of planning horizon (e.g., costs of capital, maintenance, taxes, and labour). Variable costs (e.g., cost of energy, fuel, and consumables) are proportional to the produced quantity

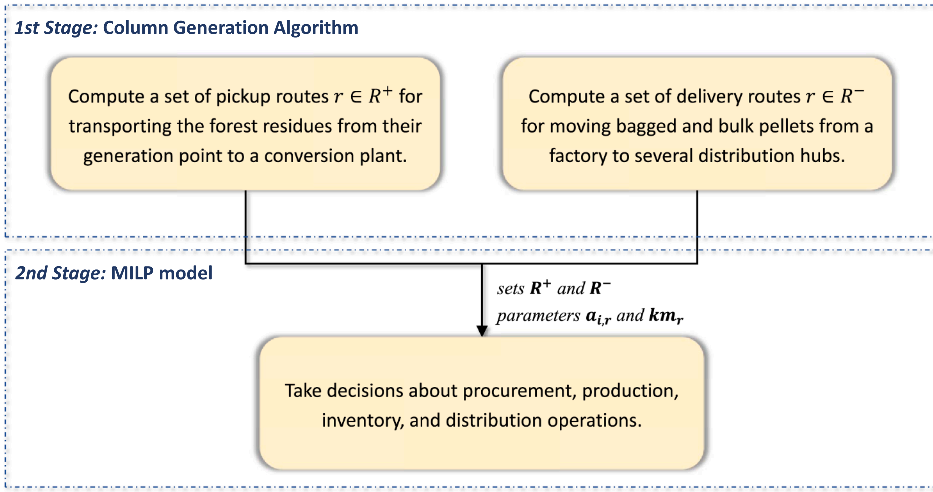

Fig. 2. Outline of the decomposition procedure.

$P_{i,k,t}$. The unit production-cost per tonne of product k at each factory i is denoted by $c^{pr}_{i,k}$.

(vii) Extra costs paid for those residues not collected within the term agreed with the suppliers. After this deadline, the suppliers can dispose these materials for other purposes.

The solution of the problem aims at determining for every period of the planning horizon:

(i) The biomass collection routes and the number of trucks to send to each route.
(ii) The quantity of raw materials to be collected by each pickup vehicle from any visited supplier.
(iii) The tonnes of bulk and bagged pellets to manufacture in each plant.
(iv) The pellet delivery routes and the number of trucks to send to each route.
(v) The quantity of products unloaded to each visited distribution-hub/port from delivery trucks.

The objective is the minimization of the total operational cost, which must be computed to determine the minimum profitable selling price of bagged and bulk pellets. The operational cost is defined as the summation of raw materials acquisition costs, pellets manufacturing costs, pickup costs, distribution costs, and inventory-holding costs for both raw materials and bulk and bagged pellets.

4. Solution approach

The collection and transportation of forest residues, their conversion into pellets, and the final delivery of bagged and bulk products to distribution hubs require a proper coordination of logistics and production activities, upstream and downstream from factories. Due to the multiplicity of interlinked decisions, the short-term planning of logistics operations in the whole SC is a complex challenge. Since the problem leads to large-scale NP-hard MILP models [42], CPU processing capacities can be easily exhausted when barely trying to solve small-size instances through conventional techniques. Therefore, other solution strategies, such as metaheuristics, hybrid methods or decomposition procedures are proved to be useful to facilitate the solution of large models [43]. Decomposition algorithms allow "softening" the combinatory explosion associated to MILP models, providing not-necessarily optimal but good-enough solutions within reasonable processing times. In this way, if decoupling of routing decisions from production decisions is possible, a procedure that first generates pools of pickup and delivery routes before determining the remaining problem decisions can be designed. Nevertheless, the problem of generating a set of feasible routes for activities at both upstream and downstream of SC is also a NP-hard optimization problem, i.e., as the number of suppliers, factories, and distribution hubs rise, CPU times consumed to compute optimal solutions will grow exponentially. It is computationally impossible to explicitly enumerate all feasible routes, which can run in millions considering the high number of facilities integrating the pellet SC. As generation and selection of routes is a critical step that may affect distribution and inventory costs, an effective routes-generation method able to produce cost effective routes in few CPU minutes must be employed. In this paper, the Column Generation (CG) approach is chosen, but any other effective technique, such as heuristics or metaheuristics, also can be used for determining a set of candidate routes. CG is a rather standard technique widely used for solving routing problems. The algorithmic procedure used to compute the biomass collection routes and the pellets delivery routes is summarized in the Appendix A. This procedure generates pickup routes that start at a factory, visit several suppliers, and finally return to the origin plant. Such a design of routes allows considering as suppliers in the SC that small-size sawmills, which generate waste volumes lower than a full truckload. Similarly, on a same delivery route, one or more distribution hubs can receive products from a given factory.

As shown by Fig. 2, once the CG procedure computes the set of promising pickup routes $r \in R^+$ and delivery routes $r \in R^-$, a mixed-integer linear programming (MILP) model containing all problem constraints is solved in the second stage of the optimization procedure. Through this model, the routes to be used during each period of the planning horizon and the number of vehicles allocated to each selected route are determined. Production levels and the consequently inventory levels for both raw materials and bulk and bagged pellets on each period of the planning horizon are also computed by the MILP model. This one receives from the first algorithmic stage the following problem data: sets R^+ and R^-, parameter $a_{i,r}$ taking 1 as value just if the facility i is included in route r and 0 otherwise, and parameter km_r indicating the total length of the route r in kilometres.

5. The MILP model

As explained above, the integrated problem is mathematically represented through a MILP model. All constraints are next described. For clarity for the reader, parameters are shown in lowercase while decision variables are written in uppercase.

Objective function: The objective function (1) seeks the minimization of the total operational cost along the whole planning horizon. Such a cost is defined as the summation of feedstock acquisition costs (FC), production costs (PC), total inventory costs (IC), raw materials recollection costs (RC^{+}), products distribution costs (RC^{-}), and the penalty DC paid for those residues perished or discarded due to any drawback in their recollection.

$$\textbf{Minimize}(FC+PC+IC+RC^{+}+RC^{-}+DC) \quad (1)$$

Cost-defining constraints: Eqs. (2) to (7) define all terms involved in the objective function. Firstly, feedstock acquisition costs are computed by Eq. (2) as the summation along the planning horizon of prices paid to the suppliers $i \in I^{S}$ for the quantity of raw materials collected at each time-period t. Continuous variable $\Lambda^{+}_{i,m,r,t}$ stands for the quantity of raw material m loaded/unloaded from/to supplier/plant i by pickup route r during period t. For computing the total production cost PC, Eq. (3) considers both the plant start-up cost $c^{stp}_{i,k}$ paid for enabling the fabrication of product k in plant i during period t and the variable cost $c^{pr}_{i,k}$ concerning the production of a tonne of product k at plant i. Continuous variable $P_{i,k,t}$ determines the quantity of product k manufactured during period t at plant i. The total inventory cost IC is computed by Eq. (4) where parameters $c^{inv}_{i,m}$ and $c^{inv}_{i,k}$ are the costs associated to the storing of a tonne of material m and product k on facility i, respectively. Continuous variables $I_{i,k,t}$ and $I_{i,m,t}$ stand respectively for the inventory levels on site i for products and raw materials at the end of each period t. With regards to transportation activities, the pickup cost, RC^{+}, is defined by Eq. (5) as the sum of costs $C^{+}_{m,r,t}$ of all routes $r \in R^{+}$ performed during every period t to transport raw-materials m from suppliers to plants. Similarly, Eq. (6) computes the total distribution cost as the sum of costs $C^{-}_{k,r,t}$ of every route $r \in R^{-}$ used to transport product k from plants to distribution hubs. Finally, Eq. (7) defines the total extra cost paid by the pellet producer for those residues not collected before a given usefulness-time after their generation. The total tonnage of residue m discarded by supplier i up to any period t due to limited storage reason or because the due date for their collection was reached is represented by continuous variable $L_{i,m,t}$. To compute the total penalty cost, Eq. (7) multiplies the penalty factor $c^{pen}_{i,m}$ by the accumulated tonnage of residues that became unusable up to the last period $t = |T|$.

$$FC=\sum_{t\in T}\sum_{i\in I^{S}}\sum_{m\in M}\left(c^{res}_{i,m}\sum_{r\in R^{+}}\Lambda^{+}_{i,m,r,t}\right) \quad (2)$$

$$PC=\sum_{i\in I^{F}}\sum_{t\in T}\sum_{k\in K}\left(c^{stp}_{i,k}+c^{pr}_{i,k}P_{i,k,t}\right) \quad (3)$$

$$IC=\sum_{i\in I^{C}}\sum_{t\in T}\sum_{k\in K}c^{inv}_{i,k}I_{i,k,t}+\sum_{i\in I^{F}}\sum_{t\in T}\left(\sum_{k\in K}c^{inv}_{i,k}I_{i,k,t}+\sum_{m\in M}c^{inv}_{i,m}I_{i,m,t}\right)+\sum_{i\in I^{S}}\sum_{t\in T}\sum_{m\in M}c^{inv}_{i,m}I_{i,m,t} \quad (4)$$

$$RC^{+}=\sum_{m\in M}\sum_{r\in R^{+}}\sum_{t\in T}C^{+}_{m,r,t} \quad (5)$$

$$RC^{-}=\sum_{k\in K}\sum_{r\in R^{-}}\sum_{t\in T}C^{-}_{k,r,t} \quad (6)$$

$$DC=\sum_{i\in I^{S}}\sum_{m\in M}c^{pen}_{i,m}L_{i,m,t} \qquad \forall t\in T:t=|T| \quad (7)$$

Inventory constraints: Eqs. (8) to (13) are defined to track the inventory level of raw materials $m \in M$ and products $k \in K$ on every facility $i \in I$ at the end of each period $t \in T$. If the manager controls the inventory of products in distribution hubs according the VMI framework, Eq. (8.a) states the product balance constraint. Otherwise, if the OBR methodology is used as business model, the quantity of product k demanded by any distribution hub during every period t must be exactly satisfied, as stated by Eq. (8.b). Continuous variable $\Lambda^{-}_{i,k,r,t}$ determines the tonnage of product k loaded/unloaded from/to factory/distribution hub i during period t through delivery route $r \in R^{-}$.

$$I_{i,k,t}=\dot{i}^{0}_{i,k}-\sum_{t^{'}\in T:t^{'}\le t}dem_{i,k,t^{'}}+\sum_{t^{'}\in T:t^{'}\le t}\sum_{r\in R^{-}}\Lambda^{-}_{i,k,r,t^{'}} \quad \forall i\in I^{C},t\in T,k\in K \quad (8.a)$$

$$dem_{i,k,t}=\sum_{r\in R^{-}}\Lambda^{-}_{i,k,r,t} \quad \forall i\in I^{C},t\in T,k\in K \quad (8.b)$$

Eqs. (9.a) and (9.b) state the inventory levels of bagged and bulk pellets, respectively, on each plant $i \in I^{F}$ at the end of every period $t \in T$. Both constraints include the initial inventory $\dot{i}^{0}_{i,k}$, the produced quantity $P_{i,k,t}$, and the total tonnage delivered $\Lambda^{-}_{i,k,r,t}$ up to each period t. Since bags of pellets are produced by taking products from bulk storage, Eq. (9.b) also considers the tonnes of pellets bagged during each period for computing the inventory of bulk pellets.

$$I_{i,t,\text{`}bag\text{'}}=\dot{i}^{0}_{i,\text{`}bag\text{'}}+\sum_{t^{'}\in T:t^{'}\le t}P_{i,\text{`}bag\text{'},t^{'}}-\sum_{t^{'}\in T:t^{'}\le t}\sum_{r\in R^{-}}\Lambda^{-}_{i,\text{`}bag\text{'},r,t^{'}} \qquad \forall i\in I^{F},t\in T \quad (9.a)$$

$$I_{i,t,\text{`}bulk\text{'}}=\dot{i}^{0}_{i,\text{`}bulk\text{'}}+\sum_{t^{'}\in T:t^{'}\le t}\left(P_{i,\text{`}bulk\text{'},t^{'}}-P_{i,\text{`}bag\text{'},t^{'}}\right)-\sum_{t^{'}\in T:t^{'}\le t}\sum_{r\in R^{-}}\Lambda^{-}_{i,\text{`}bulk\text{'}r,t^{'}} \quad \forall i\in I^{F},t\in T \quad (9.b)$$

For raw materials, the inventory tracking constrains must be defined on plants and suppliers, as specified by Eqs. (10) and (11). Continuous variables $Q^{pellet}_{i,m,t}$ and $Q^{heat}_{i,m,t}$ indicate the quantity of feedstock m consumed to produce pellets and heat, respectively, during period t at every plant i. For suppliers $i \in I^{S}$, the tonnage of residue m generated during each period t is known in advance through parameter $w_{i,m,t}$. The stored residues in any supplier are reduced because either they are collected by a truck or they are discarded ($L_{i,m,t}>0$).

$$I_{i,m,t}=\dot{i}^{0}_{i,m}-\sum_{t^{'}\in T:t^{'}\le t}\left(Q^{pellet}_{i,m,t^{'}}+Q^{heat}_{i,m,t^{'}}\right)+\sum_{t^{'}\in T:t^{'}\le t}\sum_{r\in R^{+}}\Lambda^{+}_{i,m,r,t^{'}} \quad \forall i\in I^{F},t\in T,m\in M \quad (10)$$

$$I_{i,m,t}=\sum_{t^{'}\in T:t^{'}\le t}w_{i,m,t^{'}}-\sum_{t^{'}\in T:t^{'}\le t}\sum_{r\in R^{+}}\Lambda^{+}_{i,m,r,t^{'}}-L_{i,m,t} \quad \forall i\in I^{S},t\in T,m\in M \quad (11)$$

The value that variable $L_{i,m,t}$ can take is bounded by constraints (12) and (13). Parameter tr^{max} stands for the maximum usefulness time that residues can remain at the supplier after their generation. After this time, the supplier can dispose these residues which are no longer available for the recollection.

$$L_{i,m,t}\ge\sum_{t^{'}\in T:t^{'}\le t-tr^{max}}w_{i,m,t^{'}}-\sum_{r\in R^{+}}\sum_{t^{'}\in T:t^{'}<t}\Lambda^{+}_{i,m,r,t^{'}} \quad \forall i\in I^{S},m\in M,t\in T:t>tr^{max} \quad (12)$$

$$L_{i,m,t}\ge L_{i,m,t-1} \quad \forall i\in I^{S},m\in M,t\in T:t>tr^{max}+1 \quad (13)$$

Since variable $L_{i,m,t}$ is associated to a positive term in the objective function (1) that seeks to minimize costs, the MILP solver will assign the lowest feasible value to the variable whenever the maximum storing capacity at supplier is not exceed (see Eq. (11)). Finally, upper and lower bounds for storing raw materials and products in any facility of the SC are given by Eqs. (14) and (15), respectively.

$$\dot{i}^{min}_{i,m}\le I_{i,m,t}\le\dot{i}^{max}_{i,m} \qquad \forall i\in(I^{S}\cup I^{F}),t\in T,m\in M \quad (14)$$

$$\dot{i}^{min}_{i,k}\le I_{i,k,t}\le\dot{i}^{max}_{i,k} \qquad \forall i\in\left(I^{F}\cup I^{C}\right),t\in T,k\in K \quad (15)$$

Production constraints: Eq. (16) sets the quantity of bulk pellets produced on plant i during period t as the product of the specific conversion factor cf_m by the quantity of raw material m consumed plus the reprocessed production from previous period $Z_{i,t-1}$. The conversion factor for each material is calculated as $cf_m = \frac{(1-mc_{pellet})}{(1-mc_m)}$, being mc the moisture content. The quantity of production discarded during each period t, $Z_{i,t}$, is computed by Eq. (17). The quantity of damaged pellets represents a percentage dp from the total production corresponding to every period. Finally, the production level of bagged and bulk pellets during any period t on plant i is kept between the maximum and minimum production capacity, as specified by constraint (18). Note that the total production of bagged pellets at any period t depends on the bulk storage level in that period, as specified by Eq. (9.b).

$$P_{i,\text{'bulk'},t} = \sum_{m\in M} cf_m Q^{pellet}_{i,m,t} + Z_{i,t-1} \qquad \forall i \in I^F, t \in T \tag{16}$$

$$Z_{i,t} = P_{i,\text{'bulk'},t}\, dp \qquad \forall i \in I^F, t \in T \tag{17}$$

$$p^{min}_{i,k} \le P_{i,t,k} \le p^{max}_{i,k} \qquad \forall i \in I^F, t \in T, k \in K \tag{18}$$

The mass of water $EW_{i,t}$ that must be evaporated from wet materials $m \in W$ during drying process is determined by Eq. (19). Such a variable is multiplied by the heat demand of the dryer *(hd)* to compute the total required heat $Heat_{i,t}$ at plant i during period t to obtain the raw materials target-moisture. Parameter hd stands for the energy requirement per tonne of evaporated water. Finally, Eq. (21) computes the total tonnage of wet sawdust consumed as drying fuel $Q^{Heat}_{i,\text{'sawdust'},t}$ at plant i during each period t based on the total requirement of heat ($Heat_{i,t}$), the net calorific value of the fuel ($ncv^{sawdust}$), and the boiler efficiency of plant i (γ_i).

$$EW_{i,t} = \sum_{m\in W} Q^{pellet}_{i,m,t}(1 - cf_m) \qquad \forall i \in I^F, t \in T \tag{19}$$

$$Heat_{i,t} = EW_{i,t}\, hd \qquad \forall i \in I^F, t \in T \tag{20}$$

$$Q^{Heat}_{i,\text{'sawdust'},t} = \frac{Heat_{i,t}}{ncv^{sawdust}\gamma_i} \qquad \forall i \in I^F, t \in T \tag{21}$$

Transportation constraints: Given the volumetric capacity v^M and the weight capacity q^M of pickup vehicles and (v^K, q^K) for delivery trucks, constraints (22) and (23) restrict the quantity of any type of raw material and end-product that can be transported on any selected route r of period t. Parameters ∂_m and ∂_k represent the bulk density ($t\ m^{-3}$) of raw material m and product k, respectively. The number of trucks travelling the pickup route $r \in R^+$ during period t for transporting raw material m is given by the integer variable $X^+_{r,m,t}$. The integer variables $X^-_{r,k,t}$ are used, with the same meaning, for delivery routes. The volumetric capacity constraints are given by Eqs (22.a) and (23.a) while weight capacity constraints are determined by Eqs. (22.b) and (23.b). Due to the low bulk density of forest biomass, constraint (22.a) is usually more tightening than weight capacity constraint (22.b).

$$\Lambda^+_{i,m,r,t}\Big/\partial_m \le v^M X^+_{r,m,t} \qquad \forall i \in I^F, t \in T, m \in M, r \in R^+ \tag{22.a}$$

$$\Lambda^+_{i,m,r,t} \le q^M X^+_{r,m,t} \qquad \forall i \in I^F, t \in T, m \in M, r \in R^+ \tag{22.b}$$

$$\Lambda^-_{i,k,r,t}\Big/\partial_k \le v^K X^-_{r,k,t} \qquad \forall i \in I^F, t \in T, k \in K, r \in R^- \tag{23.a}$$

$$\Lambda^-_{i,k,r,t} \le q^K X^-_{r,k,t} \qquad \forall i \in I^F, t \in T, k \in K, r \in R^- \tag{23.b}$$

The overall quantity of raw material or products loaded on every truck must be always discharged along the route, as specified by Eqs. (24) and (25), respectively.

$$\Lambda^+_{i,m,r,t} = \sum_{i'\in I^S} \Lambda^+_{i',m,r,t} \qquad \forall i \in I^F, t \in T, m \in M, r \in R^+ \tag{24}$$

$$\Lambda^-_{i,k,r,t} = \sum_{i'\in I^C} \Lambda^-_{i',k,r,t} \qquad \forall i \in I^F, t \in T, k \in K, r \in R^- \tag{25}$$

For trucks travelling a given route r, Eqs. (26) and (27) set to zero the tonnage that can be load/unloaded from/to those locations that are not covered by the specified route. Parameter $a_{i,r}$ takes value 1 if the facility i is included in the route r and 0 otherwise.

$$\Lambda^+_{i,m,r,t} \le a_{i,r} X^+_{r,m,t} q^M \quad \forall i \in (I^F \cup I^S), t \in T, m \in M, r \in R^+ \tag{26}$$

$$\Lambda^-_{i,k,r,t} \le a_{i,r} X^-_{r,k,t} q^K \quad \forall i \in (I^F \cup I^C), t \in T, k \in K, r \in R^- \tag{27}$$

The costs concerning the routes travelled during every period t are determined by constraints (28) and (29). Continuous variable $C^-_{r,k,t}$ stands for the cost entailed by all trucks that perform the route r to distribute product k during period t. In a similar way, variable $C^+_{r,m,t}$ is defined for computing the cost of pickup routes. Cost parameters rc^- and rc^+ are expressed in $USD\ km^{-1}\ t^{-1}$. The length of a route is given by parameter km_r. If route $r \in R^-$ is utilized for distributing product k during period t, i.e., $X^-_{r,k,t} > 0$, a minimum load δ^{min}_k must be paid, as stated by constraint (28a). If the real cargo exceeds such a threshold, constraint (28a) becomes redundant and (28b) is activated. The same logic set out above in relation to delivery routes is used to pickup routes, as stated by constraints (29a) and (29b).

$$C^-_{r,k,t} \ge rc^- km_r \delta^{min}_k X^-_{r,k,t} \qquad \forall t \in T, k \in K, r \in R^- \tag{28a}$$

$$C^-_{r,k,t} \ge rc^- km_r \sum_{i\in I^F} \Lambda^-_{i,k,r,t} \qquad \forall t \in T, k \in K, r \in R^- \tag{28b}$$

$$C^+_{r,m,t} \ge rc^+ km_r \delta^{min}_m X^+_{r,m,t} \qquad \forall t \in T, m \in M, r \in R^+ \tag{29a}$$

$$C^+_{r,m,t} \ge rc^+ km_r \sum_{i\in I^F} \Lambda^+_{i,m,r,t} \qquad \forall t \in T, m \in M, r \in R^+ \tag{29b}$$

6. Computational results and discussion

The optimization procedure is first validated though solving several numerical tests and by comparing the results obtained with those found by a monolithic MILP model. Then, the applicability and effectiveness of the proposal is assessed by dealing with a case study of a pellet company located in Argentina. Finally, the findings are interpreted in the context of what was already known about the short-term planning of biomass SCs. Also, new opportunities for research are discussed.

6.1. *Validating the decomposition procedure*

Several numerical examples were run to validate the proposed optimization algorithm. Each example was solved using both the decomposition procedure and a monolithic MILP model, which is described in Appendix B. This alternative includes the computation of routing decisions jointly with raw-materials and pellets flows. Both solution strategies were written in GAMS 34.3.0 and run on a PC with 8 GB ram and 8-Core 2.9 GHz 16-Thread Processor, using CPLEX as the MIP solver. Either a maximum CPU time of 3,600 s or a relative gap tolerance of 0.00 were imposed as termination criterions. Table 3 provides information of the size of each example together the results given by each solution strategy. In all cases, the decomposition procedure widely outperforms the monolithic MILP model. Note that the decomposition strategy reports the optimal solutions in examples #1, #2, and #3. On the other hand, for instances #4, #5, #6, #7, and #9,

Table 3
Results given by both solution strategies for each testing example.

Instance number	Number of elements				Monolithic approach			Decomposition Procedure	
	I^F	I^S	I^C	T	Best solution found	GAP (%)	CPU time (seconds)	Best solution found	CPU time (seconds)
1	1	4	2	1	14080.6	–	0.33	14080.6	0.05
2	1	6	3	1	11267.3	–	18.88	11267.3	0.11
3	1	4	2	2	28856.2	–	113.05	28856.2	0.08
4	1	6	3	2	26346.5	33.8	3600	26346.5	0.24
5	1	4	2	3	44821.7	5.5	3600	44821.7	0.13
6	1	6	3	3	43760.0	51.5	3600	43736.0	1.34
7	1	4	2	4	62057.3	19.0	3600	62057.3	0.44
8	1	6	3	4	62514.5	54.9	3600	62506.3	6.69
9	1	4	2	5	81075.1	28.9	3600	81075.1	0.34
10	1	6	3	5	83311.8	55.7	3600	83276.8	6.03
11	1	4	2	6	100503.2	32.0	3600	100483.2	1.28
12	1	6	3	6	104566.5	57.5	3600	104277.3	42.17
13	1	4	2	7	118295.5	34.2	3600	118291.0	5.94
14	1	6	3	7	123247.5	56.9	3600	122922.6	147.8
15	1	4	2	8	138051.5	35.5	3600	137960.4	1.84
16	1	6	3	8	143611.2	57.6	3600	143238.2	14.8
17	1	4	2	9	160236.3	37.2	3600	160092.1	14.08
18	1	6	3	9	268831.6	73.7	3600	169142.2	106,98
19	1	4	2	10	180893.7	37.9	3600	180654.7	6.81
20	1	6	3	10	196785.3	59.8	3600	192189.3	11.64
21	1	4	2	11	201372.3	38.5	3600	201124.3	40.95
22	1	6	3	11	389817.9	77.4	3600	215288.1	354.17
23	1	4	2	12	223552.1	39.7	3600	219463.8	74.25
24	1	6	3	12	624209.0	84.6	3600	235780.1	97.13

both approaches feature the same objective values, but the monolithic approach cannot demonstrate the optimality of the solutions found within the time limit imposed. For the remaining examples, the solutions reported by the monolithic MILP model after the time limit are worse than those found by the decomposition procedure in few seconds of CPU time. In general, the solutions given by the monolithic approach feature large gaps because Big-M type constraints used in its formulation lead to weak relaxations.

6.2. Case study

Once validated, the optimization procedure is used to solve a realistic case study of a pellet producer located in Argentina. The pellet industry in this country is nascent and geographically confined to the north-east Mesopotamian region, which is integrated by the provinces of Misiones, Corrientes, and Entre Ríos. According to the technical Report "Update of the Biomass Balance for Energy Purposes in Argentina" published by the Food and Agriculture Organization (FAO) in 2020 [16], the Mesopotamian region concentrates 84% of 3.3 million tonnes of reachable harvest residues generated by year in the country. In addition, such region can offer around 3,129,360 tonne/year of biomass coming from solid waste generated by wood processing companies. The latest census of sawmills made in Argentina determined that the average yield (production/raw material) is around 37%. This low production-yield leads to a huge quantity of residues, which are mostly left underutilized because the cost of collecting and transporting them is greater than the market value that they can fetch. Consequently, the woody residues are gathered outside, increasing the risk of fire, the proliferation of rodent populations, and the loss of natural resources. The wood industry in Argentina is mainly characterized by large quantity of small-size sawmills (annual production lower than 5,000 m^3). Industries using wood processing by-products, such as pulp and paper industry or the particle board companies, purchase their raw materials just from a few large-size sawmills located geographically within a radio of 70 km from the production plant. Therefore, the pellet producer can take advantage of this situation to negotiate with those sawmills that are left out of the wood residues SC. In the downstream side of the SC, the pellet company sells a part of its production into the domestic market, in the form of bulk or bagged pellets. Bulk pellets are usually sold by tonne for industrial consumers while 15 kg bags are sent to the massive market where the product is mainly consumed as bedding material for animals. Due to federal subsidies to residential public services such as electricity or gas, the Argentinean residential heating market by wood pellets has not significantly expanded over the past decade. Therefore, as the entire production cannot be absorbed by the domestic heating market, the company also exports bagged pellets to the European Union through an international port located a few kilometres from the production plant. The case study tackled in this paper involves the management of a multisite system comprising 34 facilities (1 factory, 29 suppliers, and 4 distribution hubs) along a planning horizon of 12 weeks. The left side of Fig. 3 shows the geographical location of each facility within the SC (green circles stand for suppliers, blue icon stands for pellet mill, and red circles stand for distribution hubs) while the right side of the picture depicts three circles around the plant for determining those suppliers located within a radius distance of 20, 60, and 120 kms, respectively. The shortest distance *(kms)* and travel times *(hours)* between each pair of facilities in the SC are calculated using the *Here Routing* API, which was set for selecting truck routes.

Sawdust, shaving, and wood chip are used as raw materials for pellet production. A moisture content *(mc)* of 55% is assumed for sawdust and wood chip while $mc_{shaving} = 10\%$. Since the target moisture content for pellets is $mc_{pellet} = 10\%$, shaving can skip the drying step in the production process. The conversion factor from tonne of raw material m to tonne of pellets is calculated as $cf_m = (1 - mc_{pellet})/(1 - mc_m)$. For example, the production of 1 tonne of pellets needs from 2 tonnes of sawdust with a moisture content of 55%. The pellet plant operates six days per week with a minimum of one shift of 8 h per day and a maximum of 3 shifts of 8 h per day with 4 $t\ h^{-1}$ of nominal capacity. The percentage of damaged pellets is estimated to be around 6%, at the end

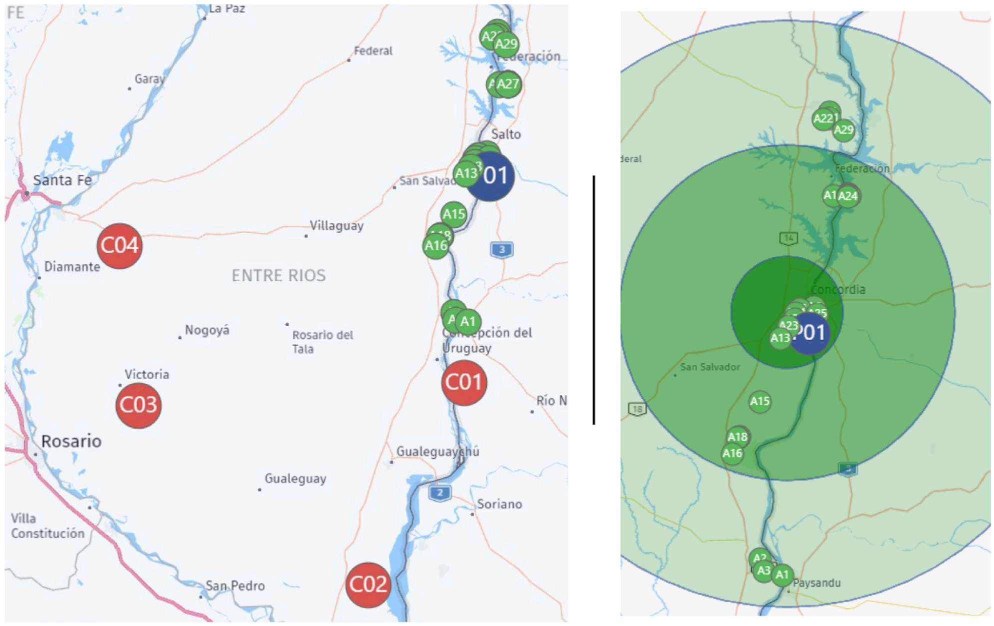

Fig. 3. Geographical distribution of facilities in the pellet supply chain.

of production line. A drum dryer is used as drying system. The required heat for the drying process is generated in a solid fuel burner with 70% of efficiency that uses wet sawdust as fuel. The heat required to evaporate 1 tonne of water is $hd = 1,200$ *kWh*. A net calorific value of wet sawdust $ncv^{sawdust} = 1,843$ $kWh\ t^{-1}$ is calculated by Eq. (30), wherein $ncv^{dry\_sawdust}$ is the calorific value of sawdust for 0% moisture content and h is the portion of hydrogen in wood (approximately 6%).

$$ncv^{sawdust} = ncv^{dry\_sawdust} * (1 - mc_{sawdust}) - (580 * (mc_{sawdust} + 9 * h)) \tag{30}$$

The transportation of raw material from suppliers to the plant and the delivery of wood pellets to the distribution hubs are performed by a hired trucking company. Each truck has a weight capacity of 33 tonnes, and the total volume of its cargo compartment is 140 cubic meters. The bulk density ($t\ m^{-3}$) of materials considered in this paper are: 0.22 for sawdust, 0.13 for shaving, 0.3 for chip, and 0.65 por pellet. The transportation costs are 0.08 $USD\ km^{-1}\ t^{-1}$ for raw material recollection and 0.1 $USD\ km^{-1}\ t^{-1}$ for pellet distribution. A maximum duration of $t_{max} = 12\ h$ is imposed for each travelled route. The loading and unloading rates for raw materials and pellets are assumed to be constant at 200 $m^3\ h^{-1}$. In addition, every truck remains a fixed time of $st_i = 0.5\ h$ at each visited facility. Regarding the permanence of residues in their generation place, a maximum time of 4 weeks is agreed between suppliers and the pellet producer. The remaining data about inventories capacities, production and inventories costs, residues prices and supply, and product demand can be obtained from *https://vitalenacho.github.io/PelletsMaps/SupplyChain*.

6.3. Scenario analysis

The CG algorithm used in the first stage of the optimization procedure was set for running up to 100 master-pricing problem iterations. As result, the routing procedure determined, after 15 min of CPU time, a set of 128 alternative routes for biomass collection and 6 potential routes for pellet distribution, i.e., $|R^+| = 128$ and $|R^-| = 6$. Both sets of routes were utilized to assess different operating scenarios in the SC. On one hand, the alternative of visiting an only sawmill (or harvesting area) in each route *(SS)* instead of multiples raw material sources *(MS)* per route is analysed. On the other hand, the option of collecting raw materials just from suppliers located at a distance lower than 60 km *(LD)* is compared with that one considering all suppliers shown in Fig. 3 *(UD)*. The four resulting scenarios (*SS-LD, SS-UD, MS-LD, MS-UD)* are solved considering the following variants:

- *V1:* original problem configuration.
- *V2:* it is a variant *V1* considering different prices of raw materials according to both the size of sawmill and the location of it. We assume that the prices of biomass are higher in those sawmills closer to the factory because the pellet producer can obtain considerable savings from transportation activities. On the other hand, the large-size sawmills can negotiate better prices of biomass with their buyers due to volume reasons.
- *V3:* it is variant *V2* but the production capacity of the plant reduced. Now, the pellet mill works five days instead of 6 days a week.

First, the twelve problem instances proposed are solved with the VMI strategy as business model. Afterwards, the same set of instances is solved again but considering the OBR strategy for satisfying product demand at the downstream side of SC. In this way, a total of 24 problem instances are solved. Each one is named according to the problem variant, the business model applied, the type of route utilized, and the suppliers considered, e.g., instance *V2-VMI-SS-LD* refers to variant 2, the VMI strategy, and routes including only a pickup location from suppliers located to a distance lower than 60 km from the plant. A relative gap tolerance of 0.01 was imposed as termination criterion for the MILP model in the second stage of procedure. Model sizes, objective values, and computational times for all instances are summarized in Table 4. The algorithm consumed 8.5 min of computational time to solve all instances. The minimum operative cost for each example is disaggregated in Table C.1 of Appendix C. It details the cost associated to

Table 4
Model sizes and computational performance for all proposed instances.

Scenario	Integer variables	Continuous variables	Constraints	Objective Function (USD)	CPU time (seconds)
V1–VMI-SS-LD	888	22,256	27,878	441,566.61	1.97
V1–VMI-SS-UD	1,140	36,368	43,565	446,009.15	2.03
V1–VMI-MS-LD	4,500	108,080	128,150	439,291.40	42.69
V1–VMI-MS-UD	4,752	147,140	168,785	443,363.99	29.63
V2–VMI-SS-LD	888	22,256	27,878	445,446.68	1.75
V2–VMI-SS-UD	1,140	36,368	43,565	449,247.08	2.05
V2–VMI-MS-LD	4,500	108,080	1281,50	444,128.94	21.73
V2–VMI-MS-UD	4,752	147,140	168,785	446,806.03	33.77
V3–VMI-SS-LD	888	22,256	27,878	445,492.20	2.13
V3–VMI-SS-UD	1,140	36,368	43,565	448,993.83	3.13
V3–VMI-MS-LD	4,500	108,080	128,150	443,931.01	24.39
V3–VMI-MS-UD	4,752	147,140	168,785	446,078.01	26.19
V1–OBR-SS-LD	888	22,160	27,686	500,691.60	4.31
V1–OBR-SS-UD	1,140	36,272	43,373	498,673.17	2.89
V1–OBR-MS-LD	4,500	107,984	127,958	488,952.28	83.50
V1–OBR-MS-UD	4,752	147,044	168,593	490,361.99	60.17
V2–OBR-SS-LD	888	22,160	27,686	503,467.39	10.44
V2–OBR-SS-UD	1,140	36,272	43,373	502,552.55	2.45
V2–OBR-MS-LD	4,500	107,984	127,958	493,576.18	57.22
V2–OBR-MS-UD	4,752	147,044	168,593	493,935.68	31.17
V3–OBR-SS-LD	888	22,160	27,686	504,476.91	5.25
V3–OBR-SS-UD	1,140	36,272	43,373	502,104.47	2.67
V3–OBR-MS-LD	4,500	107,984	127,958	493,489.65	59.05
V3–OBR-MS-UD	4,752	147,044	168,593	494,707.74	28.55

Table 5
Cost per tonne of raw material delivered to the plant (*USD* t^{-1}).

Scenario	Wet Sawdust	Shaving	Wood Chip
V1–VMI-SS-LD	9.76	16.57	11.04
V1–VMI-SS-UD	9.78	17.53	10.99
V1–VMI-MS-LD	9.87	17.46	11.01
V1–VMI-MS-UD	10.03	17.79	11.19
V2–VMI-SS-LD	10.05	17.39	11.40
V2–VMI-SS-UD	10.00	17.81	11.41
V2–VMI-MS-LD	10.03	17.96	11.34
V2–VMI-MS-UD	10.20	18.14	11.59
V3–VMI-SS-LD	10.05	17.33	12.21
V3–VMI-SS-UD	10.00	17.71	12.15
V3–VMI-MS-LD	10.03	17.98	12.26
V3–VMI-MS-UD	10.27	18.08	12.32
V1–OBR-SS-LD	9.96	16.71	11.34
V1–OBR-SS-UD	10.15	17.65	11.47
V1–OBR-MS-LD	10.94	19.36	11.42
V1–OBR-MS-UD	10.14	17.77	11.53
V2–OBR-SS-LD	10.16	17.64	11.62
V2–OBR-SS-UD	10.32	17.90	11.76
V2–OBR-MS-LD	11.06	19.74	11.56
V2–OBR-MS-UD	10.42	18.28	11.87
V3–OBR-SS-LD	10.14	17.73	12.64
V3–OBR-SS-UD	10.37	17.58	12.65
V3–OBR-MS-LD	11.18	20.03	12.63
V3–OBR-MS-UD	10.32	18.10	12.77

every logistics activity and the corresponding percentage over the total cost.

The purchase of raw materials and their transportation to the production plant represent around 27%-29% of the total operative cost. The cost concerning the inventory of raw materials is in average 0.05% of the total cost. Table 5 shows the cost per tonne of raw material delivered to the plant. Such a cost is calculated as the sum of purchase and transportation costs divided by the total quantity of raw material acquired. In average, the cost of wet sawdust is 10.22 *USD* t^{-1}, wood chip 11.76 *USD* t^{-1}, and shavings 17.93 *USD* t^{-1}.

The total quantity of raw materials collected from each supplier for the whole planning horizon is depicted in Fig. 4 while the tonnage of raw material left in its generation place are shown in Fig. 5. From this last picture, it is deduced that the pellet producer can increase its production capacity to benefit of leftover residues whenever the extra production can be introduced in the market. The quantities of raw material consumed during the whole planning horizon are shown in Fig. 6. Most wet sawdust available is used for heat generation while wood chip is the main raw material consumed for pellet production. Fig. 7 depicts the percentage of nominal capacity utilized for bulk production, in average, during every period of the planning horizon. This picture also shows, with a blue horizontal line, the maximum production capacity reached during the planning horizon. For currently levels of pellet demand, it is advisable to operate the plant five days a week since in this case, the plant availability level is kept between 85%-90% utilization range.

Distribution activities from the plant to distribution hubs determine 45% of the total cost in the VMI instances while this percentage grows up to 47% in the OBR examples. The cost related to the storing of pellets accounts for 0.6% and 0.3% for VMI and OBR examples, respectively. The final cost per tonne produced at the gate of the plant together the total quantity of products sent to each distribution hub and the associated distribution cost are given in Tables C.2 and C.3 of Appendix C. The information given in these tables allows computing the cost per tonne of product delivered to each facility at the end of the SC. The average cost of producing a tonne of bulk pellet is 48.8 *USD* t^{-1} while bagged pellets have a final production cost of 50.9 *USD* t^{-1}. Due to the proximity of the plant to the export port, the cost per tonne of bagged pellets at this location results, in average, 78.9 *USD* t^{-1}. This value is computed considering the costs associated to delivery operations. For the other distribution hubs, which are further away from the plant, the cost per tonne of (bagged or bulk) pellets, is around 100 *USD* t^{-1} or more, depending on the instances considered.

6.4. Discussion

The results obtained for the case study demonstrated that, due to the close interaction between decisions at both sides of the SC, any small change in the problem configuration may significantly impact on the generated solution. The scenarios *MS-UD* are generally the preferable with regards to recollection costs, i.e., it is recommendable to acquire raw materials from some suppliers that are further away from the plant and to use pickup routes visiting more than one supplier per tour.

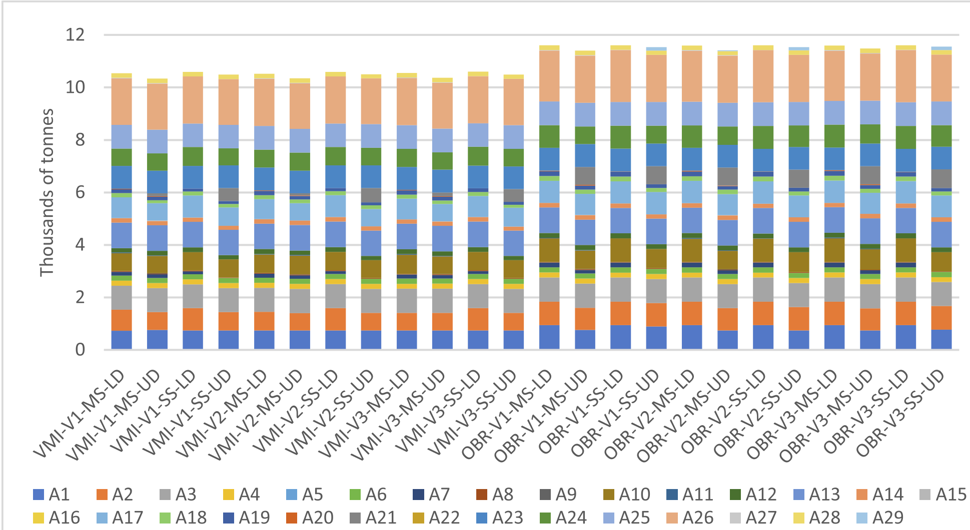

Fig. 4. Total tonnage of raw material collected from each supplier.

However, instances *MS-LD* are those that show the minimum operative costs because the pellet producer does not consume the total raw materials offered by all suppliers. Hence, more extra costs must be paid in instances *UD* for those residues that cannot be collected before the time agreed with the suppliers. On the other hand, *OBR* instances feature higher operational costs than *VMI* examples. The study performed by Alayet et al. [40] for a forest products SC also demonstrated that VMI approach is useful to reduce logistics costs through the overall SC. Particularly, the quantity of pellets produced and sent to distribution hubs is increased to cover the initial inventories of products at the last echelon of the supply chain, which are set to zero in the OBR examples. Due to the increased production, the quantity of raw material purchased is also higher in the OBR instances. In case of imposing equality on the aggregated inventory of end-products in all facilities of the SC at the start and at the end of planning horizon, the production levels for both the OBR and the VMI examples should be similar. As in other studies [29], the distribution of wood pellets accounts for one of the main logistics costs. It highlights the importance of incorporating routing decisions in the short-term planning of biomass SC operations. The minimization of distribution costs contributes to deliver the products at a price that allows the energy produced from them to compete in the marketplace with other energy forms. Here, it is worth to remark that some logistics costs, as those associated to collection or distribution activities, are fully sensitive to SC design.

While this paper focused on the use of biomass for pellet production, the optimization procedure can be useful and provide valuable insights for other bioenergy and biofuels SCs. Even though the optimization procedure showed a good computational performance to solve realistic

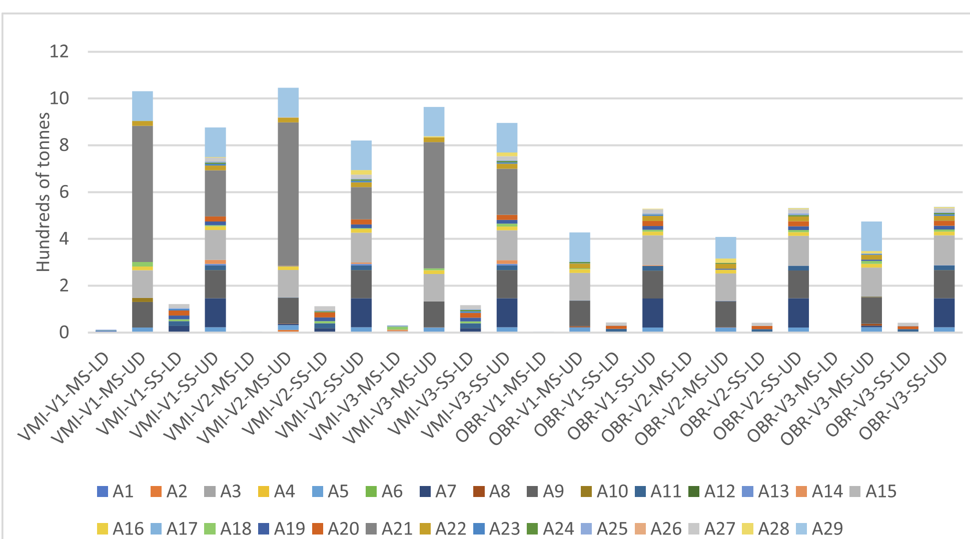

Fig. 5. Total tonnage of raw material not collected from each supplier.

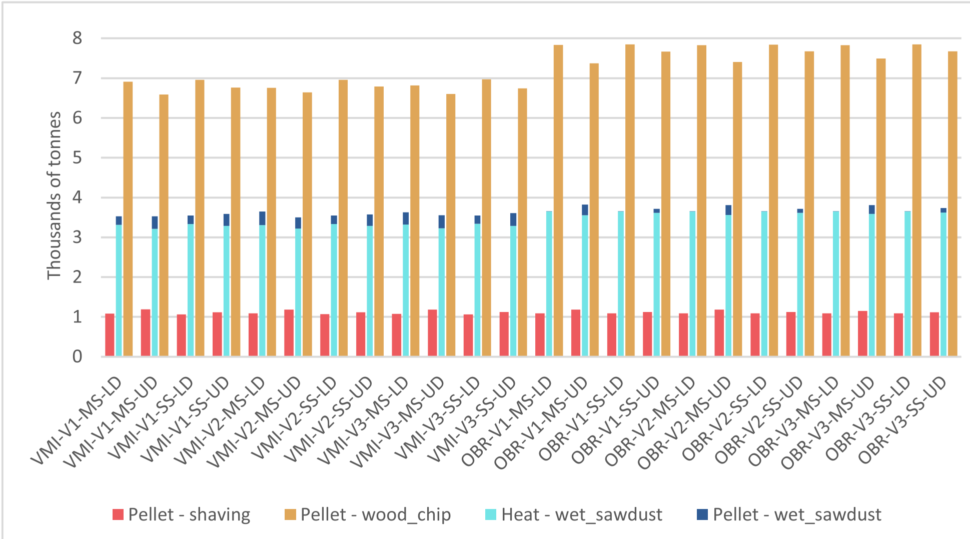

Fig. 6. Tonnage of raw material used in the production process.

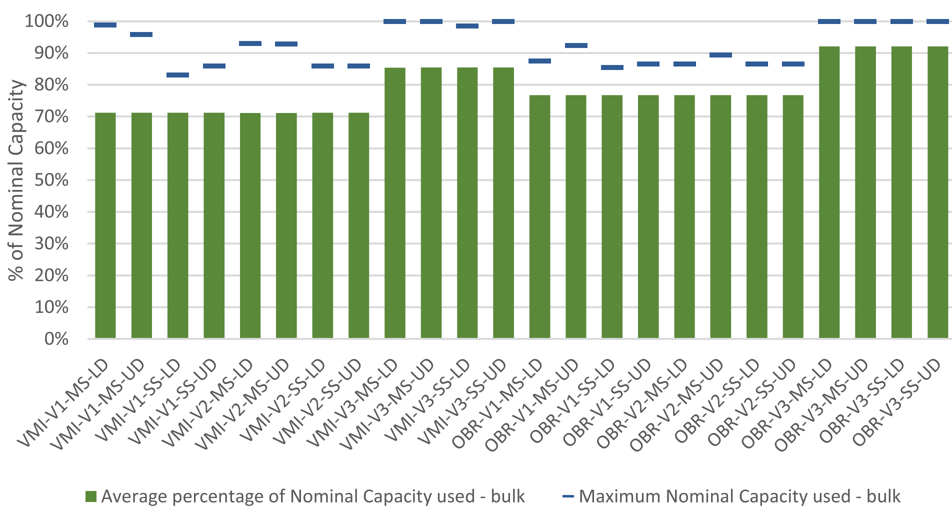

Fig. 7. Percentage of nominal capacity used at the plant.

instances of the researched problem, the proposal could be compared with other mechanisms of solution like Lagrangian relaxation, which has demonstrated to be robust and efficient to solve large SC problems [7]. The Dantzig-Wolfe decomposition & CG methodology also might be applied to the researched problem, but this would be a cumbersome task because of the need of generating raw materials pick-routes and pellets-delivery-routes that must be interlinked in a reduced master problem involving continuous variables which appear in many complicating constrains necessary to compute flows and transformations decisions. This would lead to a very complex master problem generating many sets of dual variables which must be passed to the different routes-generation sub-problems.

7. Conclusions

This paper proposed an optimization approach for managing raw materials and end-products flows along a wood pellet SC, focusing on detailed routing decisions for biomass collection and pellets distribution. The proposal allows modelling and analysing all logistics activities performed on the value chain with the goal of minimizing the total operative cost, which in turn allows determining the minimum profitable selling-price per tonne of produced pellets. Procurement, transportation, and inventory of forest biomass are considered in the upstream side of the SC while production process inside the pellet mill, inventory of end-products as bulk or bagged pellets, and the later delivery to several distribution hubs are included in the downstream side. For satisfying product demand, the OBR approach and the VMI strategy were evaluated and compared as replenishment strategies. The optimization procedure was tested on a case study from the Argentina's Mesopotamia region, and several scenarios were assessed to determine the optimal configuration for the operation of the SC. Supply of wood pellets to the distribution hubs contributed about to 46% to the total cost. Raw material procurement and transportation costs represents, in average, 28% of the total operative cost while pellet production contributes in 26% of the final cost. The estimated cost of bulk pellet was 48.8 $USD\ t^{-1}$ and bagged pellets 50.9 $USD\ t^{-1}$ at the gate of production plant. The numerical study demonstrated the capability of the developed tool for helping in the decision-making process of the pellet producer and in turn, for improving the efficiency and productivity of the industry.

CRediT authorship contribution statement

Ignacio Vitale: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Rodolfo G. Dondo:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition, Project administration. **Matías González:** Conceptualization, Validation. **Mariana E. Cóccola:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The CG approach is used for computing pools of raw material pickup routes $r \in R^+$ and pellet delivery routes $r \in R^-$. For generating pickup routes, the procedure is initialized with $i - j - i$ starting from any plant $i \in I^F$ and going to any supplier $j \in I^S$. After that, the following reduced master problem is solved:

$$MIN\left[\sum_{r \in R^+} c_r X_r\right] \tag{A1}$$

$$\sum_{r \in R^+} a_{i,r} X_r \geq 1 \quad \forall i \in I^S \tag{A2}$$

The objective (A.1) minimizes the total routing cost. In this case, the cost of each route is defined by its length in *kms*. Binary variable X_r takes value 1 when route r is included in the optimal solution of the reduced master problem. The parameter c_r gives the cost of each route r while the 0–1 parameter $a_{i,r}$ indicates if supplier $i \in I^S$ is visited by route $r \in R^+$. Eq. (A.2) assures that each supplier is visited by at least one route. The CG approach generates feasible and profitable routes in an iterative way, considering, at each iteration, both the master problem (A.1) - (A.2) restricted to a subset of routes (restricted master problem or RMP) and a pricing sub-problem. The RMP is solved by relaxing the binary variable X_r. After finding its optimal solution, the dual variable values π_i associated to constraint (A.2) are passed to the pricing sub-problems to generate new routes with negative reduced costs. Every sub-problem is solved considering just one plant as origin/end location of the routes. The routes computed by the pricing problems are then added to the RMP and the procedure is re-solved in the next iteration. The CG algorithm iterates until not a new route with a negative reduced cost can be found or until a maximum number of generated routes is achieved. The pricing subproblem is defined as follows:

$$MIN\left[TD - \sum_{i \in I^F} \pi_i Y_i\right] \tag{A3}$$

Subject to:

$$Y_i = 1 \quad \forall i \in I^F : \delta_i = 1 \tag{A4}$$

$$Y_i = 0 \quad \forall i \in I^F : \delta_i = 0 \tag{A5}$$

$$\sum_{j \in I^S} PR_{i,j} = 1 \quad \forall i \in I^F : \delta_i = 1 \tag{A6}$$

$$\sum_{j \in I^S} PR_{j,i} = 1 \quad \forall i \in I^F : \delta_i = 1 \tag{A7}$$

$$\sum_{j \in (I^F \cup I^S): i \neq j} PR_{i,j} = Y_i \quad \forall i \in (I^F \cup I^S) \tag{A8}$$

$$\sum_{j \in (I^F \cup I^S): i \neq j} PR_{j,i} = Y_i \quad \forall i \in (I^F \cup I^S) \tag{A9}$$

$$D_i \geq \sum_{j \in I^F} PR_{j,i} d_{j,i} \quad \forall i \in I^S \tag{A10}$$

$$D_j \geq D_i + d_{i,j} - M_D(1 - PR_{i,j}) \quad \forall (i,j) \in I^S : i \neq j \tag{A11}$$

$$TD \geq D_i + \sum_{j \in I^F} PR_{i,j} d_{i,j} \quad \forall i \in I^S \tag{A12}$$

$$TT \geq \sum_{i\in\left(I^F\cup I^S\right)} PR_{i,j}t_{i,j} + \sum_{i\in I^s} Y_i st_i + \frac{v^M}{ur} + \frac{v^M}{lr} \tag{A13}$$

$$TT \leq t^{max} \tag{A14}$$

Eq. (A.3) computes the reduced cost of a route as the difference between the total travelled distance TD minus the prices given by dual variables π_i collected along such a route. Eq. (A.4) selects the plant from which the vehicle departs. Parameter δ_i specifies the pellet mill $i \in I^F$ from where the vehicle route starts and ends while binary variable Y_i indicates that location i belongs to the route. Any other plant except the one specified by δ_i cannot be visited by the vehicle, as stated by Eq. (A.5). Eq. (A.6) selects the arc going from the chosen plant to the first visited sawmill by activating the binary variable $PR_{i,j}$ associated to the arc $i - j$. In turn, the last sawmill visited before the vehicle returns to the origin plant is stated by Eq. (A.7). Eqs. (A.8) and (A.9) jointly state that if a vehicle arrives to a sawmill, it also must depart from such a location. Eq. (A.10) computes the minimum traveled distance to reach the first visited sawmill. The distance D_i traveled to reach any visited sawmill i is computed by Eqs. (A.11), while Eq. (A.12) computes the total travelled distance TD until arriving back to pellet plant. Finally, Eq. (A.13) computes the total travelled time TT and Eq. (A.14) states that this variable must be smaller than the maximum allowed routing time t^{max}.

The set of routes $r \in R^-$ for delivering pellets to distribution hubs is determined in a similar way, but in this case, the set of raw material sources I^S must be replaced by the set of distribution centers I^C in constraints (A.1) to (A.14).

Appendix B

The problem researched in this paper can be mathematically represented through a monolithic MILP model integrating routing constraints together with constraints determining the raw materials and pellet flows. Therefore, constraints (1) – (21) explained in section 4 are used here without any change. However, load constraints should be redefined, and the routing constraints must be added. The new constraints are shown follows.

$$\Lambda^+_{i,m,r,t}\Big/\partial_m \leq v^M XC^+_{r,m,t} \quad \forall i \in I^F, t \in T, m \in M, r \in R^+ \tag{B1}$$

$$\Lambda^+_{i,m,r,t} \leq q^M XC^+_{r,m,t} \quad \forall i \in I^F, t \in T, m \in M, r \in R^+ \tag{B2}$$

$$\Lambda^+_{i,m,r,t} \leq q^M XL^+_{i,r,t} \quad \forall i \in (I^S \cup I^F), t \in T, m \in M, r \in R^+ \tag{B3}$$

$$\Lambda^-_{i,k,r,t}\Big/\partial_k \leq v^K XC^-_{r,k,t} \quad \forall i \in I^F, t \in T, k \in K, r \in R^- \tag{B4}$$

$$\Lambda^-_{i,k,r,t} \leq q^K XC^-_{r,k,t} \quad \forall i \in I^F, t \in T, k \in K, r \in R^- \tag{B5}$$

$$\Lambda^-_{i,k,r,t} \leq q^K XL^-_{i,r,t} \quad \forall i \in \left(I^F \cup I^C\right), t \in T, k \in K, r \in R^- \tag{B6}$$

$$\sum_{i\in I^F} \Lambda^+_{i,m,r,t} = \sum_{i^{'}\in I^S} \Lambda^+_{i^{'},m,r,t} \quad \forall t \in T, m \in M, r \in R^+ \tag{B7}$$

$$\sum_{i\in I^F} \Lambda^-_{i,k,r,t} = \sum_{i^{'}\in I^C} \Lambda^-_{i^{'},k,r,t} \quad \forall t \in T, k \in K, r \in R^- \tag{B8}$$

$$C^-_{r,k,t} \geq rc^- TTD^-_{r,t}\delta^{min}_k - M_c\left(1 - XC^-_{r,k,t}\right) \quad \forall t \in T, k \in K, r \in R^- \tag{B9}$$

$$C^-_{r,k,t} \geq TTC^-_{r,t} - M_c\left(1 - XC^-_{r,k,t}\right) \quad \forall t \in T, k \in K, r \in R^- \tag{B10}$$

$$C^+_{r,m,t} \geq rc^+ TTD^+_{r,t}\delta^{min}_m - M_c\left(1 - XC^+_{r,m,t}\right) \quad \forall t \in T, m \in M, r \in R^+ \tag{B11}$$

$$C^+_{r,m,t} \geq TTC^+_{r,t} - M_c\left(1 - XC^+_{r,m,t}\right) \quad \forall t \in T, m \in M, r \in R^+ \tag{B12}$$

$$Y^+_{r,t} \leq Y^+_{r-1,t} \quad \forall r \in R^+ : r > 1, t \in T \tag{B13}$$

$$\sum_{m\in M} XC^+_{r,m,t} = Y^+_{r,t} \quad \forall r \in R^+, t \in T \tag{B14}$$

$$\sum_{i\in I^F} XL^+_{i,r,t} = Y^+_{r,t} \quad \forall r \in R^+, t \in T \tag{B15}$$

$$XL^+_{i,r,t} \leq Y^+_{r,t} \quad \forall i \in I, r \in R^+, t \in T \tag{B16}$$

$$\sum_{j\in I: i\neq j} P^+_{i,j,r,t} = XL^+_{i,r,t} \quad \forall i \in I, r \in R^+, t \in T \tag{B17}$$

$$\sum_{j\in I: i\neq j} P^+_{j,i,r,t} = XL^+_{i,r,t} \quad \forall i \in I, r \in R^+, t \in T \tag{B18}$$

$$TD^{+}_{j,r,t} \geq \sum_{i \in I^F} P^{+}_{i,j,r,t} d_{i,j} \quad \forall j \in I^S, r \in R^+, t \in T \tag{B19}$$

$$TD^{+}_{j,r,t} \geq TD^{+}_{i,r,t} + d_{i,j} - M_d\left(1 - P^{+}_{i,j,r,t}\right) \quad \forall (i,j) \in I^S : i \neq j, r \in R^+, t \in T \tag{B20}$$

$$TTD^{+}_{r,t} \geq TD^{+}_{i,r,t} + \sum_{j \in I^F} d_{i,j} P^{+}_{i,j,r,t} \quad \forall i \in I^S, r \in R^+, t \in T \tag{B21}$$

$$TC^{+}_{j,r,t} \geq d_{i,j} \sum_{i' \in I^F} \sum_{m \in M} rc^{+} \Lambda^{+}_{i',m,r,t} - M_c\left(1 - P^{+}_{i,j,r,t}\right) \quad \forall i \in I^F, j \in I^S, r \in R^+, t \in T \tag{B22}$$

$$TC^{+}_{j,r,t} \geq TC^{+}_{i,r,t} + d_{i,j} \sum_{i' \in I^F} \sum_{m \in M} rc^{+} \Lambda^{+}_{i',m,r,t} - M_c\left(1 - P^{+}_{i,j,r,t}\right) \quad \forall (i,j) \in I^S : i \neq j, r \in R^+, t \in T \tag{B.23}$$

$$TTC^{+}_{r,t} \geq TC^{+}_{i,r,t} + d_{i,j} \sum_{i' \in I^F} \sum_{m \in M} rc^{+} \Lambda^{+}_{i',m,r,t} - M_c\left(1 - P^{+}_{i,j,r,t}\right) \quad \forall i \in I^S, j \in I^F, r \in R^+, t \in T \tag{B24}$$

$$TT^{+}_{r,t} \geq \sum_{i \in I} \sum_{j \in I} t_{i,j} P^{+}_{i,j,r,t} + \sum_{i \in I} st_i XL^{+}_{i,r,t} + \sum_{m \in M} \frac{\sum_{i \in I^F} \Lambda^{+}_{i,m,r,t}}{\partial_m ur} + \sum_{m \in M} \frac{\sum_{i \in I^S} \Lambda^{+}_{i,m,r,t}}{\partial_m lr} \quad \forall r \in R^+, t \in T \tag{B25}$$

$$TT^{+}_{r,t} \leq t^{max} \quad \forall r \in R^+, t \in T \tag{B26}$$

$$Y^{-}_{r,t} \leq Y^{-}_{r-1,t} \quad \forall r \in R^- : r > 1, t \in T \tag{B27}$$

$$\sum_{k \in K} XC^{-}_{k,m,t} = Y^{-}_{r,t} \quad \forall r \in R^-, t \in T \tag{B28}$$

$$\sum_{i \in I^F} XL^{-}_{i,r,t} = Y^{-}_{r,t} \quad \forall r \in R^-, t \in T \tag{B29}$$

$$XL^{-}_{i,r,t} \leq Y^{-}_{r,t} \quad \forall i \in I, r \in R^-, t \in T \tag{B30}$$

$$\sum_{j \in I : i \neq j} P^{-}_{i,j,r,t} = XL^{-}_{i,r,t} \quad \forall i \in I, r \in R^-, t \in T \tag{B31}$$

$$\sum_{j \in I : i \neq j} P^{-}_{j,i,r,t} = XL^{-}_{i,r,t} \quad \forall i \in I, r \in R^-, t \in T \tag{B32}$$

$$TD^{-}_{j,r,t} \geq \sum_{i \in I^F} P^{-}_{i,j,r,t} d_{i,j} \quad \forall j \in I^C, r \in R^-, t \in T \tag{B33}$$

$$TD^{-}_{j,r,t} \geq TD^{-}_{i,r,t} + d_{i,j} - M_d\left(1 - P^{-}_{i,j,r,t}\right) \quad \forall (i,j) \in I^C : i \neq j, r \in R^-, t \in T \tag{B.34}$$

$$TTD^{-}_{r,t} \geq TD^{-}_{i,r,t} + \sum_{j \in I^F} d_{i,j} P^{-}_{i,j,r,t} \quad \forall i \in I^C, r \in R^-, t \in T \tag{B35}$$

$$TC^{-}_{j,r,t} \geq d_{i,j} \sum_{i' \in I^F} \sum_{k \in K} rc^{-} \Lambda^{-}_{i',k,r,t} - M_c\left(1 - P^{-}_{i,j,r,t}\right) \quad \forall i \in I^F, j \in I^C, r \in R^-, t \in T \tag{B36}$$

$$TC^{-}_{j,r,t} \geq TC^{-}_{i,r,t} + d_{i,j} \sum_{i' \in I^F} \sum_{k \in K} rc^{-} \Lambda^{-}_{i',k,r,t} - M_c\left(1 - P^{-}_{i,j,r,t}\right) \quad \forall (i,j) \in I^C : i \neq j, r \in R^-, t \in T \tag{B.37}$$

$$TTC^{-}_{r,t} \geq TC^{-}_{i,r,t} + d_{i,j} \sum_{i' \in I^F} \sum_{m \in M} rc^{-} \Lambda^{-}_{i',k,r,t} - M_c\left(1 - P^{-}_{i,j,r,t}\right) \quad \forall i \in I^C, j \in I^F, r \in R^-, t \in T \tag{B38}$$

$$TT^{+}_{r,t} \geq \sum_{i \in I} \sum_{j \in I} t_{i,j} P^{+}_{i,j,r,t} + \sum_{i \in I} st_i XL^{-}_{i,r,t} + \sum_{k \in K} \frac{\sum_{i \in I^F} \Lambda^{-}_{i,k,r,t}}{\partial_k lr} + \sum_{k \in K} \frac{\sum_{i \in I^C} \Lambda^{-}_{i,k,r,t}}{\partial_k ur} \quad \forall r \in R^-, t \in T \tag{B.39}$$

$$TT^{-}_{r,t} \leq t^{max} \quad \forall r \in R^-, t \in T \tag{B40}$$

Appendix C

See Tables C1–C3

Table C1
Resulting operating costs (USD) for all instances solved.

Instance	Total Cost	Biomass purchase cost		Not collected biomass cost		Pickup cost		Biomass inventory cost		Production cost		Pellet inventory Cost		Delivery cost	
V1–VMI-SS-LD	441566.6	50255.1	***11.4%***	547.9	***0.12%***	72831.4	***16.5%***	232.8	***0.05%***	116094.3	***26.3%***	2551.3	***0.58%***	199053.8	***45.1%***
V1–VMI-SS-UD	446009.2	49797.3	***11.2%***	4387.9	***0.98%***	73581.7	***16.5%***	263.4	***0.06%***	116094.3	***26.0%***	2549.9	***0.57%***	199334.5	***44.7%***
V1–VMI-MS-LD	439291.4	50099.1	***11.4%***	81.2	***0.02%***	71308.1	***16.2%***	235.1	***0.05%***	116094.3	***26.4%***	2577.1	***0.59%***	198896.5	***45.3%***
V1–VMI-MS-UD	443364.0	49388.8	***11.1%***	4841.5	***1.09%***	70528.0	***15.9%***	263.9	***0.06%***	116063.3	***26.2%***	2576.8	***0.58%***	199701.8	***45.0%***
V2–VMI-SS-LD	445446.7	54181.9	***12.2%***	414.8	***0.09%***	72646.0	***16.3%***	232.9	***0.05%***	116094.3	***26.1%***	2542.2	***0.57%***	199334.5	***44.8%***
V2–VMI-SS-UD	449247.1	53514.1	***11.9%***	3569.4	***0.79%***	73923.1	***16.5%***	264.6	***0.06%***	116094.3	***25.8%***	2547.0	***0.57%***	199334.5	***44.4%***
V2–VMI-MS-LD	444128.9	53426.0	***12.0%***	29.1	***0.01%***	71767.0	***16.2%***	239.4	***0.05%***	116020.8	***26.1%***	2564.2	***0.58%***	200082.4	***45.1%***
V2–VMI-MS-UD	446806.0	53109.8	***11.9%***	4292.4	***0.96%***	70794.5	***15.8%***	262.9	***0.06%***	116031.7	***26.0%***	2574.1	***0.58%***	199740.7	***44.7%***
V3–VMI-SS-LD	445492.2	54163.3	***12.2%***	479.2	***0.11%***	72925.2	***16.4%***	231.9	***0.05%***	116094.3	***26.1%***	2544.5	***0.57%***	199053.8	***44.7%***
V3–VMI-SS-UD	448993.8	53465.4	***11.9%***	3890.8	***0.87%***	73683.0	***16.4%***	261.8	***0.06%***	116094.3	***25.9%***	2544.8	***0.57%***	199053.8	***44.3%***
V3–VMI-MS-LD	443931.0	53539.5	***12.1%***	150.7	***0.03%***	71962.8	***16.2%***	237.3	***0.05%***	116005.4	***26.1%***	2580.3	***0.58%***	199455.1	***44.9%***
V3–VMI-MS-UD	446078.0	53084.9	***11.9%***	4034.8	***0.90%***	70682.7	***15.9%***	265.0	***0.06%***	116094.3	***26.0%***	2567.1	***0.58%***	198917.5	***44.6%***
V1–OBR-SS-LD	500691.6	55442.5	***11.1%***	234.3	***0.05%***	88531.9	***17.7%***	183.7	***0.04%***	120990.1	***24.2%***	1468.1	***0.29%***	233841.0	***46.7%***
V1–OBR-SS-UD	498673.2	55019.1	***11.0%***	2550.0	***0.51%***	84574.1	***17.0%***	232.8	***0.05%***	120990.1	***24.3%***	1466.1	***0.29%***	233841.0	***46.9%***
V1–OBR-MS-LD	488952.3	55411.9	***11.3%***	27.0	***0.01%***	82173.9	***16.8%***	185.6	***0.04%***	120990.1	***24.7%***	1468.0	***0.30%***	228695.7	***46.8%***
V1–OBR-MS-UD	490362.0	54284.3	***11.1%***	2056.8	***0.42%***	82605.2	***16.9%***	236.6	***0.05%***	120990.1	***24.7%***	1493.3	***0.30%***	228695.7	***46.6%***
V2–OBR-SS-LD	503467.4	59219.2	***11.8%***	164.4	***0.03%***	87603.1	***17.4%***	183.9	***0.04%***	120990.1	***24.0%***	1465.7	***0.29%***	233841.0	***46.5%***
V2–OBR-SS-UD	502552.6	58608.5	***11.7%***	2169.3	***0.43%***	85248.1	***17.0%***	229.8	***0.05%***	120990.1	***24.1%***	1465.7	***0.29%***	233841.0	***46.5%***
V2–OBR-MS-LD	493576.2	59108.8	***12.0%***	0.0	***0.00%***	83127.6	***16.8%***	186.2	***0.04%***	120990.1	***24.5%***	1467.8	***0.30%***	228695.7	***46.3%***
V2–OBR-MS-UD	493935.7	57856.8	***11.7%***	1660.4	***0.34%***	83011.4	***16.8%***	234.2	***0.05%***	120990.1	***24.5%***	1487.2	***0.30%***	228695.7	***46.3%***
V3–OBR-SS-LD	504476.9	59237.8	***11.7%***	171.7	***0.03%***	88579.0	***17.6%***	184.6	***0.04%***	120990.1	***24.0%***	1472.8	***0.29%***	233841.0	***46.4%***
V3–OBR-SS-UD	502104.5	58612.9	***11.7%***	2221.3	***0.44%***	84735.3	***16.9%***	229.2	***0.05%***	120990.1	***24.1%***	1474.7	***0.29%***	233841.0	***46.6%***
V3–OBR-MS-LD	493489.7	59098.9	***12.0%***	0.0	***0.00%***	83045.6	***16.8%***	186.9	***0.04%***	120990.1	***24.5%***	1472.5	***0.30%***	228695.7	***46.3%***
V3–OBR-MS-UD	494707.7	58079.2	***11.7%***	1998.5	***0.40%***	83224.6	***16.8%***	231.1	***0.05%***	120990.1	***24.5%***	1488.6	***0.30%***	228695.7	***46.2%***

Table C2
Cost of bulk pellets (*USD t*$^{-1}$) at each facility on the downstream side of SC.

Instance	Pellet cost at plant (*USD t*$^{-1}$)	C01 (export port)			C02			C03			C04		
		Total delivered *(t)*	Transp. Cost *(USD)*	Pellet cost *(USD t*$^{-1}$*)*	Total delivered *(t)*	Transp. Cost *(USD)*	Pellet cost *(USD t*$^{-1}$*)*	Total delivered *(t)*	Transp. Cost *(USD)*	Pellet cost *(USD t*$^{-1}$*)*	Total delivered *(t)*	Transp. Cost *(USD)*	Pellet cost *(USD t*$^{-1}$*)*
V1–VMI-SS-LD	47.84	0	0	–	696	35967.40	99.52	661	37193.28	104.11	702	32842.30	94.63
V1–VMI-SS-UD	48.69	0	0	–	696	35967.40	100.37	661	37193.28	104.96	702	33123.00	95.87
V1–VMI-MS-LD	47.41	0	0	–	696	35967.40	99.09	661	37193.28	103.68	702	32842.30	94.20
V1–VMI-MS-UD	48.10	0	0	–	696	35967.40	99.78	661	37193.28	104.37	702	32842.30	94.88
V2–VMI-SS-LD	48.58	0	0	–	696	35967.40	100.25	661	37193.28	104.85	702	33123.00	95.76
V2–VMI-SS-UD	49.35	0	0	–	696	35967.40	101.03	661	37193.28	105.62	702	33123.00	96.53
V2–VMI-MS-LD	48.21	0	0	–	696	35967.40	99.89	661	37193.28	104.48	702	32842.30	94.99
V2–VMI-MS-UD	48.82	0	0	–	696	35967.40	100.49	661	37193.28	105.08	702	32842.30	95.60
V3–VMI-SS-LD	48.64	0	0	–	696	35967.40	100.32	661	37193.28	104.91	702	32842.30	95.43
V3–VMI-SS-UD	49.35	0	0	–	696	35967.40	101.03	661	37193.28	105.62	702	32842.30	96.14
V3–VMI-MS-LD	48.31	0	0	–	696	35967.40	99.98	661	37193.28	104.57	702	32842.30	95.09
V3–VMI-MS-UD	48.70	0	0	–	696	35967.40	100.38	661	37193.28	104.97	702	32842.30	95.48
V1–OBR-SS-LD	49.20	0	0	–	735	39130.05	102.44	706	41413.40	107.86	729	34723.01	96.83
V1–OBR-SS-UD	48.82	0	0	–	735	39130.05	102.06	706	41413.40	107.48	729	34723.01	96.45
V1–OBR-MS-LD	47.96	0	0	–	735	39130.05	101.20	706	41413.40	106.62	729	34723.01	95.59
V1–OBR-MS-UD	48.23	0	0	–	735	39130.05	101.46	706	41413.40	106.88	729	34723.01	95.86
V2–OBR-SS-LD	49.73	0	0	–	735	39130.05	102.96	706	41413.40	108.39	729	34723.01	97.36
V2–OBR-SS-UD	49.55	0	0	–	735	39130.05	102.79	706	41413.40	108.21	729	34723.01	97.18
V2–OBR-MS-LD	48.83	0	0	–	735	39130.05	102.07	706	41413.40	107.49	729	34723.01	96.46
V2–OBR-MS-UD	48.90	0	0	–	735	39130.05	102.14	706	41413.40	107.56	729	34723.01	96.53
V3–OBR-SS-LD	49.92	0	0	–	735	39130.05	103.15	706	41413.40	108.58	729	34723.01	97.55
V3–OBR-SS-UD	49.47	0	0	–	735	39130.05	102.71	706	41413.40	108.13	729	34723.01	97.10
V3–OBR-MS-LD	48.81	0	0	–	735	39130.05	102.05	706	41413.40	107.47	729	34723.01	96.45
V3–OBR-MS-UD	49.04	0	0	–	735	39130.05	102.28	706	41413.40	107.70	729	34723.01	96.68

Table C3
Cost of bagged pellets (*USD* t^{-1}) at each facility on the downstream side of SC.

Instance	Pellet cost at plant (*USD* t^{-1})	C01 (export port)			C02			C03			C04		
		Total delivered (*t*)	Transp. Cost (*USD*)	Pellet cost (*USD* t^{-1})	Total delivered (*t*)	Transp. Cost (*USD*)	Pellet cost (*USD* t^{-1})	Total delivered (*t*)	Transp. Cost (*USD*)	Pellet cost (*USD* t^{-1})	Total delivered (*t*)	Transp. Cost (*USD*)	Pellet cost (*USD* t^{-1})
V1–VMI-SS-LD	50.04	2527	68606.03	77.19	116	5994.57	101.72	169	10150.78	110.10	169	8299.46	99.15
V1–VMI-SS-UD	50.89	2527	68606.03	78.03	116	5994.57	102.56	169	10150.78	110.95	169	8299.46	99.99
V1–VMI-MS-LD	49.61	2527	69003.71	76.92	116	5994.57	101.29	169	9595.80	106.39	169	8299.46	98.72
V1–VMI-MS-UD	50.30	2527	69603.71	77.84	116	5994.57	101.97	169	9801.03	108.29	169	8299.46	99.41
V2–VMI-SS-LD	50.77	2527	68606.03	77.92	116	5994.57	102.45	169	10150.78	110.84	169	8299.46	99.88
V2–VMI-SS-UD	51.54	2527	68606.03	78.69	116	5994.57	103.22	169	10150.78	111.61	169	8299.46	100.65
V2–VMI-MS-LD	50.41	2527	70080.09	78.14	116	5998.96	102.13	169	9700.91	107.81	169	8299.46	99.52
V2–VMI-MS-UD	51.01	2527	69913.34	78.68	116	6004.01	102.77	169	9520.86	107.35	169	8299.46	100.12
V3–VMI-SS-LD	50.84	2527	68606.03	77.99	116	5994.57	102.52	169	10150.78	110.90	169	8299.46	99.95
V3–VMI-SS-UD	51.55	2527	68606.03	78.70	116	5994.57	103.23	169	10150.78	111.61	169	8299.46	100.66
V3–VMI-MS-LD	50.51	2527	69457.20	77.99	116	5994.57	102.18	169	9700.91	107.91	169	8299.46	99.61
V3–VMI-MS-UD	50.89	2527	69024.64	78.21	116	5994.57	102.57	169	9595.80	107.67	169	8299.46	100.00
V1–OBR-SS-LD	51.23	2562	69556.25	78.38	179	16371.37	142.69	185	17825.77	147.58	176	14821.14	135.44
V1–OBR-SS-UD	50.85	2562	69556.25	78.00	179	16371.37	142.31	185	17825.77	147.20	176	14821.14	135.06
V1–OBR-MS-LD	49.98	2562	77685.22	80.31	179	9446.76	102.76	185	11476.14	112.02	176	14821.14	134.20
V1–OBR-MS-UD	50.25	2562	77685.22	80.57	179	9446.76	103.03	185	11476.14	112.28	176	14821.14	134.46
V2–OBR-SS-LD	51.75	2562	69556.25	78.90	179	16371.37	143.21	185	17825.77	148.11	176	14821.14	135.96
V2–OBR-SS-UD	51.58	2562	69556.25	78.73	179	16371.37	143.04	185	17825.77	147.93	176	14821.14	135.79
V2–OBR-MS-LD	50.86	2562	77685.22	81.18	179	9446.76	103.63	185	11476.14	112.89	176	14821.14	135.07
V2–OBR-MS-UD	50.92	2562	77685.22	81.25	179	9446.76	103.70	185	11476.14	112.96	176	14821.14	135.14
V3–OBR-SS-LD	51.94	2562	69556.25	79.09	179	16371.37	143.40	185	17825.77	148.30	176	14821.14	136.15
V3–OBR-SS-UD	51.49	2562	69556.25	78.64	179	16371.37	142.95	185	17825.77	147.85	176	14821.14	135.71
V3–OBR-MS-LD	50.84	2562	77685.22	81.16	179	9446.76	103.62	185	11476.14	112.87	176	14821.14	135.05
V3–OBR-MS-UD	51.07	2562	77685.22	81.39	179	9446.76	103.85	185	11476.14	113.10	176	14821.14	135.28

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