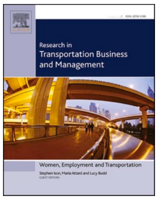
Research in Transportation Business & Management 61 (2025) 101389

Contents lists available at ScienceDirect

Research in Transportation Business & Management

journal homepage: www.elsevier.com/locate/rtbm



Transferring synchromodal principles to forest biomass supply: A holistic approach to supply chain design

Robert Prinz [a,*], Blas Mola-Yudego [b], Gernot Erber [c]

[a] Natural Resources Institute Finland (Luke), Production systems, P.O. Box 68, FI-80100 Joensuu, Finland
[b] School of Forest Sciences, University of Eastern Finland, PO Box 111, FI-80101 Joensuu, Finland
[c] University of Natural Resources and Life Sciences, Department of Forest and Soil Sciences, Institute of Forest Engineering, Peter-Jordan-Straße 82, 1190 Vienna, Austria

ARTICLE INFO

Keywords:
Collaborative supply chain management
ICT technology
Service provider
Biomass transportation
Timber transportation

ABSTRACT

Forest biomass supply chains face persistent challenges due to their complexity, fragmentation, and sensitivity to spatial and temporal variability. Traditional supply chain planning methods often lack the flexibility and integrative capacity required to manage these systems efficiently. This conceptual study introduces a holistic planning framework, *synchromodality* from a supply chain perspective (SSCP)—adapted from recent advancements in the logistics sector, to address the unique characteristics of forest biomass handling. The SSCP framework integrates transportation, production, and inventory decisions, allowing for synchronized, real-time responses to dynamic conditions. This study explores how the SSCP model can be transferred and applied to forest biomass supply chains, highlighting its potential to improve flexibility, coordination, and system-wide efficiency. The findings emphasize the importance of digital infrastructure, stakeholder collaboration, and real-time data availability for implementation. While the framework is conceptual, it provides actionable insights for supply chain managers and policymakers seeking to enhance resilience and responsiveness in biomass logistics. Limitations include the current lack of empirical validation and the need for advanced algorithmic support for decision-making under uncertainty. Future research should focus on practical testing of the model and the development of ICT-supported coordination platforms tailored to the forest sector.

1. Introduction

In recent years, global supply chains and logistics have encountered unprecedented challenges, most notably during the COVID-19 pandemic and geopolitical changes, prompting a re-evaluation of previously implemented solutions. The forest biomass and wood sector has also experienced firsthand the repercussions of recent disruptions to global logistics systems, noticeable in the redirection of raw material flows and changes affecting the security of supply. Further challenges are anticipated in this sector, stemming from the implementation of global sustainability policies. These policies are anticipated to result in increased demand for forest biomass and timber as a substitute for non-renewable resources. This, in turn, is expected to not only increase competition for forest resources, but also the need for more efficient transportation and logistics solutions in this sector. Concepts of global sustainability, including the green economy, the circular economy and the bioeconomy — which are based on the overarching ideal of simultaneously addressing economic, environmental, and social issues (D'Amato et al., 2017) — are currently considered the most appropriate solution to this problem. In addition, disruptions have prompted increased attention to security of supply, storage capacity and environmental impact issues. In this respect, the objectives of the EU Freight Transport Logistics Action Plan, which aims to improve environmental sustainability and ensure security of energy supply, while promoting transport safety and security, and emphasizes the key role of logistics in these tasks (COM, 2007), have recently been complemented by resilience aspects in the EU Sustainable and Smart Mobility Strategy (European Commission, 2020).

The collection, storage, processing and transportation of forest biomass presents a multifaceted challenge, with numerous factors influencing the efficiency of the supply (Acuna et al., 2019). The operating environment is characterized by high variability with regard to feedstock, transportation, and handling and storage (Väätäinen et al., 2021). They are complex systems characterized by a multi-layered network design, incorporating multiple intermediate points in addition to supply and demand (Acuna et al., 2019; Ghaffariyan et al., 2017). Consequently, there are multiple pathways from production to the

---

* Corresponding author.
E-mail addresses: robert.prinz@luke.fi (R. Prinz), blas.mola@uef.fi (B. Mola-Yudego), sci_gernot.erber@outlook.com (G. Erber).

https://doi.org/10.1016/j.rtbm.2025.101389
Received 8 November 2023; Received in revised form 10 April 2025; Accepted 29 April 2025

recipient or end user of the goods. Depending on the type of feedstock, raw materials from one harvesting site may end up in different end-use facilities, such as a sawmill, a pulp and paper mill, or a power plant. In addition, large-scale bioproducts mills, utilizing wood-based feedstocks to produce a wide range of products, have emerged in recent years (Ajao et al., 2018). In contrast to other manufactured products, such as those derived from fossil-based materials, wood-based biomass and timber products are inherently organic, which can lead to degradation during storage due to microbial activity (Jirjis, 1995). Temporary storage of material is, however, essential to balance the fluctuations in supply and demand (Väätäinen et al., 2021), but may entail significant economic losses in the worst case (Routa et al., 2018). Despite considerable research efforts in recent years, shifting in trends, and changes in focus over time, finding strategies and measures to enhance the efficiency of fuelwood supply systems remains a key challenge (Kühmaier & Erber, 2018).

Conventional, well established forest biomass supply chains are challenged by the recent need for more flexibility and efficiency. Nevertheless, the digital transformation and its integration of digital technologies into operations have created new opportunities in this regard. These opportunities are due to the provision of access to crucial data on vehicles and their movements operating within forest biomass supply chains. To leverage this data across the entire supply chain, novel holistic approaches or concepts are required that can orchestrate the activities of supply chain stakeholders. These approaches must facilitate the realization of sustainability objectives while ensuring security of supply in the face of risks and uncertainties.

Synchromodality, a concept that has recently received considerable attention in the field of logistics, is defined by Giusti et al. (2019) as "the provision of efficient, reliable, flexible, and sustainable services through the coordination and cooperation of stakeholders and the synchronization of operations within one or more supply chains driven by information and communication technologies (ICT) and intelligent transportation system (ITS) technologies". In this, the definition of synchromodality concept has parallels with the less specific definitions of other well-established transportation paradigms, which originate from multimodal transportation, and include multimodal, intermodal, combined, co-modal, and as the latest concept, synchromodal transportation (Reis, 2015). By adopting a holistic approach, synchromodal supply chains have the potential to address the need for reliability and flexibility within inherently volatile operating environments in forestry and to mitigate the effects of recent disruptions in global logistics networks on the forest sector. Despite academic interest in the concept of synchromodality across a wide range of disciplines, it has not yet been applied to forest biomass supply chains.

The present paper proposes the implementation of a framework based on synchromodality for coordinating the activities of stakeholder's activities in the context of forest procurement and logistics. In this study, we delineate the framework of synchromodal logistics, emphasizing its fundamental components and their potential application to the challenges encountered in the forest sector, particularly in the domains of forest biomass and timber supply. Furthermore, the study identifies the features or elements of synchromodal logistics that are already present in the forest industry, as well as those that are not yet in place. Overall, this study aims to promote a more holistic approach to the management of the forest biomass supply chain.

2. Procurement and logistics of wood biomass

Industrial roundwood supply chains are characterized by short lead times, mainly due to quality requirements and capital commitment (Väätäinen et al., 2021; Venäläinen et al., 2017). In contrast, energy assortments are stored for longer storage periods (Väätäinen et al., 2021) to balance fluctuating seasonal demand and to take advantage of increased value and transport efficiency by reducing moisture content (Erber et al., 2016; Röser et al., 2011).

Efficiency gains are also needed through means of supply management to reduce the costs of logistics. They can constitute a substantial proportion of the aggregate costs of forest industry companies, as evidenced by research in pulp production (Carlsson & Rönnqvist, 2005). While procurement via terminals has been shown to increase costs compared to direct supply (Kanzian et al., 2009), these facilities can also support the supply fleet and ensure supply during seasonal peaks in demand (Fernandez-Lacruz et al., 2020; Väätäinen et al., 2017). For bioenergy facilities, a predefined feedstock assortment is the key factor in feedstock procurement decisions, although the feedstock characteristics preferred by industrial end users are subject to variation (Kons et al., 2022).

Logistic hubs present an effective alternative to direct supply. The concept of collaborative intermodal hub networks, proposed by Groothedde et al. (2005), involves the parallel transportation of goods, thereby accommodating periods of high demand by direct transportation while maintaining a stable portion of the material flow through a hub network. In comparison to traditional supply chains, collaborative supply chains have been demonstrated to exhibit enhanced profitability and increased resilience to variations in lead times (Ponte et al., 2018). In the context of forest biomass procurement and logistics, a similar concept is employed for the supply of forest biomass through the so-called "bio-hubs", which have recently emerged in the field (Valipour et al., 2024). These bio-hubs supplement existing terminal concepts (Enström et al., 2021; Kons, 2019; Väätäinen et al., 2017; Virkkunen et al., 2016). Nicholls et al. (2022) describe forest bio-hubs as networks of collection points that facilitate biomass supply chains from forests to central processing points, thus supporting the emerging bioeconomy. So-called "logistics centres" and their forest network have been studied under North American conditions (Sarrazin et al., 2019), while designs of biomass supply chain networks have been reviewed in a comprehensive and systematic manner, with a particular focus on modelling and optimization (see De Meyer et al., 2014; Ghaderi et al., 2016; Sharma et al., 2013).

Decisions regarding transportation management are imperative in both the upstream and downstream supply processes. In principle, a multitude of options exist for forest biomass transportation in the upstream segment of the supply process. However, in practice, only a few of these options are commonly employed. In the Nordic countries, for instance, the most prevalent methods include single-modal truck transportation, truck transportation through a terminal, and multimodal transportation methods that utilize trucks for inbound logistics and rail or waterways for outbound logistics (Väätäinen et al., 2021). Given the inaccessibility of forests to many means of transportation, road transportation typically is the initial step in the supply chain of primary forest fuel, with rail or waterway transportation being preferred for longer transportation distances (Wolfsmayr & Rauch, 2014). The quality of the feedstock is a critical factor in the supply chain, with economic and environmental ramifications. Research has demonstrated that a reduction in moisture content within the raw material results in a lower number of truckloads required to fulfil the demand in energy wood supply networks. This, in turn, leads to a decrease in emissions and has a significant impact on profit (Kanzian et al., 2016).

In the downstream process, the global pellet sector is a good example of multi-modal transportation. For instance, following their production in Canada, pellets are imported to Europe, with the logistics encompassing transportation by ship and rail and delivery by truck. This exemplifies the predominant logistical challenge, which is the need for storage at either end (Selkimäki et al., 2010). A further example within the context of wood materials, is the transportation of wood from Europe to the North American or Asian markets.

Uncertainty is another key factor that must be addressed in biomass logistics management decisions. Demand uncertainty and supply variability have the potential to increase costs within a regional timber supply network; however, these costs can be mitigated by strategically selecting the optimal number and location of distribution centres (Chen et al., 2020). As demonstrated in a Canadian case study, the cost of uncertain supply can reach up to 15 to 22 % of planned costs. However, the incorporation of data quality into planning decisions has been shown to reduce implementation costs (Simard et al., 2023). Harvested volumes are affected by harvesting services where a high variability in contractors' workflows, both in volume and time, has been identified, requiring flexibility in forest harvesting services and procedures (Johansson et al., 2022). In the context of transportation of goods, the transportation of forest materials is also influenced by the quality of the material and dry matter losses during storage. It has been demonstrated that in-forest drying can exert positive economic and environmental impacts (Acuna et al., 2022; Erber et al., 2016).

A model that considers both active machine activities and passive activities such as quality changes during storage has been presented by Eriksson et al. (2017) to evaluate forest fuel supply chain scenarios and analyse various delivery strategies under different conditions. It is evident that weather conditions have a direct impact on transportation payload capacity, as evidenced by the effect of winter weather on the tare weight of timber trucks (Anttila et al., 2020). In a recent study, Kogler and Rauch (2023) evaluated different unimodal and multimodal transportation strategies using discrete-event simulation to track the development of roundwood quality throughout the supply chain, considering lead time and the associated devaluation of roundwood quality.

Furthermore, it has become increasingly important to consider different aspects of sustainability in logistics operations. For instance, greenhouse gas (GHG) emissions can be determined for the entire forest supply chain (Kühmaier et al., 2022), and specified amounts of GHG can be considered. Emission limits and emission allocation schemes have, for instance, been examined in an intermodal transportation network (Heinold & Meisel, 2020). Social aspects, such as ensuring a balanced workload for trucking contractors to minimize total logistics costs, can also be incorporated into optimization models (see Ghotb et al., 2022).

A distinctive feature of supply of wood biomass is the spatial distribution of the material, a factor which requires particular attention when applying logistical solutions. While supply chain performance analyses are frequently case studies, the utilization of spatial data through geographic information systems in energy biomass supply chain research has seen marked increase in recent years, particularly when high-quality spatial biomass and transport network data are available (Korpinen et al., 2023). The diversity of operation characteristics at the numerous spatially dispersed locations from which forest raw materials originate, however, prevents the use of standardized logistical solutions. Consequently, numerous logistical concepts for wood-based materials have been documented in the literature (e.g., Kogler & Rauch, 2018). The forestry sector is and will continue to be comparatively active in this regard, due to the utter necessity and the specific characteristics of the operational environment.

Furthermore, natural disturbances are a prevalent threat to the wood supply, necessitating management attention, in addition to disturbances of other origins, such as the ones recently observed. In order to maintain resilience in the face of such disruptions, there is a necessity for reliability and flexibility in operating environments that are subject to change. In response to irregularities in wood harvesting and transportation, such as those caused by natural disturbances or supply chain risks, a combination of unimodal and multimodal transportation in the regional wood supply chain can increase resilience and outperform alternative strategies (Kogler & Rauch, 2019). Esmaeili et al. (2023) demonstrated that an integrated data-driven approach can improve the accuracy of biomass supply and demand forecasts, facilitating more resilient routing decisions. Auer and Rauch (2021) conducted a comprehensive review of the key risk mitigation strategies within the wood-based bioeconomy, concluding that, in addition to supply chain integration, these include resource and feedstock diversification, increasing process resilience, technology innovation, product shelf life, long-term contracts, and supplier integration.

In this regard, the repercussions of disruptions such as the COVID-19 pandemic have had a significant impact on forest industry activities. However, certain sectors, such as the Canadian wood pellet industry demonstrated notable resilience in the face of this challenges. This resilience may be attributed to feedstock flexibility, long-term supply contracts, the provision of essential services by producers and end-users, and the integrated nature of the forest sector (Gagnon et al., 2022). In relation to post-COVID-19 recovery, Kulisic et al. (2021) concluded that the bioenergy industry should be expanded by integrating the biomass supply chain with the product value, industrial and capital chains to achieve effects on energy system resilience, job creation, and economic growth.

Consequently, an enhanced collaboration and cooperation among stakeholders is a viable strategy to combat uncertainties and disruptions within the wood biomass supply. However, despite the importance of cross-sector collaboration in the forest industry has been recognized, particularly in logistics cooperation within the forest biomass and timber supply chain, limited progress has been made in this regard (Guerrero & Hansen, 2018). A comprehensive review of the drivers and barriers of such collaboration by Guerrero and Hansen (2018) identified cost reduction, competitiveness, and environmental sustainability as its main drivers. Conversely, forest business culture, a lack of trust, and a lack of cost assessment and savings parameters were identified as the primary barriers to such collaboration.

3. The framework of synchromodal logistics

In this chapter, we delineate the framework of synchromodal logistics, with particular emphasis on its fundamental components, as determined by the extant literature.

Synchromodal planning may be described as a variant of multimodal planning, in which the optimal combination of transportation modes is selected for each specific transport order (Mes & Iacob, 2016). Within a synchromodal network, the selection of transportation modes is flexible, responding dynamically to the prevailing circumstances, and the evaluation of performance is conducted across the entire network and over an extended period (Rivera & Mes, 2022). A pivotal aspect of synchromodality is the availability of real-time information (Giusti et al., 2019; Reis, 2015). In addition to the physical movement of goods, information is exchanged between stakeholders within the supply chain, either directly or indirectly. The coordination of stakeholders within such complex networks is therefore crucial. According to Giusti et al. (2019), the networks consist primarily of four main stakeholders: customers (a), terminals (b), carriers (c), and logistics service providers (d). Specifically, "customers" (a) include manufacturers, suppliers, or companies that ship goods, "terminals" (b) are responsible for transshipment operations, "carriers" (c) provide transportation services, and "logistics service providers" (LSPs) (d) assume the responsibility for delivering services such as supply chain management or transportation (Giusti et al., 2019). These LSPs can be divided into two types: 1) Third-party logistics (3PL) service providers as intermediaries between buyers and sellers providing basic logistics services; and 2) fourth-party logistics (4PL) service providers as a link between customers and various stakeholders with full control over their customers' supply chain.

Whilst 3PL service providers coordinate between carriers and suppliers, and optimize the performance of the entire supply chain (e.g., by providing services such as transportation, warehousing, or freight forwarding), the new type of 4PL service providers can be regarded as a moderating single actor that monitors and manages the customers' entire supply chain (Giusti et al., 2019). The authors also discuss the vision of fifth-party (5PL) service providers using technology solutions to solve logistics and strategic management problems in supply chains with complex networks using a 5PL platform, although the 5PL concept is still in an early stage.

In order to ensure efficiency and the flexible use of resources, a fundamental aspect of the concept of synchromodality is the cooperation between stakeholders in the transportation chain. This cooperation requires not only a mental shift, but also a legal and political framework that regulates the dynamics of this concept (Pfoser et al., 2016). Other critical success factors (CSFs) include an adequate physical infrastructure with smart hubs, terminals and production sites, a technical infrastructure with ICT and ITS systems to ensure a steady data or information flow between network stakeholders, a sophisticated planning system, and pricing cost and service quality aspects (Pfoser et al., 2016).

In the logistics sector, Uckelmann (2008) conceptualized smart logistics as a paradigm shift from conventional supply chains to open supply networks, a transformation that necessitates the integration of novel technologies. A key feature of synchromodality is its extensive utilization of technology, which facilitates the intelligent use of the provided information. In this context, several key enabling technologies have been identified in the literature, that have an impact on the aforementioned CSFs. They facilitate decision making, collaboration, and trust, as well as the exchange of data and relevant interactions (Giusti et al., 2019). Examples of such technologies are traceability; intelligent systems; data analytics; optimization tools; simulation models; and integration platforms. In addition, green logistics and Industry 4.0 technologies have been shown to enhance supply chain efficiency, whilst simultaneously reducing carbon emissions and waste (Sharma et al., 2023). The utilization of dynamic synchromodal solutions, characterized by a flexible mode choice and real-time information (Reis, 2015), has been demonstrated to be effective in the presence of disruptions (Ambra et al., 2019).

In considering the concept of synchromodality in a more holistic manner, Dong et al. (2018) incorporated additional supply chain elements, including inventory management, transportation, and production, into its scope. In contrast to the transportation perspective, which focuses on the transportation network, the supply chain perspective is more comprehensive in its consideration of the supply chain from end to end, including its trade-offs and synergies (Dong et al., 2018). Consequently, the concept of synchromodality from a supply chain perspective (SSCP) encompasses not only the synchronization and scheduling of various modes of transportation but signifies a shift towards synchronizing transportation with other supply chain operations. These include inventory management and the service level setting (Dong et al., 2018), a feature that has already been highlighted by Groothedde et al. (2005) as being essential for the continued development of supply chains. The necessity to incorporate the supply chain management perspective within synchromodality has recently also been acknowledged by Acero et al. (2022).

4. Components of synchromodality in forestry

In this chapter we build upon the general framework description and its key components. We then proceed to assess the relevant components of synchromodality in the forest biomass supply. Finally, we examined the extent to which synchromodality or its key features are already implemented in this field.

To date, the application of the concept of synchromodality to the design of biomass supply chains in academic literature has been limited. During the period 2014–2023, a total of 319 scientific publications have been identified as referring to the concept (40 articles and 3 reviews in *Web of Science*; 254 articles and 22 reviews in *Scopus*), although none with direct connection within forest sciences, forest biomass supply or the procurement of forest-based materials. Synchromodal logistics have so far played a limited role in the logistics of the forestry sector, possibly due to the challenges associated with the transport of forest biomass and wood. These specific encounters include long transport distances and associated fuel consumption, and the complexity of transport due to the variety of assortments. Furthermore, the presence of relatively small storage units at a substantial number of production sites, terminals, and bio-hubs, in conjunction with a diverse array of potential transport modes and the numerous route options between logistical nodes, further complicates the situation. These aforementioned factors impede the seamless integration of synchromodal logistics systems with strategic management systems that require strategic coordination to achieve cost reductions and mitigate emissions (Palander & Vesa, 2022).

Nevertheless, there are indications that these limitations may be overcome in the near future. The advent of information and communication technologies has led to the availability of a substantial corpus of data pertaining to vehicles and their movements. This includes, for example, real-time vehicle positions, the status of various operational activities, productivity, speed and fuel consumption of operations, and to some extent, information on the operational environment. Furthermore, information is available on the resource availability, produced quantities of raw materials (e.g., roundwood assortments, biomass for energy) including the time and place of production, their storage location and their condition (e.g., volume, weight and quality parameters). When this existing data - considering temporal and spatial constraints - is then combined with real-time supply and demand information, this collective data can be used to coordinate, optimize and plan vehicle routes, the timing of certain operations and the (immediate) response to unforeseen factors (including fluctuating or rapidly changing conditions such as calamities) ensuring the effectiveness of the entire holistic supply chain. Depending on the priorities, different factors or key performance indicators (KPIs) can be addressed. For instance, there is potential to reduce operational costs or emissions, whilst simultaneously optimizing both fleet and personnel utilization. Furthermore, material loss or devaluation during storage can be avoided and material deliveries to customers (e.g., pulp and paper mills, sawmills, heating plants or biorefineries) can be ensured while being less vulnerable to disruptions. The implementation of a holistic supply chain management framework, utilizing real-time information through coordination and collaboration, can facilitate the resilience of biomass supply by building upon increased flexibility in terms of the transportation mode or route choice, thereby ensuring the provision of raw materials to end users in accordance with their demand.

Despite the distinctive characteristics of forest-based biomass procurement, which include seasonal variations and the capacity to adapt to changes that affect logistics costs, general logistics theory offers a suitable framework for examining the key procurement processes (Uusitalo, 2005). Furthermore, it has been demonstrated that the replanning of freight transportation resulting from uncertainties that cause deviations from schedules and operational plans can be modelled based on the framework of synchromodality, with high operating flexibility and coordination in terms of shipment flows that support replanning (Qu et al., 2019). The situation in forest biomass supply chains bears similarities to the transshipment location–allocation problem addressed by a synchromodal network. In this scenario, flows are synchronized at intermediate facilities under the uncertainty of transshipment capacities and utilities (Giusti et al., 2021). The problem consists of locating transshipment facilities (e.g., intermodal hubs) of a transportation network and allocating freight flows through them, such as biomass terminals or biohubs, from various origins to several destinations in order to satisfy limitations regarding supply and demand.

In view of the requirement for efficient, reliable, and sustainable forest biomass supply services, the coordination and cooperation of stakeholders through the synchronization of operations may provide a viable solution for the future needs of a growing bioeconomy. Kogler et al. (2021) have recently addressed the need for the synchronization of wood supply chains, highlighting the importance of coordinated transportation and integrated wood supply chains, characterized by deepened cooperation and information exchange. The integration of the diverse supply chains, particularly the linkage of the forest supply chain with other forest products supply chains, has been identified as a significant challenge for the industry (D'Amours et al., 2008). Additionally, the forest management and the processing industry are rarely linked through innovation, underscoring the necessity for enhanced communication and integrated research with the forest and wood value chain (Hoeben et al., 2023). Biomass transportation chains that minimize supply risks are needed to facilitate large-scale investment decisions (Nicholls et al., 2022). Mafakheri and Nasiri (2014) have identified the issue of stakeholder coordination, with the aim of improving the collective performance of supply chains as one of the gaps for future research. In this regard, the adaptation of collaborative supply chain control strategies has been identified as a potential mechanism to support risk management and enhance the resilience, efficiency, and sustainability of supply chains (Kogler & Rauch, 2019). Furthermore, Acuna et al. (2019) identify a need for integrated frameworks in forest biomass supply chain management that enable optimization methods to be implemented at strategic, tactical, or operational levels. The necessity for coordination and cooperation among relevant stakeholders, as well as their intuitive effects, have also been demonstrated through the application of serious game-based learning tools (Abasian et al., 2020; D'Amours et al., 2017; Kogler & Rauch, 2020a).

Demand forecasting is a pivotal aspect of decision-making in business and supply chains. Various techniques of predictive big data analytics have been identified, and their algorithms have been classified (Seyedan & Mafakheri, 2020). In Sweden, it has been demonstrated that the feed area of wood biofuel heating plants is strictly local, which limits potential logistics and procurement solutions (Awais et al., 2021). In the context of remote communities, the results of Mafakheri et al. (2021) highlight the key role of hubs as buffers, which can leverage economies of scale for the benefit of the local economy. Similarly, the study by Vazifeh et al. (2021) demonstrates the benefits of supply chain coordination through demand aggregation to improve economies of scale. A game-theoretic analysis has also been used to demonstrate the effect of different government incentives on the coordination and performance of a biomass supply chain case (Vazifeh et al., 2023). However, there are further alternative strategies for coordinating biomass supply chains (Khoddami et al., 2021). In the concept of agility, a firm's capacity to discern and respond efficiently to changing demands, as well as flexibility, responsiveness, and timeliness have been identified as essential factors to enhance its agility. The key enablers that allow these capabilities to be realized are flexible supply, flexible logistics, integrated planning, collaboration, and information technology (Gautam et al., 2013).

4.1. Assessment of the critical success factors and enabling technologies

The management of forests and supply chains is undergoing a transformation in response to the emergence of big data and the associated data analytics methods and tools (Zhang et al., 2020). Computational results, such as the mixed integer linear programming model and heuristic solution approach on a forest fuel supply chain problem presented by Gunnarsson et al. (2004), are capable of generating solutions that facilitate the evaluation of diverse strategies and scenarios. Consequently, these outcomes offer distinct advantages and enhanced flexibility in comparison to a manual planning method. Industry 4.0 applications have been identified throughout the entire timber supply chain (Müller et al., 2019). Furthermore, technologies and commercial products to support the digitalization of forest operations, including technologies for the detection or tracking of individual forest products throughout smart operational supply chains, are nowadays available (Keefe et al., 2022). The need for agile software tools and concepts to support forest service productivity and customer experience has also been identified, especially with the availability of open forest data and the development of service platforms (Kankaanhuhta et al., 2021). Research efforts are also progressively shifting towards digital twins of supply chains. For instance, it has been demonstrated that discrete-event simulation method is a useful approach for transport simulation, owing to its emphasis on business processes and the generation of a digital representation of supply chains (Kogler, 2023). Additionally, a recent study has proposed a data-driven evolutionary algorithm to optimize the inventory policy of supply chain digital twins (Liu & Nishi, 2023). Data-driven decision support systems have also been shown to support the strategic management of logistics (Palander & Vesa, 2022). Big data applications are also considered applicable to logistics, service, and planning processes, although further research is required to achieve a comprehensive understanding and successful application in supply chain management (Brinch et al., 2018). Nevertheless, data-driven methodologies have assumed significance to strategic logistics management, providing a foundation for informed decision-making in the forest industry (Palander & Vesa, 2022).

The following available features provide an observation of the enabling elements of synchromodal logistics that already exist in forestry, although at various degrees of establishment status (see Table 1). Enabling technologies, such as fleet management systems (e.g., applied by Anttila et al., 2022), global positioning systems (GPS) or global navigation satellite systems (GNSS), and vehicle tracking have been found to be useful in practice in the forest industry (Sikanen et al., 2005). Examples of smart technologies employed in forest operations, particularly in the production phase, include CAN-bus and StanForD data collected by forest machines for the monitoring of working performance (Kemmerer & Labelle, 2021). Furthermore, positioning methods such as Global Navigation Satellite Systems (GNSS) and Global Navigation Satellite Systems (GNSS-RF) for machine positioning are available (Keefe et al., 2019). Existing solutions include Light Detection and Ranging (LiDAR) and Structure for Motion (SfM) photogrammetry as tools for tracking soil rutting and disturbances, or monitoring systems based on smartwatches or smartphones in addition to various kinds of sensors (Picchio et al., 2019; Venanzi et al., 2023). Optimization approaches are also common enabling technologies widely applied in forest biomass and timber logistics (Acuna, 2017; Cambero & Sowlati, 2014; Malladi & Sowlati, 2018). The method of simulation is also employed (Kogler & Rauch, 2018; Prinz et al., 2019; Väätäinen et al., 2017), as are heuristic and hybrid methods (cf. Audy et al., 2022), process mapping (Lindström & Fjeld, 2014; Sterner et al., 2023; Windisch et al., 2013) or integrated simulation-based optimization approaches (Shahi & Pulkki, 2013).

4.2. A theoretical holistic approach for forest biomass logistics and the timber supply chain

One of the aforementioned synchromodal concepts, the SSCP approach, has a more holistic scope that synchronizes transport also with other supply chain activities. Consequently, the SSCP concept encompasses several crucial elements that are also present and relevant within forest biomass supply chains. For this reason, the SSCP concept was deemed to be potentially applicable to the forest biomass sector. The concept enables the synchronization of a supply chain problem with transportation options with other decisions in the forest biomass logistics and timber supply chain (Fig. 1). The proposed concept is designed to include the flexible utilization of transportation modes, synchronized with the inventory and production, in addition to other relevant aspects that define the respective holistic forest biomass and timber supply chains. The SSCP concept is notable for its comprehensive consideration of variability in additional input factors, such as those related to production and inventory, a need identified by Koirala et al. (2018). The authors demonstrated that the variability and uncertainty of forest biomass transportation costs are predominately associated with and influenced by biomass yield, transportation distance, road conditions, and vehicle utilization.

In the proposed SSCP example, it is imperative to have a profound understanding of inventory management. This is due to the fact that it encompasses the integration of storage capacities and the quantification of goods stored across various nodes in the supply chain, including terminals and bio-hubs. This intricate process also takes into consideration the unique dynamics of supply and demand. The inventory management aspect further involves a meticulous consideration of

Table 1
Assessment of the critical success factors and enabling technologies of synchromodal logistics and their current role of application in forest biomass handling. These are categorized as follows: (+) well established, (+/−) existing with further development needed, and (−) not well established. The classification into current roles is derived from the authors' own assessment based on the available literature and their insights on each success factor.

Critical success factors of synchromodal logistics		Forest biomass handling	Related references
Physical infrastructure			
	Smart hubs	+/−	Valipour et al., 2024; Nicholls et al., 2022
	Terminals	+	Enström et al., 2021; Kons, 2019; Väätäinen et al., 2017; Virkkunen et al., 2016
	Production sites	+	Väätäinen et al., 2021
Technical infrastructure			
	ICT and ITS systems	+/−	Palander, 2022; Gautam et al., 2013
	Sophisticated planning system	+/−	Gautam et al., 2013
Other			
	Pricing cost	+	Simard et al., 2023; Kanzian et al., 2009; Carlsson & Rönnqvist, 2005
	Quality aspects	+	Kons et al., 2022; Routa et al., 2018; Kanzian et al., 2016
Enabling technologies			
	Traceability	+/−	Keefe et al., 2019
	Intelligent systems	−	Liu & Nishi, 2023; Palander & Vesa, 2022
	Data analytics	+	Seyedan & Mafakheri, 2020; Zhang et al., 2020
	Optimization	+	Malladi & Sowlati, 2018; Acuna, 2017; Cambero & Sowlati, 2014
	Simulation	+	Kogler, 2023; Väätäinen et al., 2020; Kogler & Rauch, 2020b; Kogler et al., 2020; Korpinen et al., 2019; Prinz et al., 2019; Kogler & Rauch, 2018; Väätäinen et al., 2017
	Integration platforms	−	Kankaanhuhta et al., 2021

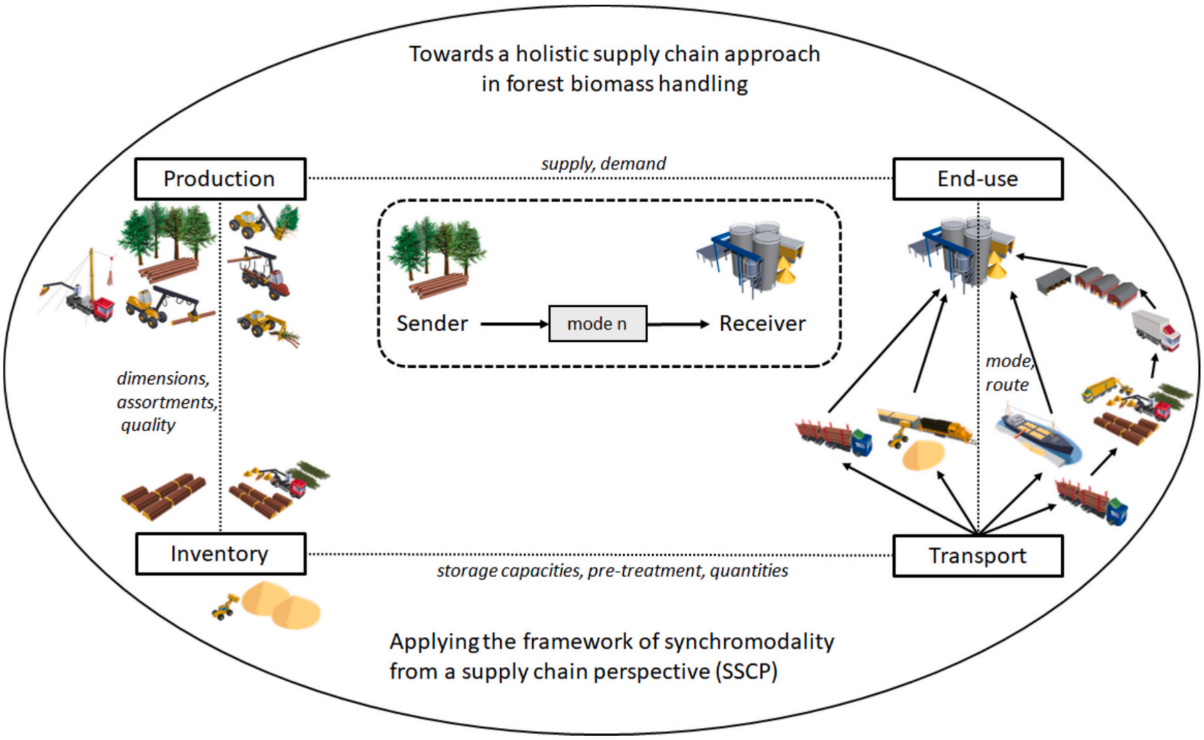


Fig. 1. A holistic supply chain approach. The concept of synchromodality is applied to the forest biomass sector, where a supply chain problem with transportation options is synchronized with other decisions in the supply chain.

assortment parameters and quality attributes. The production facet of this approach includes the initial stages of roundwood and biomass logistics, starting from the felling of trees to the processing of logs in strict accordance with customer-defined specifications regarding dimension and quality. This phase necessitates a comprehensive evaluation of harvesting and procurement aspects, ensuring the efficient orchestration of these vital components. This holistic approach is in line with the findings of Gautam et al. (2013), who asserted that in a wood procurement system, logistics encompasses the management of harvesting systems, transportation systems, and inventory strategies.

The critical success factors with their key enabling technologies are gaining increasing attention in practice, such as the improvement of the physical and technical infrastructure, including the use of intelligent systems and integrated platforms. A number of these technologies are already being utilized, including positioning and machine communication as well as optimization and simulation approaches to inform decision making. The physical infrastructure is a key aspect, essential not only for providing alternatives that facilitate flexible choice of transportation modes, but also for the provision of storage and buffering facilities, such as terminals or bio-hubs.

However, the full implementation of the concept still requires coordination between stakeholders, supported by information flows and technical infrastructure. Despite the paucity of information on fourth-party logistics (4PL) service providers operating within the biomass logistics and the timber supply chain, the requirement for reliable information and information and communication technology (ICT) to enhance the synchronization and efficiency of supply chain operations has been recognized (Palander, 2022).

Fourth-party logistics (4PL) service providers function as the conduit between customers, and multiple stakeholders, who have complete control over their customers' supply chain. This arrangement necessitates the establishment of trust and a mental shift towards this concept. However, the forest industry is a traditional sector with a long history that has led to the implementation of the current structures in practice. Creating acceptance for a shift towards fourth-party logistics (4PL) service providers, or even towards a 5PL vision is therefore, in the authors' view, a critical issue for the successful implementation of synchromodal concepts.

Nevertheless, as Giusti et al. (2019) have previously indicated, each planning level (strategic/tactical, operational, real-time) may well consider the characteristics of synchromodality and consider plans as a complete entity rather than as detached entities. As postulated by Pfoser et al. (2016), the objective is to transition from unimodal transportation to intelligent, flexible, and sustainable synchromodal transportation in general, including the forest biomass and roundwood supply chain. In the light of prevailing challenges, particularly with regard to the security of supply, supply uncertainties, and under the aim to reduce the environmental and general impacts of climate change, new approaches of thinking and cooperation, embodied by novel concepts, are needed to meet future needs and challenges.

5. Conclusions

Forest biomass supply chains are widely recognized as complex systems, making their planning, management, and design particularly challenging. Although numerous studies have addressed logistics and supply chain planning in this field, there remains a lack of holistic frameworks and alternative supply chain design approaches tailored to the unique characteristics of forest biomass handling.

This conceptual study introduces a potential future-oriented alternative by transferring an emerging holistic supply chain framework from the general logistics sector, synchromodality from a supply chain perspective (SSCP), to the domain of forest biomass. The SSCP model integrates transport planning with production and inventory management, all of which are crucial for effectively managing biomass flows. As such, SSCP presents a comprehensive approach that aligns well with the structural and operational demands of forest biomass supply chains. The novelty lies in its application of the SSCP framework specifically to the forest biomass sector, where such integrated planning models have not yet been widely explored. In doing so, the study aims to initiate a broader discussion about the need for holistic supply chain planning in forest-based bioeconomy contexts.

While synchromodal logistics offers significant potential for improving flexibility and coordination in biomass and timber transportation, its practical application raises several research questions. Future research should focus on developing suitable optimization algorithms capable of processing large volumes of real-time data to support synchronized decision-making. The increasing availability of forest inventory data, real-time vehicle tracking, and digital representations of forest stands and infrastructure provides a strong foundation for data-driven decision support. However, leveraging these resources effectively requires robust ICT infrastructure and end-to-end traceability across the supply chain. Furthermore, implementing coordination platforms will depend on stakeholder involvement and the careful consideration of diverse needs and interests, especially within a traditionally structured and often conservative forest sector.

Digital transformation, coupled with access to real-time data, presents a critical opportunity to enhance flexibility and operational efficiency in forest biomass logistics. While digital tools and analytics are increasingly available, they often address isolated problems. There is a pressing need for integrated frameworks that can guide broader decision-making and strategic planning. By enabling real-time coordination and collaboration, a holistic supply chain framework such as SSCP has the potential to improve supply chain resilience. Specifically, it can enhance flexibility in mode and route selection, helping ensure a consistent and efficient supply of raw material to end users in line with their specific requirements.

CRediT authorship contribution statement

Robert Prinz: Conceptualization, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. **Blas Mola-Yudego:** Writing – review & editing. **Gernot Erber:** Writing – review & editing.

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.

Acknowledgments

The authors gratefully acknowledge financial support from the Bio4EmiCon—Bioenergy supply chain solutions and climate policy actions for emission control—project, funded by Natural Resources Institute Finland (Luke) as well as the SINTETIC—Single item identification for forest production, protection and management—project, funded by the European Union's Horizon Europe programme (project number: 101082051). The authors also wish to acknowledge Acolad Finland Oy for its language review.

References

Abasian, F., Rönnqvist, M., Marier, P., & Fjeld, D. (2020). Game—The transportation game. *INFORMS Transactions on Education, 21*(1), 52–63. https://doi.org/10.1287/ited.2019.0223

Acero, B., Saenz, M. J., & Luzzini, D. (2022). Introducing synchromodality: One missing link between transportation and supply chain management. *Journal of Supply Chain Management, 58*(1), 51–64. https://doi.org/10.1111/jscm.12269

Acuna, M. (2017). Timber and biomass transport optimization: A review of planning issues, solution techniques and decision support tools. *Croatian Journal of Forest Engineering, 38*, 279–290.

Acuna, M., Sánchez-García, S., & Canga, E. (2022). An optimization approach to assess the impact of drying and dry matter losses of Eucalyptus globulus Roundwood and biomass on supply chains costs and GHG emissions. *Forests, 13*(5). https://doi.org/10.3390/f13050701. Article 701.

Acuna, M., Sessions, J., Zamora, R., Boston, K., Brown, M., & Ghaffariyan, M. R. (2019). Methods to manage and optimize Forest biomass supply chains: A review. *Current Forestry Reports, 5*, 124–141. https://doi.org/10.1007/s40725-019-00093-4

Ajao, O., Marinova, M., Savadogo, O., & Paris, J. (2018). Hemicellulose based integrated forest biorefineries: Implementation strategies. *Industrial Crops and Products, 126*, 250–260. https://doi.org/10.1016/j.indcrop.2018.10.025

Ambra, T., Caris, A., & Macharis, C. (2019). Should I stay or should I go? Assessing intermodal and Synchromodal resilience from a decentralized perspective. *Sustainability, 11*(6). https://doi.org/10.3390/su11061765. article 1765.

Anttila, P., Nummelin, T., Väätäinen, K., & Laitila, J. (2020). The effect of winter weather on timber truck tare weights. *Silva Fennica, 54*(4). https://doi.org/10.14214/sf.10385. Article id 10385.

Anttila, P., Nummelin, T., Väätäinen, K., Laitila, J., Ala-Ilomäki, J., & Kilpeläinen, A. (2022). Effect of vehicle properties and driving environment on fuel consumption and CO2 emissions of timber trucking based on data from fleet management system. *Transportation Research Interdisciplinary Perspectives, 15*. https://doi.org/10.1016/j.trip.2022.100671. Article 100671.

Audy, J.-F., Rönnqvist, M., D'Amours, S., & Yahiaoui, A.-E. (2022). Planning methods and decision support systems in vehicle routing problems for timber transportation: A review. *International Journal of Forest Engineering*. https://doi.org/10.1080/14942119.2022.2142367

Auer, V., & Rauch, P. (2021). Wood supply chain risks and risk mitigation strategies: A systematic review focusing on the northern hemisphere. *Biomass and Bioenergy, 148*. https://doi.org/10.1016/j.biombioe.2021.106001. Article 106001.

Awais, F., Flodén, J., & Svanberg, M. (2021). Logistic characteristics and requirements of Swedish wood biofuel heating plants. *Renewable and Sustainable Energy Reviews, 138*. https://doi.org/10.1016/j.rser.2020.110650. Article 110650.

Brinch, M., Stentoft, J., Jensen, J. K., & Rajkumar, C. (2018). Practitioners understanding of big data and its applications in supply chain management. *The International Journal of Logistics Management, 29*(2), 555–574. https://doi.org/10.1108/IJLM-05-2017-0115

Cambero, C., & Sowlati, T. (2014). Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature. *Renewable and Sustainable Energy Reviews, 36*, 62–73. https://doi.org/10.1016/j.rser.2014.04.041

Carlsson, D., & Rönnqvist, M. (2005). Supply chain management in forestry—Case studies at Södra cell AB. *European Journal of Operational Research, 163*(3), 589–616. https://doi.org/10.1016/j.ejor.2004.02.001

Chen, C., Gan, J., Zhang, Z., & Qiu, R. (2020). Multi-objective and multi-period optimization of a regional timber supply network with uncertainty. *Canadian Journal of Forest Research, 50*, 203–214. https://doi.org/10.1139/cjfr-2018-0551

COM. (2007). Communication from the commission. *Freight Transport Logistics Action Plan. Brussels*, 12, 18.10.2007, COM (2007) 607 final. Accessed 5 March 2022 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52007DC0607&from=EN.

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., … Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. *Journal of Cleaner Production, 168*, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

D'Amours, S., Marier, P., Rönnqvist, M., Azouzi, R., & Fjeld, D. (2017). Game—The online wood supply game. *INFORMS Transactions on Education, 18*(1), 71–87. https://doi.org/10.1287/ited.2017.0174

D'Amours, S., Rönnqvist, M., & Weintraub, A. (2008). Using operational research for supply chain planning in the Forest products industry. *INFOR: Information Systems and Operational Research, 46*(4), 265–281. https://doi.org/10.3138/infor.46.4.265

De Meyer, A., Cattrysse, D., Rasinmäki, J., & Van Orshoven, J. (2014). Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. *Renewable and Sustainable Energy Reviews, 31*, 657–670. https://doi.org/10.1016/j.rser.2013.12.036

Dong, C., Boute, R., McKinnon, A., & Verelst, M. (2018). Investigating synchromodality from a supply chain perspective. *Transportation Research Part D: Transport and Environment, 61*, 42–57. https://doi.org/10.1016/j.trd.2017.05.011

Enström, J., Eriksson, A., Eliasson, L., Larsson, A., & Olsson, L. (2021). Wood chip supply from forest to port of loading – A simulation study. *Biomass and Bioenergy, 152*. https://doi.org/10.1016/j.biombioe.2021.106182. Article 106182.

Erber, G., Kanzian, C., & Stampfer, K. (2016). Modelling natural drying of European beech (Fagus sylvatica L.) logs for energy based on meteorological data. *Scandinavian Journal of Forest Research, 31*(3), 294–301. https://doi.org/10.1080/02827581.2015.1080294

Eriksson, A., Eliasson, L., Sikanen, L., Hansson, P.-A., & Jirjis, R. (2017). Evaluation of delivery strategies for forest fuels applying a model for weather-driven analysis of Forest fuel systems (WAFFS). *Applied Energy, 188*, 420–430. https://doi.org/10.1016/j.apenergy.2016.12.018

Esmaeili, F., Mafakheri, F., & Nasiri, F. (2023). Biomass supply chain resilience: Integrating demand and availability predictions into routing decisions using machine learning. *Smart Science, 11*(2), 293–317. https://doi.org/10.1080/23080477.2023.2176749

European Commission. (). *Factsheet - The Transport and Mobility Sector. Sustainable & smart mobility strategy*, 12.09.2020. Accessed 5 March 2022 https://ec.europa.eu/commission/presscorner/detail/en/fs_20_2350. https://doi.org/10.2775/932. NA-06-20-172-EN-N.

Fernandez-Lacruz, R., Eriksson, A., & Bergström, D. (2020). Simulation-based cost analysis of industrial supply of chips from logging residues and small-diameter trees. *Forests, 11*(1). https://doi.org/10.3390/f11010001. Article 1.

Gagnon, B., MacDonald, H., Hope, E., Blair, M. J., & McKenney, D. W. (2022). Impact of the COVID-19 pandemic on biomass supply chains: The case of the Canadian wood pellet industry. *Energies, 15*. https://doi.org/10.3390/en15093179. Article 3179.

Gautam, S., LeBel, L., & Beaudoin, D. (2013). Agility capabilities in wood procurement systems: A literature synthesis. *International Journal of Forest Engineering, 24*(3), 216–232. https://doi.org/10.1080/14942119.2013.851367

Ghaderi, H., Pishvaee, M. S., & Moini, A. (2016). Biomass supply chain network design: An optimization-oriented review and analysis. *Industrial Crops and Products, 94*, 972–1000. https://doi.org/10.1016/j.indcrop.2016.09.027

Ghaffariyan, M. R., Brown, M., Acuna, M., Sessions, J., Gallagher, T., Kühmaier, M., Spinelli, R., Visser, R., Devlin, G., Eliasson, L., Laitila, J., Laina, R., Iwarsson Wide, M., & Egnell, G. (2017). An international review of the most productive and cost effective forest biomass recovery technologies and supply chains. *Renewable and Sustainable Energy Reviews, 74*, 145–158. https://doi.org/10.1016/j.rser.2017.02.014

Ghotb, S., Sowlati, T., Mortyn, J., Roeser, D., & Griess, V. C. (2022). A goal programming model for the optimization of log logistics considering sorting decisions and social objective. *Canadian Journal of Forest Research, 52*, 1–11. https://doi.org/10.1139/cjfr-2021-0203

Giusti, R., Manerba, D., Bruno, G., & Tadei, R. (2019). Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues. *Transportation Research Part E: Logistics and Transportation Review, 129*, 92–110. https://doi.org/10.1016/j.tre.2019.07.009

Giusti, R., Manerba, D., & Tadei, R. (2021). Multiperiod transshipment location–allocation problem with flow synchronization under stochastic handling operations. *Networks, 78*, 88–104. https://doi.org/10.1002/net.22007

Groothedde, B., Ruijgrok, C., & Tavasszy, L. (2005). Towards collaborative, intermodal hub networks: A case study in the fast moving consumer goods market. *Transportation Research Part E: Logistics and Transportation Review, 41*(6), 567–583. https://doi.org/10.1016/j.tre.2005.06.005

Guerrero, J. E., & Hansen, E. (2018). Cross-sector collaboration in the forest products industry: A review of the literature. *Canadian Journal of Forest Research, 48*, 1269–1278. https://doi.org/10.1139/cjfr-2018-0032

Gunnarsson, H., Rönnqvist, M., & Lundgren, J. T. (2004). Supply chain modelling of forest fuel. *European Journal of Operational Research, 158*, 103–123. https://doi.org/10.1016/S0377-2217(03)00354-0

Heinold, A., & Meisel, F. (2020). Emission limits and emission allocation schemes in intermodal freight transportation. *Transportation Research Part E: Logistics and Transportation Review, 141*. https://doi.org/10.1016/j.tre.2020.101963. Article 101963.

Hoeben, A. D., Stern, T., & Lloret, F. (2023). A review of potential innovation pathways to enhance resilience in wood-based value chains. *Current Forestry Reports, 9*, 301–318. https://doi.org/10.1007/s40725-023-00191-4

Jirjis, R. (1995). Storage and drying of wood fuel. *Biomass and Bioenergy, 9*, 181–190. https://doi.org/10.1016/0961-9534(95)00090-9

Johansson, M., Erlandsson, E., Kronholm, T., & Lindroos, O. (2022). The need for flexibility in forest harvesting services – A case study on contractors' workflow variations. *International Journal of Forest Engineering*. https://doi.org/10.1080/14942119.2022.2071142

Kankaanhuhta, V., Packalen, T., & Väätäinen, K. (2021). Digital transformation of Forest Services in Finland—A Case Study for improving business processes. *Forests, 12*. https://doi.org/10.3390/f12060781. Article 781.

Kanzian, C., Holzleitner, F., Stampfer, K., & Ashton, S. (2009). Regional energy wood logistics – Optimizing local fuel supply. *Silva Fennica, 43*(1). https://doi.org/10.14214/sf.464. Article 464.

Kanzian, C., Kühmaier, M., & Erber, G. (2016). Effects of moisture content on supply costs and CO2 emissions for an optimized energy wood supply network. *Croatian Journal of Forest Engineering, 37*, 51–60.

Keefe, R. F., Wempe, A. M., Becker, R. M., Zimbelman, E. G., Nagler, E. S., Gilbert, S. L., & Caudill, C. C. (2019). Positioning methods and the use of location and activity data in forests. *Forests, 10*(5). https://doi.org/10.3390/f10050458. Article 458.

Keefe, R. F., Zimbelman, E. G., & Picchi, G. (2022). Use of individual tree and product level data to improve operational forestry. *Current Forestry Reports, 8*, 148–165. https://doi.org/10.1007/s40725-022-00160-3

Kemmerer, J., & Labelle, E. R. (2021). Using harvester data from on-board computers: A review of key findings, opportunities and challenges. *European Journal of Forest Research, 140*, 1–17. https://doi.org/10.1007/s10342-020-01313-4

Khoddami, S., Mafakheri, F., & Zeng, Y. (2021). A system dynamics approach to comparative analysis of biomass supply chain coordination strategies. *Energies, 14*. https://doi.org/10.3390/en14102808. Article 2808.

Kogler, C. (2023). Discrete event simulation-based risk analysis for efficient, Sustainable and Resilient Transportation. *Soudní inženýrství, 34*(1), 74–78, 10.13164/SI.2023.1.74.

Kogler, C., & Rauch, P. (2018). Discrete event simulation of multimodal and unimodal transportation in the wood supply chain: A literature review. *Silva Fennica, 52*(4). https://doi.org/10.14214/sf.9984. Article 9984.

Kogler, C., & Rauch, P. (2019). A discrete-event simulation model to test multimodal strategies for a greener and more resilient wood supply. *Canadian Journal of Forest Research, 49*, 1298–1310. https://doi.org/10.1139/cjfr-2018-0542

Kogler, C., & Rauch, P. (2020a). Game-based workshops for the wood supply chain to facilitate knowledge transfer. *International Journal of Simulation Modelling, 19*(3), 446–457. https://doi.org/10.2507/IJSIMM19-3-526

Kogler, C., & Rauch, P. (2020b). Contingency plans for the wood supply chain based on bottleneck and queuing time analyses of a discrete event simulation. *Forests, 11(4), Article 396*. https://doi.org/10.3390/f11040396

Kogler, C., & Rauch, P. (2023). Lead time and quality driven transport strategies for the wood supply chain. *Research in Transportation Business & Management, Article, 100946*. https://doi.org/10.1016/j.rtbm.2023.100946

Kogler, C., Schimpfhuber, S., Eichberger, C., & Rauch, P. (2021). Benchmarking procurement cost saving strategies for wood supply chains. *Forests, 12, Article 1086*. https://doi.org/10.3390/f12081086

Kogler, C., Stenitzer, A., & Rauch, P. (2020). Simulating combined self-loading truck and semitrailer truck transport in the wood supply chain. *Forests, 11*(12). https://doi.org/10.3390/f11121245. article 1245.

Koirala, A., Kizha, A. R., De Hoop, C. F., Roth, B. E., Han, H.-S., Hiesl, P., … Sahoo, K. (2018). Annotated bibliography of the global literature on the secondary transportation of raw and comminuted Forest products (2000–2015). *Forests, 9, Article 415*. https://doi.org/10.3390/f9070415

Kons, K. (2019). Management of Forest Biomass Terminals. Swedish University of Agricultural Sciences, Uppsala, Sweden. 2019.

Kons, K., Blagojević, B., Mola-Yudego, B., Prinz, R., Routa, J., Kulisic, B., … Bergström, D. (2022). Industrial end-users' preferred characteristics for wood biomass feedstocks. *Energies, 15, Article 3721*. https://doi.org/10.3390/en15103721

Korpinen, O.-J., Aalto, M., Raghu, K. C., Tokola, T., & Ranta, T. (2023). Utilisation of spatial data in energy biomass supply chain research—A review. *Energies, 16, Article 893*. https://doi.org/10.3390/en16020893

Korpinen, O.-J., Aalto, M., Venäläinen, P., & Ranta, T. (2019). Impacts of a high-capacity truck transportation system on the economy and traffic intensity of pulpwood supply in Southeast Finland. *Croatian Journal of Forest Engineering, 40*(1), 89–105.

Kühmaier, M., & Erber, G. (2018). Research trends in European Forest fuel supply chains: A review of the last ten years (2007-2016) - part two: Comminution, Transport & Logistics. *Croatian Journal of Forest Engineering, 39*, 139–152.

Kühmaier, M., Kral, I., & Kanzian, C. (2022). Greenhouse Gas Emissions of the Forest Supply Chain in Austria in the Year 2018. *Sustainability, 14*. https://doi.org/10.3390/su14020792. Article 792.

Kulisic, B., Gagnon, B., Schweinle, J., Van Holsbeeck, S., Brown, M., Simurina, J., … McDonald, H. (2021). The contributions of biomass supply for bioenergy in the post-COVID-19 recovery. *Energies, 14, Article 8415*. https://doi.org/10.3390/en14248415

Lindström, J., & Fjeld, D. (2014). A process perspective on the timber transport vehicle routing problem. *Journal of Green Engineering, 4*(4), 291–306. https://doi.org/10.13052/jge1904-4720.443

Liu, Z., & Nishi, T. (2023). Data-driven evolutionary computation for service constrained inventory optimization in multi-echelon supply chains. *Complex & Intelligent Systems*. https://doi.org/10.1007/s40747-023-01179-0

Mafakheri, F., Adebanjo, D., & Genus, A. (2021). Coordinating biomass supply chains for remote communities: A comparative analysis of non-cooperative and cooperative scenarios. *International Journal of Production Research, 59*(15), 4615–4632. https://doi.org/10.1080/00207543.2020.1767312

Mafakheri, F., & Nasiri, F. (2014). Modeling of biomass-to-energy supply chain operations: Applications, challenges and research directions. *Energy Policy, 67*, 116–126. https://doi.org/10.1016/j.enpol.2013.11.071

Malladi, K. T., & Sowlati, T. (2018). Biomass logistics: A review of important features, optimization modeling and the new trends. *Renewable and Sustainable Energy Reviews, 94*, 587–599. https://doi.org/10.1016/j.rser.2018.06.052

Mes, M. R. K., & Iacob, M. E. (2016). Synchromodal transport planning at a logistics service provider. In H. Zijm, M. Klumpp, U. Clausen, & M. Hompel (Eds.), *Logistics and supply chain innovation. Lecture notes in logistics*. Cham: Springer. https://doi.org/10.1007/978-3-319-22288-2_2.

Müller, F., Jaeger, D., & Hanewinkel, M. (2019). Digitization in wood supply – A review on how industry 4.0 will change the forest value chain. *Computers and Electronics in Agriculture, 162*, 206–218. https://doi.org/10.1016/j.compag.2019.04.002

Nicholls, D., Vaughan, D., Mitchell, D., Han, H.-S., Smidt, M., & Sessions, J. (2022). Forest bio-hubs to enhance Forest health while supporting the emerging bioeconomy—A comparison between three U.S. Regions. *Energies, 15, Article 931*. https://doi.org/10.3390/en15030931

Palander, T. (2022). Outsourcing issues of wood supply chain Management in the Forest Industry. *Forest Science, 68*(5–6), 521–532. https://doi.org/10.1093/forsci/fxac029

Palander, T., & Vesa, L. (2022). Data-driven optimization of forestry and wood procurement toward carbon-neutral logistics of Forest industry. *Forests, 13, Article 759*. https://doi.org/10.3390/f13050759

Pfoser, S., Treiblmaier, H., & Schauer, O. (2016). Critical success factors of Synchromodality: Results from a case study and literature review. *Transportation Research Procedia, 14*, 1463–1471. https://doi.org/10.1016/j.trpro.2016.05.220

Picchio, R., Proto, A. R., Civitarese, V., Di Marzio, N., & Latterini, F. (2019). Recent contributions of some fields of the electronics in development of Forest operations technologies. *Electronics, 8*. https://doi.org/10.3390/electronics8121465. article 1465.

Ponte, B., Costas, J., Puche, J., Pino, R., & de la Fuente, D. (2018). The value of lead time reduction and stabilization: A comparison between traditional and collaborative supply chains. *Transportation Research Part E: Logistics and Transportation Review, 111*, 165–185. https://doi.org/10.1016/j.tre.2018.01.014

Prinz, R., Väätäinen, K., Laitila, J., Sikanen, L., & Asikainen, A. (2019). Analysis of energy efficiency of forest chip supply systems using discrete-event simulation. *Applied Energy, 235*, 1369–1380. https://doi.org/10.1016/j.apenergy.2018.11.053

Qu, W., Rezaei, J., Maknoon, Y., & Tavasszy, L. (2019). Hinterland freight transportation replanning model under the framework of synchromodality. *Transportation Research Part E: Logistics and Transportation Review, 131*, 308–328. https://doi.org/10.1016/j.tre.2019.09.014

Reis, V. (2015). Should we keep on renaming a +35-year-old baby? *Journal of Transport Geography, 46*, 173–179. https://doi.org/10.1016/j.jtrangeo.2015.06.019

Rivera, A. E. P., & Mes, M. R. K. (2022). Anticipatory scheduling of synchromodal transport using approximate dynamic programming. *Ann. Oper. Res.*. https://doi.org/10.1007/s10479-022-04668-6

Röser, D., Mola-Yudego, B., Sikanen, L., Prinz, R., Gritten, D., Emer, B., Väätäinen, K., & Erkkilä, A. (2011). Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass and Bioenergy, 35*(10), 4238–4247. https://doi.org/10.1016/j.biombioe.2011.07.011

Routa, J., Kolström, M., & Sikanen, L. (2018). Dry matter losses and their economic significance in forest energy procurement. *International Journal of Forest Engineering, 29*(1), 53–62. https://doi.org/10.1080/14942119.2018.1421332

Sarrazin, F., LeBel, L., & Lehoux, N. (2019). Analyzing the impact of implementing a logistics center for a complex forest network. *Canadian Journal of Forest Research, 49*, 179–189. https://doi.org/10.1139/cjfr-2018-0346

Selkimäki, M., Mola-Yudego, B., Röser, D., Prinz, R., & Sikanen, L. (2010). Present and future trends in pellet markets, raw materials, and supply logistics in Sweden and Finland. *Renewable and Sustainable Energy Reviews, 14*(9), 3068–3075. https://doi.org/10.1016/j.rser.2010.06.009

Seyedan, M., & Mafakheri, F. (2020). Predictive big data analytics for supply chain demand forecasting: Methods, applications, and research opportunities. *Journal of Big Data, 7*, 53. https://doi.org/10.1186/s40537-020-00329-2

Shahi, S., & Pulkki, R. (2013). Supply chain network optimization of the Canadian Forest products industry: A critical review. *American Journal of Industrial and Business Management, 3*(7), 631–643. https://doi.org/10.4236/ajibm.2013.37073

Sharma, B., Ingalls, R. G., Jones, C. L., & Khanchi, A. (2013). Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. *Renewable and Sustainable Energy Reviews, 24*, 608–627. https://doi.org/10.1016/J.RSER.2013.03.049

Sharma, M., Luthra, S., Joshi, S., Kumar, A., & Jain, A. (2023). Green logistics driven circular practices adoption in industry 4.0 era: A moderating effect of institution pressure and supply chain flexibility. *Journal of Cleaner Production, 383*. https://doi.org/10.1016/j.jclepro.2022.135284. Article 135284.

Sikanen, L., Asikainen, A., & Lehikoinen, M. (2005). Transport control of forest fuels by fleet manager, mobile terminals and GPS. *Biomass and Bioenergy, 28*(2), 183–191. https://doi.org/10.1016/j.biombioe.2004.08.011

Simard, V., Rönnqvist, M., LeBel, L., & Lehoux, N. (2023). Improving the decision-making process by considering supply uncertainty – A case study in the forest value chain. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2023.2169382

Sterner, K., Edman, T., & Fjeld, D. (2023). Transport management – A Swedish case study of organizational processes and performance. *International Journal of Forest Engineering*. https://doi.org/10.1080/14942119.2023.2202614

Uckelmann, D. (2008). (2008). A definition approach to smart logistics. In S. Balandin, et al. (Eds.), *NEW2AN 2008, LNCS 5174, pp. 273–284*. Berlin Heidelberg: Springer.

Uusitalo, J. (2005). A framework for CTL method-based wood procurement logistics. *International Journal of Forest Engineering, 16*(2), 37–46. https://doi.org/10.1080/14942119.2005.10702512

Väätäinen, K., Anttila, P., Eliasson, L., Enström, J., Laitila, J., Prinz, R., & Routa, J. (2021). Roundwood and biomass logistics in Finland and Sweden. *Croatian Journal of Forest Engineering, 42*, 39–61. https://doi.org/10.5552/crojfe.2021.803

Väätäinen, K., Laitila, J., Anttila, P., Kilpeläinen, A., & Asikainen, A. (2020). The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators – Discrete event simulation case study in Central Finland. *International Journal of Forest Engineering, 31*(2), 156–170. https://doi.org/10.1080/14942119.2020.1757324

Väätäinen, K., Prinz, R., Malinen, J., Laitila, J., & Sikanen, L. (2017). Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. *GCB Bioenergy, 9*, 1657–1673. https://doi.org/10.1111/gcbb.12463

Valipour, M., Mafakheri, F., Gagnon, B., Prinz, R., Bergström, D., Brown, M., & Wang, C. (2024). Integrating bio-hubs in biomass supply chains: Insights from a systematic literature review. *Journal of Cleaner Production, 467*. https://doi.org/10.1016/j.jclepro.2024.142930. Article 142930.

Vazifeh, Z., Mafakheri, F., & An, C. (2021). Biomass supply chain coordination for remote communities: A game-theoretic modeling and analysis approach. *Sustainable Cities and Society, 69*. https://doi.org/10.1016/j.scs.2021.102819. Article 102819.

Vazifeh, Z., Mafakheri, F., & An, C. (2023). Coordination of bioenergy supply chains under government incentive policies: A game-theoretic analysis. *Clean Technologies and Environmental Policy*. https://doi.org/10.1007/s10098-023-02498-z

Venäläinen, P., Alanne, H., Ovaskainen, H., Poikela, A., & Strandström, M. (2017). Kausivaihtelun kustannukset ja vähentämiskeinot puun toimitusketjussa. [Additional costs of season variation and mitigation possibilities in wood procurement.]. *Metsätehon tuloskalvosarja 8/2017, slides, 76* [In Finnish].

Venanzi, R., Latterini, F., Civitarese, V., & Picchio, R. (2023). Recent applications of smart Technologies for Monitoring the sustainability of Forest operations. *Forests, 14*. https://doi.org/10.3390/f14071503. article 1503.

Virkkunen, M., Raitila, J., & Korpinen, O. J. (2016). Cost analysis of a satellite terminal for forest fuel supply in Finland. *Scandinavian Journal of Forest Research, 31*, 175–182. https://doi.org/10.1080/02827581.2015.1082617

Windisch, J., Röser, D., Mola-Yudego, B., Sikanen, L., & Asikainen, A. (2013). Business process mapping and discrete-event simulation of two forest biomass supply chains. *Biomass and Bioenergy, 56*, 370–381. https://doi.org/10.1016/j.biombioe.2013.05.022

Wolfsmayr, U. J., & Rauch, P. (2014). The primary forest fuel supply chain: A literature review. *Biomass and Bioenergy, 60*, 203–221. https://doi.org/10.1016/j.biombioe.2013.10.025

Zhang, X., Wang, J., Vance, J., Wang, Y., Wu, J., & Hartley, D. (2020). Data analytics for enhancement of Forest and biomass supply chain management. *Current Forestry Reports, 6*, 129–142. https://doi.org/10.1007/s40725-020-00111-w