Technologies and Industry 4.0 in Forest Supply Chain

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Forestry products and forestry organizations play an essential role in our lives and significantly contribute to the global economy. They are also being impacted by the rapid development of advanced technologies and Industry 4.0. More specifically, several technologies associated with Industry 4.0 have been identified for their potential to optimize traditional forest supply chains. This research systematically investigated these technologies and the scientific evidence on their impact on forest supply chains.

Industry 4.0 systematic literature review forest products forest supply chain

Industry 4.0 framework

1. Introduction

The term Industry 4.0 has become one of the most popular new topics in technology among researchers. A wide range of research across multiple disciplines has discussed and conducted research related to Industry 4.0 [1]. According to a Google trend, the topic of Industry 4.0 has witnessed a rapid increase in interest over the last 10 years [2]. Indeed, most industries are exploring how Industry 4.0 may have significant impacts on the economic, social and environmental aspects of their supply chains.

As a concept, Industry 4.0 was initially introduced by the German government in 2011 [3]. Industry 4.0 is also known as 'smart manufacturing', 'Industrie 4.0′ or 'the Fourth Industrial Revolution' [4][5]. It has been argued by its advocates that Industry 4.0 has the potential to stimulate a phase of significant industrial transformations comparable to the three previous industrial revolutions. The First Industrial Revolution introduced mechanical looms driven by steam engines from 1760 to 1850 [6]. The Second Industrial Revolution from 1870 to 1914 witnessed the growth of huge economies of scale in manufacturing [7]. The Third Industrial Revolution introduced the growth of electronics and modern ICTs such as automation systems [8]. The Fourth Industrial Revolution encompasses cutting-edge technologies and integrated systems such as the Internet of Things (IoT) and cyber-physical systems (CPS). The fundamental concepts underpinning Industry 4.0 are: the Smart Factory, CPS, decentralized self-organization, digitalization and virtualization and intelligent industrial manufacturing [9][10]. These concepts of Industry 4.0 were proposed to enable businesses to improve decision-making at the strategic and operational levels by analyzing large amounts of real-time data [11].

The concept of Industry 4.0 can use various technologies or techniques in its implementation [12]. Importantly, the new technologies included in Industry 4.0 stimulate changes in a wide range of business activities, leading to changes in supply chains [13]. They include Big Data, analytics, mobile technology, additive manufacturing, artificial intelligence, Cloud technology, IoT, radio-frequency identification (RFID), simulation, sensors, Global Positioning System (GPS), unmanned aerial vehicle (UAV) and blockchain [11][14][15]. In addition to these technologies, in some research papers the disruptive technologies related to Industry 4.0 have also been listed, which can be summarized as follows: virtual reality, 3D printing, cyber security, machine-to-machine communication, automatic identification, business intelligence and nanotechnology [1][16]. The concept of the IoT was created based on RFID-enabled identification and tracking technologies [12]. In this systematic review paper, a broad and inclusive definitional approach to this range of technologies was adopted to ensure relevant research could be identified and included. As a result, technologies related to Industry 4.0 were deemed to be those that supported collecting, storing, processing, analyzing and sharing data.

In examining the forest industry, it is evident that the demand for forest products is increasing around the world [17]. The forest supply chain refers to a temporal sequence of activities and processes from standing trees to the end-users that transform the woody raw material to final forest-based products [18][19]. The chain starts with raw material as the standing tree in the forest. In the forest supply chain, the woody material can be turned into logs, roundwood, lumber, panel and engineered wood, pulp and paper, biomass, bioenergy (for electricity and heat) and other forest product [18][19][20][21]. The production processes transfer the woody raw materials through a biorefinery, pulp mill, sawmill, panel mill and pellet mill [18][19]. Based on the forest supply chain in the literature, as shown in **Figure 1**, the processes include procurement, production, distribution and sales/market [18][19][22]. The activities include forest management, harvesting and transportation [19][23][24]. The independent entities involved in the forest supply chain are forest owners, harvesting enterprises, haulage companies, logistic (transportation) companies, storage sheds, terminals, power plants and bioethanol facilities [19][22].

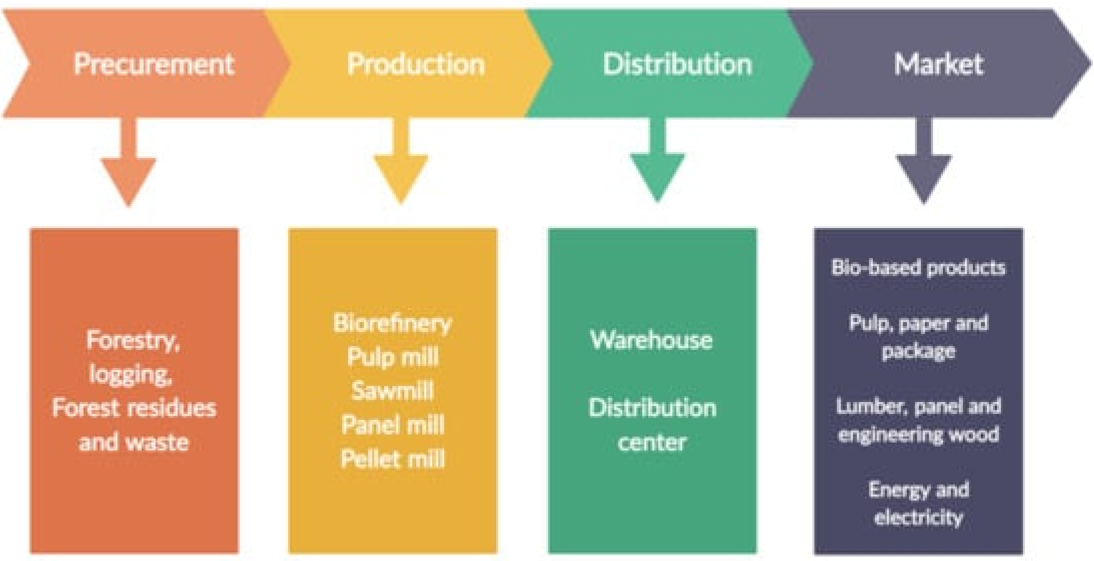

Figure 1. The processes of the forest supply chain, adapted from [18][22].

It is also evident that globally most forestry supply chains are not sophisticated using new technologies and the data that they produce. With the growth of the forestry industry around the world, there are some issues and challenges reported that are impacting the forest supply chain. For instance, there are some illegal activities in the forest supply chain. The FAO reported illegal logging and timber trade, especially from Russia and China, for the processing and manufacture of final products [25]. Illegal logging and wood laundering have also been reported in Mexico and the forest supply chain has inefficient low-tech practices [26]. Moreover, the non-optimal use of resources is also an issue in the forest supply chain [27]. In this untrustworthy environment, parties in supply chains would like to perform transactions in a transparent environment. Customers would like to obtain information about the raw materials of forest-based products to know whether the products are eco-friendly [28]. Recently, Industry 4.0 and technologies have been identified by some research has offering potential solutions to these types of issues and inefficiencies. Several studies have indicated that the implementation of new technologies could optimize the forest supply chain. For instance, the automated real-time tracking system could be the solution for the non-optimal use of resources in wood processing [27]. Several technologies associated with Industry 4.0 have been used or studied to optimize the forest-based supply chain, including blockchain, IoT, RFID, and smartphone applications. However, to the best of our knowledge, there is limited research that has systematically investigated the benefits of Industry 4.0 and its technologies in supporting the forest supply chain.

Prior to performing this systematic review, the research team identified pre-existing literature reviews that had been conducted on related topics. The existing studies have tended to focus on: the optimization solutions of digital technologies in the forest supply chain [19]; and only considered part of forest supply chain [23][24]. The review developed by [23] was mainly based on three activities of the forest supply chain [23]. The authors in [24] reviewed technologies implemented in wood supply but not the entire supply chain [24]. Noticeably, these previous reviews have only analyzed either a part of the forest supply chain or did not consider Industry 4.0 at all. Thus, it is necessary to identify research exploring how the new technologies in Industry 4.0 are or may improve the forest supply chain and the expected outcomes of the implementation of these technologies.

2. Supportive Physical and Digital Technologies Implemented in the Forest Supply Chain

This subsection focuses on the supportive technologies applied in different phases of the forest supply chain towards Industry 4.0. Multiple technologies are applied to change or optimize the traditional operation of the forest supply chain. The results of the systematic review show that there 16 disruptive technologies have been applied to the forest supply chain to date. These technologies have implemented a range of phases, operations and processes of the supply chain in multiple ways. According to the data we extracted, as shown in **Table 1**, 16 physical and digital technologies were considered by the authors of the included articles. These technologies are simulations (Sim), artificial intelligence (AI), geographic information system (GIS), Global Positioning System (GPS), machine learning (ML), IoT, RFID, smartphone applications (SA), Cloud technology (CT), blockchain (BC), Bluetooth (BT), remote sensing (RS), data analytics (DA), unmanned aerial vehicle (UAV), terrestrial laser scanning (TLS) and airborne laser scanning (ALS).

Table 1. Technologies considered by the authors of the included studies.

Reference	Sim	AI	GIS	GPS	ML	IoT	RFID	SA	CT	BC	BT	RS	UAV	TLS	ALS	DA
[28]							X									
[29]	X															
[30]	X															
[31]	X															
[32]	X															
[33]	X															
[34]	X															
[35]	X		X													
[36]	X		X													
[37]	X															
[38]	X															
[39]			X	X												
[40]			X													
[41]			X													
[42]	X		X	X												
[43]			X													
[44]			X													
[45]			X													
[46]			X													
[47]			X													
[48]				X			X	X					X	X		
[49]													X			X
[50]								X							X	
[51]						X										

Reference	Sim	AI	GIS	GPS	ML	IoT	RFID	SA	CT	BC	BT	RS	UAV	TLS	ALS	DA
[52]					X											
[53]	X															
[54]	X															
[55]				X		X	X	X	X							
[56]		X														
[57]		X														
[58]			X													
[59]		X	X													
[60]			X													
[61]												X				
[62]							X									
[63]							X									
[64]							X									
[65]				X		X	X	X		X	X					
[66]	X															
[67]										X						
[68]										X						
[69]			X													
[70]			X													
[71]							X									
[72]							X									
Total	14	3	16	5	1	3	9	4	1	3	1	1	2	1	1	1

extracted
4.0 were

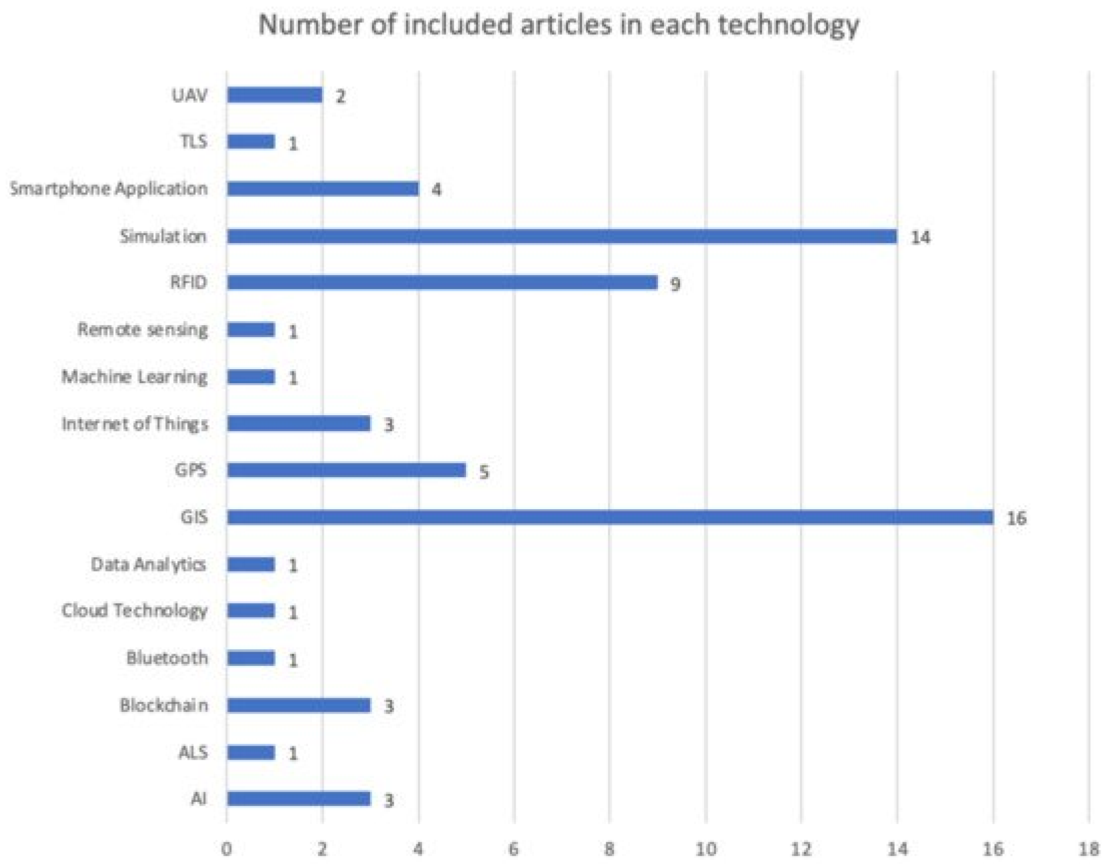

Figure 2. Number of articles mentioning each technology.

2.1. Tools of Supportive Technologies in the Forest Supply Chain

Several tools of GIS, simulation and GPS were considered by researchers in optimizing the forest supply chain. The simulation software are support tools that have contributed to visualize and optimize the forest supply chain. Simulations used simulation software as a tool to simulate the optimal options for the research problems. Three simulation software appeared more than once in the results: Witness® [29][30][31][32], AnyLogic® [33][34][35][36] and ExtendSim® [37][38]. The simulation software are able to evaluate, compare and optimize their designed model. Two simulation models were mostly used by selected studies to achieve their objectives. These simulation models were the agent-based simulation model and discrete event simulation model. Karttunen et al. [36] used a combination of agent-based and discrete-event simulation models to compare an intermodal container's cost efficiency in truck logistics for the long-distance transportation of forest chips.

GIS software and GPS devices were used to collect territorial data and analyze the road networks of transportation. The results of the review show that most GIS are used for biomass supply to allocate biomass or to select bioethanol facilities (biomass energy plants). Raghu et al. [35] indicated that the benefit of using GIS for biomass-supply studies is that GIS can accurately calculate transportation truck parameters (travel distances, times and cost) and optimize routes. The results show that two GIS software were used in the forest supply chain: ArcGIS and QGIS. ArcGIS is a network analysis tool to perform spatial analysis [39][40][41][42][43]. The authors in [40] used the ArcGIS Network Analyst combined with the Dijkstra algorithm to find the least-cost paths based on distance, time or weighted cost [40]. The GIS software has also been used for road transportation network [41]. QGIS is an open source GIS software used for territorial analysis [44][45][46]. The authors in [44] used QGIS software and Google Maps Directions API to obtain territorial information for studying the economic potential of wood biomass. The authors in [46] used the QGIS network analysis library to compute the public road network. Some studies used the GPS to collect data of trucks' transportation movements [39][40][42]. GPS can track and monitor the movement information of truck transportation [40]. GIS is also widely used to identify an optimal location for forest biomass facilities or factories. Zhang et al. [41] developed an optimization model using GIS technology to collect the data of candidate locations of bioethanol facilities. Lin et al. [47] used a simulation model with GIS to locate the biomass-to-biofuel factories.

The authors in [42] used GPS to track movement information, resource measurement and managing forestry operations [42]. Two GPS devices were considered by the authors of the included studies: Trimble® ProXH coupled with a Trimble® NOMAD [42] and Visiontac VGPS-900 GPS receiver [39]. The GPS receiver can record the location and speed information of the trucks [39].

2.2. Supportive Technologies Implemented in Different Phases of the Forest Supply Chain

Table 2 shows the different technologies used in the different processes in the supply chain with references to included studies. According to the content analysis of included studies, the processes mainly focus on forest management, forest inventory, harvesting, planning, procurement, production, transportation, sales and the entire supply chain. Several integrated systems or methods combined with multiple technologies were developed to apply to the supply chain in the included studies. Multiple technologies were applied to forest management and inventory. Pichler et al. [48] built a 3D forest model based on UAV and TLS technology for forest inventory, forest management and harvesting. Puliti and Granhus [49] performed data analytics with UAV data on the operational management of regeneration forests compared to the model with ALS data. Siipilehto et al. [44] used the ALS-based method and a smartphone application called Trestima for forest inventory. Trestima is an image analysis application for stand-wise forest inventory [50]. Yu et al. [51] developed a collection platform called FEFCP using IoT technology (ZIGBEE protocol) to monitor, manage and control the forest environmental factors for forest management. The ZIGBEE protocol is a highly reliable wireless data transmission net (IoT technology) which is one type of wireless connection [51].

Some studies applied technologies to the planning and procurement of the forest supply chain. A machine learning approach was developed for sawmills to generate a learning model in wood allocation planning [52]. Fernandez-Lacruz et al. [37] used simulations on forest chip suppliers and integrated supply planning. Gautam et al. [53] used simulations to develop a novel approach on the operational level of the wood procurement system in the forest products industry. Windisch et al. [54] used simulation software to develop a business process model for forest biomass procurement.

Technologies also cover the harvest operations and pre-harvest. A new computer-aided approach was developed by Pichler et al. [48] on the basis of RFID for tree marking to replace standard survey procedures. The Treemetrics Forest application was used to store the tree parameters of RFID [48].

Several technologies are applied in the production phases of the forest supply chain. Šulyová and Koman [55] proposed a platform that applied IoT technology in wood monitoring wood processing in sawmills. This platform integrated RFID technology monitors, QR codes, a mobile application called SmartTree, a website, and a Cloud platform to provide real-time data to support management and better decision-making. Thomas and Thomas [56] proposed a designed approach using the artificial neural network in a simulation application used for a sawmill workshop. Alexandru Borz and Păun [57] proposed a system with object tracking, signal processing and AI to monitor wood operations in sawmills. Morin et al. [52] developed a machine learning-based model for wood allocation which could be a learning model for decision making in the wood-planning of sawmills. Zhang et al. [58] developed a decision support system using a GIS-based approach to select biofuel facility locations.

Fifteen included articles considered supportive technologies in the transportation of the forest supply chain. Araújo et al. [59] proposed an intelligent system using AI and the ArcGis software to adapt changes during the transportation process. Simulations were used to study the transportation method of forest chips and timber. Karttunen et al. [29] studied the optimal long-distance waterway transport logistics of forest chips by using discrete-event simulations. Vaatainen et al. [30] used a discrete-event simulation method to compare the truck performance indicators with different gross vehicle weights and payloads. Simulation software can calculate the processing time, weights, costs and working times of transportation methods in the supply chain [34]. Some studies considered using GIS data as simulation data to solve problems in transportation. Fernandes et al. [45] used GIS to perform an optimal route simulation to test the influence of wood stacking locations on forest transport costs. GIS and simulations are also able to estimate the transportation cost of forest chips and by-products [60]. Simon et al. [44] developed a tool using the territorial information obtained with QGIS, Python, and the Google Maps Directions API to simulate the economic potential of wood biomass. Smart sensors are used to measure and record large wood movement (transportation) [61].

Several studies considered using RFID to monitor the performance of the supply chain and trace forest wood (product) and biomass. Björk et al. [62] developed an RFID reader prototype for forest harvesting to trace logs from trees to sawmills using RFID-marking to connect the physical objects (wood) with their database counterparts. This prototype allows the automatic tracking of wood. Ranta et al. [63] developed an RFID-based tracking system called RfIDER to trace forest biomass which used RFID to manage biomass logistics to provide reliable, accurate and real-time information to biomass owners. In a similar paper, Sipilä et al. [64] proposed a passive RFID technology prototype for automatic identification, the tracking of wood products and the control of the supply chain. Furthermore, this prototype is passive, small and battery-free, which can be permanently embedded into wood. RFID-related technology was integrated with other technologies such as IoT, blockchain, QR codes and smartphone applications used for the traceability and tracking systems of (woody or biomass) products. Appelhanz et al. [28] developed an RFID traceability information system with databases and web applications to process and collect information on eco-friendly wood furniture for customers.

Some studies have attempted or successfully applied supportive technologies to the forest-based supply chain. Figorilli et al. [65] developed a blockchain technology prototype for the traceability of wood in the forest wood supply chain. This prototype involved an integrated system, Infotracing, using blockchain technology for the electronic traceability of wood from standing trees (timber marking) to final users (customers). It integrated multiple digital technologies, including RFID sensors, blockchain, IoT, GPS and smartphone applications. The RFID traceability information system developed by Appelhanz et al. [28] can provide transparent information on the whole supply chain to gain the customer's trust.

Table 2. Technologies used in the different processes of the forest supply chain.

Processes	Technologies
Forest management	Simulation [33][66] IoT [51] UAV [48][49] Data analytics [49] TLS [48] GPS [48] Smartphone application [48]
Forest inventory	ALS [50] UAV [48] TLS [48] Smartphone application [50]
Planning	Simulation [37] Machine learning [52]
Procurement	Simulation [53][54] Blockchain [67]
Harvesting	Simulation [53] UAV [48] TLS [48] RFID [48] GPS [48] Smartphone application [48]
Production—sawmill	Simulation [33] AI [56][57] Machine learning [52] IoT [55] GPS [55] RFID [55] Smartphone application [55] Could technology [55]
Production—biofuel factory	Simulation [47][58] GIS [47][58]
Production—bioethanol factory	GIS [41]

Processes	Technologies
Production—biomass energy plants	GIS [43]
Transportation—forest chips	Simulation [29][32][36][39][40][60], GPS [39], GIS [36][39][40][60]
Transportation—wood/timber	Simulation [30][34][42][45], GIS [41][42][45][59] GPS [42] AI [59] Remote sensing [61]
Transportation—forest biomass	Simulation [44], GIS [44] RFID [63]
Sales	Blockchain [68]
Entire supply chain	Simulation [31][35][38][46][69][70], GIS [35][46][69][70] RFID [28][62][64][71][72] Blockchain [65] IoT [65] GPS [65] Bluetooth [65] Smartphone applications [65]

3. Improvement and Characteristics of the Forest Supply Chain in Industry 4.0

In this subsection, we present the second component of the framework. The supportive technologies provide several improvements to the forest supply chain. These improvements could be summarized in several domains: real-time data management; interoperability; virtualization; agility; and integration. The technologies improve or provide new characteristics for the forest supply chain in the context of Industry 4.0.

Real-time data management: With the supportive technologies implemented, the stakeholders in the forest supply chain are capable of making better decisions based on real-time information. IoT-based technology can provide real-time information between departments, smartphones, smartwatches and managers among parties in the forest supply chain to accelerate operational analyses, finding flexible solutions and better decision making [55]. IoT technology is also able to monitor forest environmental factors in real time [51]. The real-time FUELCONTROL® system provides the same monitoring function to monitor biomass quality [35]. RFID systems provide real-time information to managers as well [48]. The RFID tracking systems are able to provide real-time information, which allows stakeholders to allocate biomass according to customer needs [63].

Agility: The agility of the forest supply chain refers to the management of competency, flexibility, and speed among supply chain managers. For instance, the simulations provide statistical analysis to improve the agility of wood procurement systems [53]. Agility could be facilitated by real-time data management.

Interoperability: Interoperability refers to the technologies that are able to share seamless data and information sharing among the entities and organizations in the forest supply chain. Multiple technologies fulfill an enabler role to dynamically optimize the forest supply chain in Industry 4.0, such as IoT and RFID. These technologies achieve interoperability between sensors and actuators in the forest supply chain.

Integration: Integration means that the parties in the forest supply chain work closely together. Interoperability leads the integration. For instance, IoT's integrated blockchain tracking system achieved horizontal integration across the forest supply chain [65].

Virtualization: Visualization can be achieved through technologies such as UAV and TLS technology. The new computer-aided approach developed by Pichler et al. [48] is able to generate a 3D forest model of forest inventory that can replace the traditional survey procedure.

4. Strategic Outcomes

Strategic outcomes refer to the desired benefits and impacts of applying these technologies to forest supply chains in the era of Industry 4.0. This subsection discusses the expected benefits and impacts of the forest supply chain in Industry 4.0. Based on the analysis of the results of the systematic review, the strategic outcomes have three dimensions: the economic, environmental and social levels. Under each domain, the main outcome focuses were categorized. In **Table 3**, a summary of strategic outcomes in the different domains and focuses are presented with references. The strategic outcomes provide economic benefits, including cost reduction, efficiency, increased transparency and reduced complexity. For instance, RFID systems provide economic benefits to the forest industry because they provide real-time information to managers to enable better decision making [45]. This subsection presents the strategic outcomes. The strategic outcomes in environmental benefits include reducing greenhouse gas (GHG) emissions and optimal energy consumption. Some research has focused on the social benefit by applying technologies to the forest supply chain, including increasing job opportunities and reducing illegal activity.

Cost reduction: The outcome could be reducing several costs among parties of the forest supply chain. Mobini et al. [38] concluded that using bark as drying fuel instead of sawdust can reduce cost by approximately 1.5%. Fernandes et al. [45] indicated that the closer wood is stacked to the carbonization plant, the lower the transportation cost is. An integrated system with IoT technology can reduce operating costs in the wood processing of sawmills [60]. The intelligent system was developed by [59] to minimize the cost of timber transportation for different routes and trucks. Simulations were used in multiple studies to reduce the costs of the supply chain. A simulation-based model was developed to find the optimum inventory policy to minimize the total inventory cost in the forest products industry [33]. According to the discrete-event simulation conducted by Fernandez-Lacruz et al. [37], the supply cost could be reduced by increasing the utilization of forest biomass. Vaatainen et al. [30] confirmed that the tendency of the size increase in gross vehicle weights in timber trucking could reduce trucking costs and exhaust gas emissions.

Efficiency: The forest supply chain become more efficient in the era of Industry 4.0 with the development of supportive technologies. Intelligent technologies could increase timber harvesting efficiency [48]. RFID-related prototypes and tracking systems provide benefits at the economic level to improve efficiency as well. They provide real-time data to stakeholders/managers for efficiency improvement at the management and operational level of the supply chain. There is great potential to improve efficiency by using new technology and weight limits for heavy vehicles when transporting forest chips and forest industry by-products [60]. In a similar study, Prinz et al. [32] found that new vehicle types with an increased chip load capacity can improve the forest chip supply's fuel economy and efficiency.

Increase transparency: The environment of the forest supply chain becomes more transparent for secure transaction between parties in the supply chain. The RFID traceability information system (with databases and web applications) provides information on products collected across the whole supply chain from the raw materials to final products [28]. The purpose of this system was to provide the transparent information of the whole supply chain to gain the customer's trust. Morten Komdeur and Ingenbleek [67] reached a similar conclusion that the blockchain has significant effect on purchasers' trust regarding purchasing timber products. The blockchain technology prototype for the traceability of wood provides a transparent environment for confident transactions alone with the wood supply chain [65]. The untrustworthy environment came along with the growth of the economy and technology. The integrated systems combined with multiple technologies can be the solution to improve transparency.

Complexity reduction: The operations and activities are simpler than the traditional forest supply chain. Two included studies have focused on using technologies to reduce the complexity in the forest supply chain. The machine learning approach for wood-planning proposed by Morin et al. [52] can simplify the data computation phase of wood allocation. Using an artificial neural network (ANN) for simulation applications is simpler and less time-consuming for researchers/managers to perform simulations in the forestry industry [56]. The result shows that the machine learning-related method is a way to simplify the process of decision making in sawmills. However, there is only a small number of studies that have used machine learning in sawmills. Machine learning or AI has not been well studied or applied in the forest supply chain. It may be potentially beneficial for the entire supply chain to study this avenue in future research.

Reduce GHG emissions: The purpose of several studies was to reduce transportation and facility emissions in the logistics of transporting forest-based products. Raghu et al. [35] observed that the real-time monitoring of biomass quality helped save 2% of the GHG emissions from the supply chain. The trend of the increasing gross vehicle weight in timber trucking was studied, and the results show that it can reduce exhaust gas emissions [30].

Optimal energy consumption: One strategy outcome of the forest supply chain in Industry 4.0 was finding an optimal way of energy consumption by implementing the emerging technologies. For instance, Zhang et al. [41] developed an integrated decision support system to determine optimized energy and GHG emissions for candidate locations of biomass facilities.

Reduce illegal activities: Reducing illegal activities could be one of the strategic outcomes at the social level. Pichler et al. [48] suggested that using RFID for tree marking can be a solution to reduce illegal logging. In similar studies, an RFID log tracking system can prevent illegal logging activities [71]. As a result, RFID-related technology can be the most promising solution to eliminate illegal wood material trading activities worldwide. RFID systems can track wood or biomass to monitor activities throughout the supply chain.

Employment: The increase in job opportunities is one of the social benefits as well. Technologies can increase job opportunities among parties of the forest supply chain. Lin et al. [47] focused on social benefits by using the method of the simulation model with GIS data to locate the biomass-to-biofuel factories to provide 16% more job offers.

Table 3. Summary of strategic outcomes extracted from the included studies.

Strategic Outcomes	Main Focus	Reference
Economic level	Efficiency	[30][32][33][34][36][42][60][62][70][72]
	Cost reduction or profitability	[28][30][32][34][36][37][38][40][41][42][44][45][46][55][58][59][60][62][70][72]
	Reduce Complexity	[52][56]
	Transparency	[40][41][48][67]
Environmental level	Reduce greenhouse gas (GHG) emissions	[30][35][41][58][62]
	Energy consumption	[41][58]
Social level	Increase job opportunity	[47]
	Reduce illegal activity	[48][68][71]

References

1. Oztemel, E.; Gursev, S. Literature review of Industry 4.0 and related technologies. J. Intell. Manuf. 2020, 31, 127–182.
2. Abdirad, M.; Krishnan, K. Industry 4.0 in Logistics and Supply Chain Management: A Systematic Literature Review. Eng. Manag. J. 2021, 33, 187–201.
3. Rojko, A. Industry 4.0 Concept: Background and Overview. Int. J. Interact. Mob. Technol. 2017, 11, 14.
4. Liao, Y.X.; Deschamps, F.; Loures, E.D.R.; Ramos, L.F.P. Past, present and future of Industry 4.0—A systematic literature review and research agenda proposal. Int. J. Prod. Res. 2017, 55, 3609–3629.

5. Qin, J.; Liu, Y.; Grosvenor, R. A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. Procedia Cirp 2016, 52, 173–178.
6. Stokey, N.L. In A quantitative model of the British industrial revolution, 1780–1850. In Carnegie-Rochester Conference Series on Public Policy; Elsevier: Amsterdam, The Netherlands, 2001; pp. 55–109.
7. Mokyr, J.; Strotz, R.H. The second industrial revolution, 1870–1914. Stor. Dell'economia Mond. 1998, 21945, 1.
8. Drath, R.; Horch, A. Industrie 4.0: Hit or hype? . IEEE Ind. Electron. Mag. 2014, 8, 56–58.
9. Lasi, H.; Fettke, P.; Kemper, H.-G.; Feld, T.; Hoffmann, M. Industry 4.0. Bus. Inf. Syst. Eng. 2014, 6, 239–242.
10. Cordeiro, G.A.; Ordóñez, R.E.C.; Ferro, R. Theoretical proposal of steps for the implementation of the Industry 4.0 concept. Braz. J. Oper. Prod. Manag. 2019, 16, 166–179.
11. Dalenogare, L.S.; Benitez, G.B.; Ayala, N.F.; Frank, A.G. The expected contribution of Industry 4.0 technologies for industrial performance. Int. J. Prod. Econ. 2018, 204, 383–394.
12. Xu, L.D.; Xu, E.L.; Li, L. Industry 4.0: State of the art and future trends. Int. J. Prod. Res. 2018, 56, 2941–2962.
13. Frederico, G.F.; Garza-Reyes, J.A.; Anosike, A.; Kumar, V. Supply Chain 4.0: Concepts, maturity and research agenda. Supply Chain. Manag. 2020, 25, 262–282.
14. Bai, C.G.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. Int. J. Prod. Econ. 2020, 229, 107776.
15. Lu, Y. Industry 4.0: A survey on technologies, applications and open research issues. J. Ind. Inf. Integr. 2017, 6, 1–10.
16. Tjahjono, B.; Esplugues, C.; Ares, E.; Pelaez, G. What does industry 4.0 mean to supply chain? Procedia Manuf. 2017, 13, 1175–1182.
17. Baghizadeh, K.; Zimon, D.; Jum'a, L. Modeling and Optimization Sustainable Forest Supply Chain Considering Discount in Transportation System and Supplier Selection under Uncertainty. Forests 2021, 12, 964.
18. D'Amours, S.; Ronnqvist, M.; Weintraub, A. Using Operational Research for Supply Chain Planning in the Forest Products Industry. INFOR 2008, 46, 265–281.
19. Scholz, J.; De Meyer, A.; Marques, A.S.; Pinho, T.M.; Boaventura-Cunha, J.; Van Orshoven, J.; Rosset, C.; Kunzi, J.; Kaarle, J.; Nummila, K. Digital Technologies for Forest Supply Chain Optimization: Existing Solutions and Future Trends. Environ. Manag. 2018, 62, 1108–1133.

20. Sowlati, T. Modeling of forest and wood residues supply chains for bioenergy and biofuel production. In Biomass Supply Chains for Bioenergy and Biorefining; Elsevier: Amsterdam, The Netherlands, 2016; pp. 167–190.
21. Liu, W.Y.; Lin, C.C.; Yeh, T.L. Supply chain optimization of forest biomass electricity and bioethanol coproduction. Energy 2017, 139, 630–645.
22. Ouhimmou, M.; Ronnqvist, M.; Lapointe, L.A. Assessment of sustainable integration of new products into value chain through a generic decision support model: An application to the forest value chain. Omega-Int. J. Manag. S 2021, 99, 102173.
23. Feng, Y.; Audy, J.-F. Forestry 4.0: A framework for the forest supply chain toward Industry 4.0. Gest. Prod. 2020, 27, e5677.
24. Muller, F.; Jaeger, D.; Hanewinkel, M. Digitization in wood supply—A review on how Industry 4.0 will change the forest value chain. Comput. Electron. Agric. 2019, 162, 206–218.
25. Food and Agriculture Organization of the United Nations (FAO). The Russian Federation Forest Sector: Out-Look Study to 2030. Rome, Italy. 2012. Available online: https://agris.fao.org/agris-search/search.do?recordID=XF2013001279 (accessed on 26 April 2021).
26. Torres-Rojo, J.M. Illegal Logging and the Productivity Trap of Timber Production in Mexico. Forests 2021, 12, 838.
27. Pizzi, A.; Despres, A.; Mansouri, H.-R.; Leban, J.-M.; Rigolet, S. Wood joints by through-dowel rotation welding: Microstructure, 13C-NMR and water resistance. J. Adhes. Sci. Technol. 2006, 20, 427–436.
28. Appelhanz, S.; Osburg, V.-S.; Toporowski, W.; Schumann, M. Traceability system for capturing, processing and providing consumer-relevant information about wood products: System solution and its economic feasibility. J. Clean. Prod. 2016, 110, 132–148.
29. Karttunen, K.; Väätäinen, K.; Asikainen, A.; Ranta, T. The operational efficiency of waterway transport of forest chips on Finland's lake Saimaa. Silva Fenn. 2012, 46, 395–413.
30. Vaatainen, K.; Laitila, J.; Anttila, P.; Kilpelainen, A.; Asikainen, A. The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators—Discrete event simulation case study in Central Finland. Int. J. For. Eng. 2020, 31, 156–170.
31. Windisch, J.; Väätäinen, K.; Anttila, P.; Nivala, M.; Laitila, J.; Asikainen, A.; Sikanen, L. Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain. Appl. Energy 2015, 149, 315–325.
32. Prinz, R.; Väätäinen, K.; Laitila, J.; Sikanen, L.; Asikainen, A. Analysis of energy efficiency of forest chip supply systems using discrete-event simulation. Appl. Energy 2019, 235, 1369–1380.

33. Shahi, S.; Pulkki, R. A simulation-based optimization approach to integrated inventory management of a sawlog supply chain with demand uncertainty. Can. J. For. Res. 2015, 45, 1313–1326.
34. Kogler, C.; Stenitzer, A.; Rauch, P. Simulating combined self-loading truck and semitrailer truck transport in the wood supply chain. Forests 2020, 11, 1245.
35. Raghu, K.C.; Aalto, M.; Korpinen, O.J.; Ranta, T.; Proskurina, S. Lifecycle Assessment of Biomass Supply Chain with the Assistance of Agent-Based Modelling. Sustainability 2020, 12, 14.
36. Karttunen, K.; Lattila, L.; Korpinen, O.J.; Ranta, T. Cost-efficiency of intermodal container supply chain for forest chips. Silva Fenn. 2013, 47, 24.
37. Fernandez-Lacruz, R.; Eriksson, A.; Bergström, D. Simulation-based cost analysis of industrial supply of chips from logging residues and small-diameter trees. Forests 2020, 11, 1.
38. Mobini, M.; Sowlati, T.; Sokhansanj, S. A simulation model for the design and analysis of wood pellet supply chains. Appl. Energy 2013, 111, 1239–1249.
39. Simwanda, M.; Sessions, J.; Boston, K.; Wing, M.G. Modeling biomass transport on single-lane forest roads. For. Sci. 2015, 61, 763–773.
40. Sosa, A.; Acuna, M.; McDonnell, K.; Devlin, G. Managing the moisture content of wood biomass for the optimisation of Ireland’s transport supply strategy to bioenergy markets and competing industries. Energy 2015, 86, 354–368.
41. Zhang, F.L.; Wang, J.J.; Liu, S.H.; Zhang, S.M.; Sutherland, J.W. Integrating GIS with optimization method for a biofuel feedstock supply chain. Biomass Bioenergy 2017, 98, 194–205.
42. Marinello, F.; Grigolato, S.; Sartori, L.; Cavalli, R. Analysis of a double steering forest trailer for long wood log transportation. J. Agric. Eng. 2013, 44, 10–15.
43. Woo, H.; Acuna, M.; Moroni, M.; Taskhiri, M.S.; Turner, P. Optimizing the location of biomass energy facilities by integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS). Forests 2018, 9, 585.
44. Simon, F.; Girard, A.; Krotki, M.; Ordoñez, J. Modelling and simulation of the wood biomass supply from the sustainable management of natural forests. J. Clean. Prod. 2021, 282, 124487.
45. Fernandes, D.L.; Matos, L.M.A.; Magalhães, E.C.; Cabacinha, C.D.; de Assis, A.L.; Araújo Júnior, C.A. Influence of wood stacking location on forest transport costs. Floresta 2020, 50, 1047–1052.
46. Laurén, A.; Asikainen, A.; Kinnunen, J.P.; Palviainen, M.; Sikanen, L. Improving the financial performance of solid forest fuel supply using a simple moisture and dry matter loss simulation and optimization. Biomass Bioenergy 2018, 116, 72–79.

47. Lin, C.C.; Kang, J.R.; Huang, G.L.; Liu, W.Y. Forest biomass-to-biofuel factory location problem with multiple objectives considering environmental uncertainties and social enterprises. J. Clean. Prod. 2020, 262, 15.
48. Pichler, G.; Poveda Lopez, J.A.; Picchi, G.; Nolan, E.; Kastner, M.; Stampfer, K.; Kühmaier, M. Comparison of remote sensing based RFID and standard tree marking for timber harvesting. Comput. Electron. Agric. 2017, 140, 214–226.
49. Puliti, S.; Granhus, A. Drone data for decision making in regeneration forests: From raw data to actionable insights1. J. Unmanned Veh. Sys. 2020, 9, 45–58.
50. Siipilehto, J.; Lindeman, H.; Vastaranta, M.; Yu, X.; Uusitalo, J. Reliability of the predicted stand structure for clear-cut stands using optional methods: Airborne laser scanning-based methods, smartphone-based forest inventory application trestima and pre-harvest measurement tool EMO. Silva Fenn. 2016, 50, 1568.
51. Yu, Z.; Xugang, L.; Xue, G.; Dan, L. IoT forest environmental factors collection platform based on ZIGBEE. Cybern. Inf. Technol. 2014, 14, 51–62.
52. Morin, M.; Gaudreault, J.; Brotherton, E.; Paradis, F.; Rolland, A.; Wery, J.; Laviolette, F. Machine learning-based models of sawmills for better wood allocation planning. Int. J. Prod. Econ. 2020, 222, 107508.
53. Gautam, S.; LeBel, L.; Beaudoin, D. Value-adding through silvicultural flexibility: An operational level simulation study. Forestry 2015, 88, 213–223.
54. Windisch, J.; Röser, D.; Mola-Yudego, B.; Sikanen, L.; Asikainen, A. Business process mapping and discrete-event simulation of two forest biomass supply chains. Biomass Bioenergy 2013, 56, 370–381.
55. Šulyová, D.; Koman, G. The significance of IoT technology in improving logistical processes and enhancing competitiveness: A case study on the World’s and Slovakia’s wood-processing enterprises. Sustainability 2020, 12, 7804.
56. Thomas, P.; Thomas, A. Multilayer perceptron for simulation models reduction: Application to a sawmill workshop. Eng. Appl. Artif. Intell. 2011, 24, 646–657.
57. Alexandru Borz, S.; Păun, M. Integrating offline object tracking, signal processing, and artificial intelligence to classify relevant events in sawmilling operations. Forests 2020, 11, 1333.
58. Zhang, F.; Johnson, D.; Johnson, M.; Watkins, D.; Froese, R.; Wang, J. Decision support system integrating GIS with simulation and optimisation for a biofuel supply chain. Renew. Energy 2016, 85, 740–748.
59. Araújo, C.A.; Leite, H.G.; Soares, C.P.B.; Binoti, D.H.B.; Souza, A.P.d.; Santana, A.F.; Torre, C.M.M.E. A multi-agent system for forest transport activity planning. Cerne 2017, 23, 329–337.

60. Laitila, J.; Asikainen, A.; Ranta, T. Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass Bioenergy 2016, 90, 252–261.

61. Spreitzer, G.; Gibson, J.; Tang, M.; Tunnicliffe, J.; Friedrich, H. SmartWood: Laboratory experiments for assessing the effectiveness of smart sensors for monitoring large wood movement behaviour. Catena 2019, 182, 104145.

62. Björk, A.; Erlandsson, M.; Häkli, J.; Jaakkola, K.; Nilsson, Å.; Nummila, K.; Puntanen, V.; Sirkka, A. Monitoring environmental performance of the forestry supply chain using RFID. Comput. Ind. 2011, 62, 830–841.

63. Ranta, T.; Föhr, J.; Karttunen, K.; Knutas, A. Radio frequency identification and composite container technology demonstration for transporting logistics of wood biomass. J. Renew. Sustain. Energy 2014, 6, 013115.

64. Sipilä, E.; Virkki, J.; Sydänheimo, L.; Ukkonen, L. Experimental study on brush-painted passive RFID-based humidity sensors embedded into plywood structures. Int. J. Antennas Propag. 2016, 2016, 1203673.

65. Figorilli, S.; Antonucci, F.; Costa, C.; Pallottino, F.; Raso, L.; Castiglione, M.; Pinci, E.; Del Vecchio, D.; Colle, G.; Proto, A.R.; et al. A blockchain implementation prototype for the electronic open source traceability of wood along the whole supply chain. Sensors 2018, 18, 3133.

66. Broz, D.; Milanesi, G.; Rossit, D.A.; Rossit, D.G.; Tohmé, F. Forest management decision making based on a real options approach: An application to a case in northeastern Argentina. For. Stud. 2017, 67, 97–108.

67. Morten Komdeur, E.; Ingenbleek, P.T. The potential of blockchain technology in the procurement of sustainable timber products. Int. Wood Prod. J. 2021, 12, 249–257.

68. Vilkov, A.; Tian, G. Blockchain as a Solution to the Problem of Illegal Timber Trade between Russia and China: SWOT Analysis. Int. For. Rev. 2019, 21, 385–400.

69. Aalto, M.; Korpinen, O.J.; Ranta, T. Feedstock availability and moisture content data processing for multi-year simulation of forest biomass supply in energy production. Silva Fenn. 2019, 53, 10147.

70. Aalto, M.; Korpinen, O.J.; Ranta, T. Dynamic simulation of bioenergy facility locations with large geographical datasets—A case study in European region. Bull. Transilvania Univ. Brasov Ser. For. Wood Ind. Agric. Food Eng. 2017, 10, 1–10.

71. Kaakkurivaara, T.; Kaakkurivaara, N. Comparison of radio frequency identification tag housings in a tropical forestry work environment. Aust. Forest 2019, 82, 181–188.

72. Sundberg, P.; Hermansson, S.; Tullin, C.; Ohman, M. Traceability of bulk biomass: Application of radio frequency identification technology on a bulk pellet flow. Biomass Bioenergy 2018, 118,

149–153.