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Forest Supply Chains During Digitalization: Current Implementations and Prospects in Near Future

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Abstract

Purpose of Review The forest industry has deployed systems of information and communication technology to improve the productivity of forest supply chains. In this sense, the digitalization of data flows significantly impacts wood supply chains, from forest to mills, which must react flexibly to market fluctuations of forest products. The goal of this study was to conduct a literature review on data flow implementations in management systems of wood supply chains and to evaluate their applicability in supply chains to analyze the opportunities for improving them in practice.

Recent Findings We utilized the ScienceDirect database, Scopus, and Web of Science in order to document data flows in systems and actual applications. Due to ongoing outsourcing, the wood procurement chains and the wood supply chains were identified in the forest industry. In addition to industrial wood data, several different data collection technologies can be implemented in wood supply chains to digitalize the forest data depending on the specific needs of organizations. In this regard, the digitalization of big data causes significant changes in available data elements of practical operations that are integrated and standardized in the optimization and simulation systems.

Summary A modeling guide is suggested for accurate dynamic solution of problems of forest logistics. Then, the opportunities in digitalization for connecting different data flows, technologies, and stakeholders are discussed thoroughly. We conclude that data-driven dynamic optimization and locally implemented digitalization contribute to wood supply modeling in the ongoing establishment of standards for cloud-based platforms because modeling time-related and sequential measures will ensure successful forest logistics through planning and monitoring wood supply chains.

Keywords Data-driven optimization · Dynamics · Logistics · Simulation · Technology

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Abbreviations

ICT	Information and communication technology
ERP	Enterprise resource planning
WSC	Wood supply chain
WPC	Wood procurement chain
IMEI	Integrated material and energy industry
DSS	Decision support system
DDSE	Data-driven systems engineering
DDM	Data-driven model
GIS	Geographical information system
IT	Information technology
HPC	High-performance computing
LP	Linear programming
MOLP	Multiple objective linear programming
IoT	Internet of things
DP	Dynamic programming
DLP	Dynamic linear programming
GP	Goal programming
UAV	Unmanned aerial vehicle

API Application programming interfaces
AI Artificial intelligence
MODLP Multiple objective dynamic linear programming

Introduction

Various systems of information and communication technology (ICT) have been applied in the forestry and forest industry to improve the collection and analysis of data and management and monitoring of wood supply chains [1] providing products and services to consumers which are produced by forest-based industry. However, the forest-related supply chains remain at a rather general level without a focus on logistics or even wood procurement by the forest industry. Furthermore, the upstream logistics part of these supply chains is seen differently in various countries, partly based on historical reasons. In this regard, there are two generic types of forest supply chain management schemes related to the integrated material and energy industry (IMEI): wood supply chains (WSCs) and wood procurement chains (WPCs). WSCs are managed by decentralized enterprise resource planning (ERP) schemes, whereas WPCs are managed by more centralized schemes. In Finland, IMEIs managed all forest information by using the centralized ERP systems (i.e., as WPC) until the 2010s [2•], whereas in eastern EU countries, the WPC is still applied. Contrary, in Western EU countries, the WSCs have been introduced since the 2000s [3]. Finland provides a very good example as a basic reference with both supply schemes implemented to analyze changes in information systems triggered by digitalization. Furthermore, Finland appears even as an example for prospects because of current modern comprehensive data transmission networks are operating well also in forest operations far from urban areas.

Traditionally, the WPC scheme has been described by integrating data from forests' wood resources, which are related to monetary flows, wood flows, and information flows related to mills' wood demand [4•]. In addition, IMEI's ERP database systems collect information from wood purchasing, wood harvesting, wood storing, wood transportation, and mills' woodyard. Currently, in Finland, wood resources are mainly owned and managed (70% from forest growth) by private forest owners [5]. Furthermore, over 80% of wood purchased and used by the Finnish forest industry comes from these forests. The industry only owns 9% from forests, while in Sweden, it owns or manages over 50%. Therefore, wood purchasing is in IMEI's hands in Finland and has not been outsourced to WSC organizations. Recently, some subprocesses of the WSC like wood harvesting and transportation have been outsourced to suppliers [2•, 6] and therefore can be seen as WSC operations [3]. Under the WSC scheme, typically small and medium-sized enterprises collect and manage more supply chain information themselves than under the WPC scheme. This characterizes the recent outsourcing trend driven by the development to a WSC, which creates the need to integrate separated decentralized information systems of a WSC and to share digital data between the involved stakeholders [7•].

Digitalized data-driven modeling can improve information management and the performance of decision support systems (DSSs) in the WSC management scheme of the forest industry. In this study, this aspect will be highlighted from productivity simulations of single human–machine systems of wood harvesting to management optimizations of whole WSCs from forest to the IMEI. Data-driven systems engineering (DDSE) is seen as a key enabler for such complex DSSs. It provides suitable data to different mathematical optimization models and simulation models that are used to solve WSC management problems to assess the impacts of ecological, economic, environmental, and social changes (cf. e.g. [8••, 9]). Systems' structures differ widely from useful deterministic systems to complex stochastic systems [10]. Despite the technical differences between WSC management systems, there are common methodological problems related to data application. In this paper, actual deficits are considered in data, models, and solution methods, and how the DDSE may contribute description of them toward better WSC's management systems in the IMEI.

The organizations of IMEI should use theoretically sound dynamic models in their DSSs for an effective management of the WPC and WSC [4•]. Initially, a system based on the pull principle of wood demand of the IMEI can be formulated as a dynamic model that converts inputs to outputs. There are two types of inputs in its dynamics: stages (phases) and states. Stages describe functions of a WPC model, which are so-called logistics activities (e.g., harvesting, transportation), whereas states are stocks created by stages at a single moment in time (e.g., amounts of wood storages). Stocks and flows must be synchronized regarding each other at all time moments through the entire WSC or WPC periods under consideration. Deficiencies may be present both in model components (stages, states) and in the model structure itself, which affect the system's output. Furthermore, if understanding or accurate data is missing about the magnitude of the deficiencies, there are also systematic inaccuracies. Unfortunately, not many modeling studies include a comprehensive analysis of inaccuracies, possibly because most operations research methods of WSCs have not been standardized in respect to data used [11].

During the last 10 years, there has been a trend in operations research to base constraints of dynamics on a data-driven theory [7•]. This approach is taken in this study for consideration by combining it with WSC modeling. We aim to show that defining the dynamics of WSC with data-driven model components reduces inaccuracies when new data becomes available for solving the model. The data-driven approach is known in the literature by many different names: system identification, statistical identification, direct controller identification, or iterative feedback tuning. While the different names refer to different applications of data-driven modeling, all share the idea of specifying time-varying parameters which are modified for models of DSS according to the rules of data-driven theory. This idea also may facilitate the comprehensive analysis of inaccuracies.

The modeling guide presented in this paper can be applied to any kind of WSC modeling and problem solving, simple or complex, static or dynamic, site-based or area-based, deterministic or stochastic. Scholtz et al. introduce several review papers of WSCs covering the use of various operations research (OR) methods: (e.g., [12, 13]), and more widely to use of biomass-based supply chains: (e.g., [14–17]). Furthermore, examples will be taken from the literature on deterministic data-driven models (DDM) of the WSCs in the IMEI that can be used for improving the decision support needed by IMEI [18]. These models also belong to a class of dynamic models that simulate or optimize WSCs in the DSS [7•, 19]. Large DDMs tend to include a lot of activities and constraints and are therefore computationally demanding. We explain how model characteristics may cause problems in the application of the DDM in current dynamic multi-criteria analyses of WSC managers and which modeling approaches have been proposed so far.

The structure of the paper is as follows. The paper begins by defining key terms that will be used in the review, including "dynamics" and "time-varying parameters," and digital ERP concepts that are used in data descriptions of DDMs. Then, the data-driven approach is described for modeling time-varying parameters, and the most common computational restrictions are explained in solution methods. After that, inaccuracies of model structure are declared, and different ways of avoiding these issues are proposed. The paper finishes with a general discussion on future digital ERP solutions and prospects for data-driven modeling. In this last phase, the importance of DDSE and DDM are emphasized in ERPs and cloud-based platforms available in group decision-making of WSCs.

Terminology and Concepts

Over the last decade, digitalization has produced larger, more complex datasets, especially for ERP data sources. This data has been characterized by big amount, variety, and velocity [20]. Under the big data concept, such large datasets cannot be analyzed sufficiently by statistical data processing applications [21]. For example, when a single wood-harvesting machine processes trees at two shifts during a day, it produces a record of over a million single rows in a database. This data characterizes the work of a single machine and two operators in a human–machine system [22, 23]. Such a dataset constitutes a typical data-mining problem, which is solved by transforming it into useful smaller files or databases. In the data-mining process, it is necessary to use the DDSE and the DDMs to find separate patterns or/and groups within big data [21]. The refined data can then be analyzed, e.g., by statistical methods for producing meaningful information for work studies, which may be used in turn as initial data in simulation models of WSCs.

GIS data is important for modeling the WSC operations and providing sufficient information for digital wood trade (selling and purchasing). There is a need to describe the operational environment as realistically as possible using sufficient digital abstraction which can refer to both the spatial precision of the geographical information system (GIS) data and the operations included in the WSC or WPC. Different planning needs (strategic, tactical, operative) also affect abstraction needs. For example, the locations of planned activities of IMEI, which are determined by the positions of the mills, terminals, and transportation routes, are used in strategic planning, while the list should be extended by the locations of roadside storages in tactical planning and by the locations of machines and vehicles in operative planning [24••]. Because the forest industries optimize their production by obtaining timber assortments that best fit their feedstock needs [25], timber buyers of WPC organizations acquiring roundwood can make better pricing decisions if they have detailed spatially collected pre-harvest information [26]. Furthermore, WSC organizations use GIS-based wood transportation planning systems in daily work. In these models, both raster data (also referred as "grid-based data") and vector data ("line-based data") can be used [27].

Big data has come to prominence within WPC management of IMEI as ERPs support organizations for WSC management more efficiently than common management systems. Especially big data analytics streamlines the collection and distribution of digital data by using information technology (IT) [28••]. In this paper, the use of big data analytics to resolve data collection issues within organizations is called information technology operations analytics (ITOA). On the other hand, operational data analytics (ODA) as defined by [29] relates to the studies with high-performance computing (HPC) which increases operational efficiency. ITOA supports IT and the management of outsourced operations by applying big data analytics to large datasets inside the scope of simulation and optimization. In addition, ITOA may offer a platform for operations management that brings separate data of the WSC operations together and enables to gain business insights in the entire dynamic system rather than from analysis of partial data. At the same time, this provides a possible approach or method for automation to retrieve, analyze, and report data for the planning of WSC operations so that regional organizations can easily optimize local WSC problems [30•]. When ITOA technologies are integrated in WSC, they might either increase revenue or reduce costs depending on selected criteria [31].

System dynamics provides a method for modeling and analyzing the behavior of a time-dependent system consisting of moving stages of a system. WPC and WSC schemes are typical examples of such systems (Fig. 1). Ideally, systems' states move from the current to the next states according to the dynamic method [32]. In addition to time-related dynamics, the dynamics of the WSCs also consist of simultaneous sequential dynamics, which are described by flow and effect arrows in Fig. 1 for WPC operations [33]. Operations analysis of WPCs can be implemented by using mathematical optimization with linear programming (LP) as the most useful method. Numerous more sophisticated methods have also been suggested by researchers [34, 35•], but they are not so commonly used in DSSs of WPCs in practice. When ITOA is used for providing initial data (e.g., time-varying parameters of cost or spatial data) for LP, optimization may follow the principle of data-driven modeling of the WPC. It is an innovative technique to adjust rather general LP models to solve local WPC situations [36]. In cases of outsourced wood supply, data-driven modeling with optimization may also serve as an efficient technique to offer the necessary ERP or DSS to the WSC management. Another approach uses simulation in WSC management, which produces a partial analysis of the WPC problem with a restricted number of WSCs, time-related elements, and selected sequential operations.

Data-Driven Approach for Modeling WSC in WPC Network

Data-driven operation analyses with aggregated data from different wood sources of the WPC can provide IMEI valuable insights to derive comprehensive strategies for their logistics network. The analyses can also be used to resolve operative effects of WSC-related issues in sensitivity analyses of the network. In this work, predictive analytics accurately predict future strategic trends, forecast inventory levels, and manage available resources (cf. [35•]). Prescriptive analytics also answers "what-if" questions supporting tactical and strategic decision-making for WSC management in practice. Previous studies already showed that with more accurate data in hand, analytical scenarios can be solved by optimization, which is more useful in strategic planning for the WPC network [30•]. In their work, a five-step analytics procedure with data-driven modeling was introduced for optimization of the WPC network:

- o Step 1: Alternative WPC strategies.
- o Step 2: Identify key WPC issues.
- o Step 3: Data targeting to the issues.
- o Step 4: Analyzing data for data-driven modeling.
- o Step 5: Strategic insight turning into WSC action via optimization.

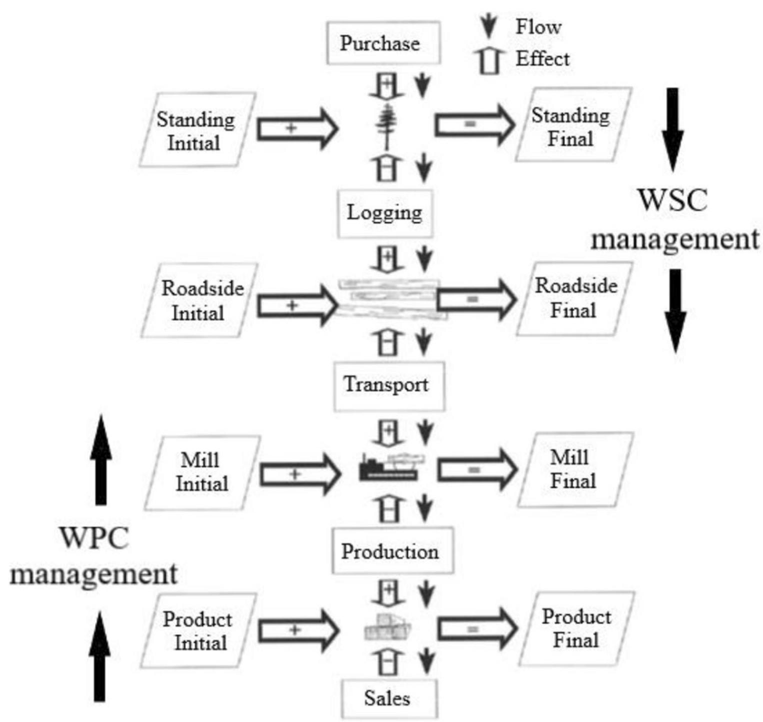


Fig. 1 Basic principles of wood material management in dynamics of WPC (pull) and WSC (push). Character "+" means wood offering and "−" wood demand in separate functions of wood flow

When organizations are looking for new ways to optimize WSCs, they incorporate ITOA of ERP data or the Internet of things (IoT) or edge computing into Step 4 (Analyzing data for data-driven modeling), which supports organizations to gain in-depth insight into complex WSCs. In this respect, the amount of digital unstructured data is even greater, which makes data more complex and difficult for organizations to manage and analyze with ordinary tools. Data-driven optimization was developed for this purpose. It is defined as a systematic process that gathers ITOA outcome-based assessment data (for example, data derived from results of statistics analysis) and merges this data, e.g., with trend, forecast, or capacity data. Somehow, all this data must be incorporated systematically into a DDM before solving the optimization problem, e.g., as time-varying parameters or constraints.

A study of NewVantage Partners [37] recently reported that organizations have invested a lot to modernize their business, but 70% of these initiatives have failed because they prioritized technology investments without building a data-driven culture to support it. It seems that organizations aspire actively to a data-driven culture, while only a third of them were successful. In pursuit of developing data-driven modeling, many WPC organizations are developing two capabilities, data proficiency, and analytics agility. However, transforming the way in which an organization undertakes planning and decisions is a challenging task. Palander et al. [38] described a group decision-making method that is used in WPC organizations. Incorporating current digital big data and its analytics into group decision-making methods and ERP could provide a promising approach. This level of transformation requires a dedicated approach to refine DDMs of the WSC for a cloud-based platform, which would have a considerably transformative impact on both WPC and WSC organizations.

Suggestions have been made about cloud-based platforms [39] and data-reducing tools of the forest machine [40]. Environmental issues have increased the data needs of forestry, which have been collected by forest machines in preliminary studies. Organizations of forestry and forest industry have realized that the data, which is valuable and important for the data owner, can be more valuable, if it is shared and some other data obtained as an exchange. However, the accumulation of data in wood-harvesting processes is overwhelming and will create a group of challenges for data users. Computing power of harvesters and opportunities of edge computing of ITOA may provide a solution to this issue. In Finland, due to good infrastructure and relatively short distances, mobile communication can already be used to advance data-driven solutions. However, the preliminary processing of the data in machines or in “edges of the clouds” may be needed to “optimize” the amount of data to be transferred for further processing. In addition, this requires standardization of transfer procedures like it has already been made in timber harvesting in Nordic Countries.

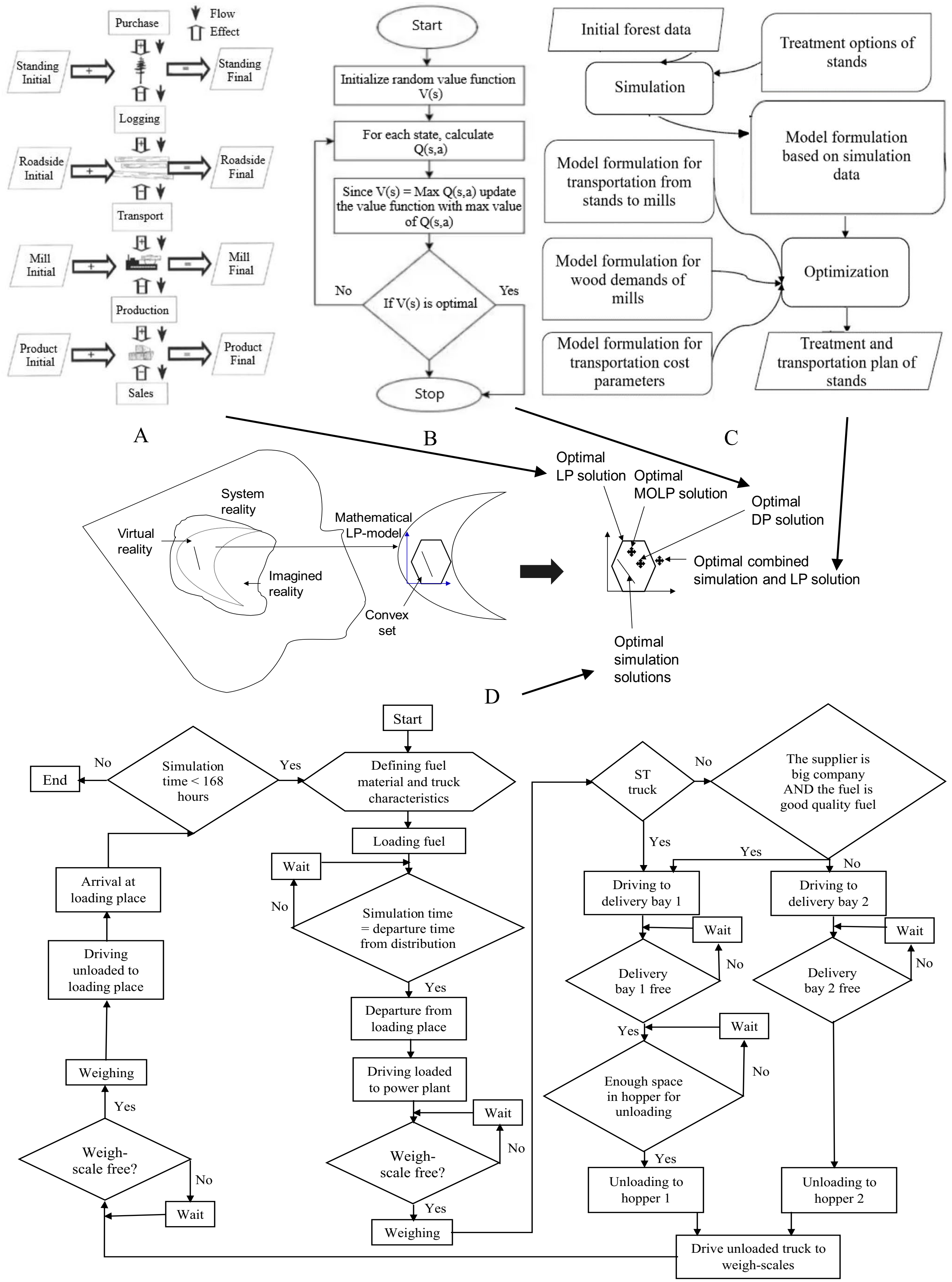
Inaccuracies in Model Structure

Digital Data Issues

Regarding data management, a model can be designed for centralized WPC management, or for a more decentralized WSC management applied to outsourced wood procurement. Models can also be designed separately for all management levels of forestry and industry, i.e., normative, strategic, tactical, and operative planning. Furthermore, the fundamental issue before selecting a modeling approach is to hold a suitable and an available solution methodology. Different models must be designed for different solution methods, which also may use different data analytics. In respect to the data issue, we compare five models with each other and analyze their suitability for decentralized WSC management in wood procurement organizations of forest industry. Four of them (A, B, C, and D) are described as flowcharts in Fig. 2. Two models (models D and E) are both solved by using the Witness simulation program [41, 42]. Therefore, the flowchart of the model E is presented in a supplementary file. For IMEI organizations developing automatized digital ways to find solutions to their WPC networks, incorporating ITOA of unstructured data into ERPs supports them in modeling and therefore gaining better models on the WSCs.

Model A uses LP as a solution method solving a dynamic linear model of the industrial WPC reality. The solution of the model is the global optimal solution that provides the benchmark for the convex set of acceptable solutions (Fig. 2). The model can be used for the formulation of large wood flow models as networks for centralized and decentralized decision-making at tactical or strategic level in wood procurement organizations [4•]. In addition to timely dynamics, this model structure includes sequential dynamics of the entire wood flow from forest to production, as main characteristics in WPC optimization. Moreover, LP can be used to solve multiple objective linear programming (MOLP) models [8••]. Parts of the general models can also be used for the formulation of WSC problems. Organizations may automatize data collection before modeling for tactical analysis of their WPC networks as well as for gaining in-depth local results of models of the WSC.

Model B uses dynamic programming (DP) as a solution method [32]. Compared to the convex set of model A, the optimal solution of model B is inside the convex set of acceptable solutions (Fig. 2). The chart describes Bellman’s general DP model that can be reformulated for analysis of mechanized cut-to-length harvesting issues in reducing WPC costs of sawn timber (e.g., [43, 44]). In addition to



Flow
Effect
Purchase
Standing Initial
Standing Final
Logging
Roadside Initial
Roadside Final
Transport
Mill Initial
Mill Final
Production
Product Initial
Product Final
Sales
A
Start
Initialize random value function V(s)
For each state, calculate Q(s,a)
Since V(s) = Max Q(s,a) update the value function with max value of Q(s,a)
If V(s) is optimal
No
Yes
Stop
B
Initial forest data
Treatment options of stands
Simulation
Model formulation based on simulation data
Model formulation for transportation from stands to mills
Model formulation for wood demands of mills
Model formulation for transportation cost parameters
Optimization
Treatment and transportation plan of stands
C
System reality
Virtual reality
Imagined reality
Mathematical LP-model
Convex set
Optimal LP solution
Optimal MOLP solution
Optimal DP solution
Optimal combined simulation and LP solution
Optimal simulation solutions
D
Start
Defining fuel material and truck characteristics
Loading fuel
Wait
No
Simulation time = departure time from distribution
Yes
Departure from loading place
Driving loaded to power plant
Wait
Weigh-scale free?
No
Yes
Weighing
Simulation time < 168 hours
Yes
No
End
Arrival at loading place
Driving unloaded to loading place
Weighing
Yes
Weigh-scale free?
No
Wait
ST truck
No
The supplier is big company AND the fuel is good quality fuel
Yes
Yes
No
Driving to delivery bay 1
Driving to delivery bay 2
Wait
Delivery bay 1 free
No
Wait
Delivery bay 2 free
No
Yes
Wait
Enough space in hopper for unloading
No
Yes
Unloading to hopper 1
Unloading to hopper 2
Drive unloaded truck to weigh-scales

◂**Fig. 2** Flowcharts of WSC models and their methodological effects on optimal solution. **A** LP model of industrial wood procurement, **B** general DP model, **C** simulation LP model of Finnish forest resources, **D** discrete simulation model of industrial roundwood supply chains. MOLP, multiple objective LP

this well-known use of DP in forest harvesters for tree's cutting to logs [45], the DP model can be useful in the current practice of the WSC in Finland because timber harvesting and transportation have been outsourced to entrepreneurs by wood procurement organizations of IMEI [2•, 46]. However, the WSC model of DP misses the sequential dynamics of the entire wood flow network that is the main cornerstone in WPC optimization [4•]. This is caused by the slowness of the solution of the DP model, which takes a lot of computational time. Therefore, applications of DP are useful for ERPs in solving operational problems of WSCs.

Model C is based on a solution method combining simulation and optimization. The initial input data of the model is collected from different data sources, which are handled by data analytics tools and restored in a database system. After data processing, part of the data elements is put into the simulation system that produces output data which is later used as input of the optimization model. Another part of the processed initial data goes directly to the optimization model. The example joins up the optimization of WSCs with regional forest resource management units [47, 48] as a case study of North Karelia in Finland [49]. The treatment schedule of forest stands of this region provides potential stands for wood harvesting from which some stands are picked by using a transport optimization to fulfill a given delivery schedule to mills. Consequently, this model's structure misses the entire sequential dynamics of WSCs (transportation is included as only one stage) that is important both in WSC and WPC optimizations. From the point of view of wood procurement in the forest industry, this model can be used to solve operational WPC or WSC problems [4•] which also provides long-term forestry information that forest owners can use for strategic purposes.

Model D uses discrete simulation as a solution method and can be used for analysis of the impact of transport fleet size, harvesting site reserve, and timing of machine relocations on performance indicators of mechanized cut-to-length harvesting in Finland [41]. Another example (Model E) simulates skyline systems in Norwegian conditions, which is a good example about synchronizing of logging and transportation operations [42]. The main simulation program solves queuing problems between both operations. Both models miss sequential dynamics of the WPC network which is the main characteristic in WPC and WSC optimization. Therefore, without structural extensions, this model structure can be used to solve the operational WSC problems. Likely, the extensions would cause the complexity of the model formulation and the slowness of the simulation solution, which takes a lot of resources and computational time.

Risk Management of Transportation Simulation in WSCs

Literature reviews on the usage of simulation and/or optimization concentrate on optimizing wood transport [50], forest biomass supply chains [51••], transport logistics in Nordic countries [52], and unimodal and multimodal wood transport including terminal logistics [53, 54]. Depending on the planning level(s), most models include more or less aggregated data about supply and demand points, transport tasks, travel distances, and travel times as well as on transportation mode-specific parameters (e.g., payload, legal working hours). Decisions on transport plans mainly omit stochastic elements leading in the real world to short-term prioritization or stopping of transport tasks. On the contrary, wood supply managers factor the actual weather situation and its effects on wood harvest and road availability in the operational planning for next week(s) transportation jobs.

Models handle enormous quantity of data, especially on the operational level (cf. [12]), but the lack of quality data is one of the biggest limitations for operational modeling of supply chains, specifically in countries with less forest area applicable to fully mechanized harvesting systems [55] or in countries where modern mechanized harvesting systems are not available. Especially available data on transport mainly lacks coverage of local weather as a stochastic element and models to forecast short-term driven weather effects on transportation on forest roads or on weather-dependent wood quality development [35•] are still rare or insufficiently accurate. Therefore, WSC modelers must reduce the complexity of the real-world wood supply situation tending to focus on broadly available data and to underestimate factors not covered by primary data.

Applying various alternatives with changing parameter combinations to cover uncertainties (e.g., about processing times, demand and supply fluctuations) or to include some stochastic events triggering disturbances to the WSC (e.g., unplanned machine breakdowns, worker strikes) are commonly used techniques to gain more robust results (what-if simulation). Furthermore, picking stochastic parameter values from probability distributions and calculating a larger number of simulations runs as done in Monte Carlo simulations (e.g. [10]) or District Event Simulation (cf. [56]) is a way to handle data quality issues, to capture supply chain dynamics and include unexpected events in order to quantify their potential impact [57]. However, the question of necessity for short-term modeling arises in practice. So far, accurate data has caused the slowness of the solution, which is so expensive that it is more efficient to decide daily WSC transportation schedule by the managers of transportation organizations. In addition, the simulation model still misses the sequential dynamics of the entire wood flow network [17], which would also take a lot of computational time.

Partial Optimization of WSC Network Models

Sometimes, the WSC optimization problem may be regarded as a semi-structured management process, although Fig. 2 shows that LP can provide a global solution. Traditional shortcomings are data disruptions in databases and therefore unmanaged separate WSCs in relation to the entire logistics network. In general, well-structured information systems can help organizations to manage WSCs but can never replace human involvement in the management process. On the other hand, combined optimization of WSCs with forest management illustrates well partial optimization [49]. Initial data-driven systems produce and mine each treatment schedule of forest management providing unique estimates of extracted wood volumes by different assortment categories for each period. However, the transportation formulation of this WSC model produces a partial model of the logistics network, only dynamic in respect to either sequential or timely formulation of operations because transportation should be connected to all other WSC operations. Formulation and coding of comprehensive dynamic models for wood procurement of IMEI including all network operations seem to be difficult and laborious [4•].

Most WSC models have an inherent dynamic goal conflict as something that is minimized (e.g., cost) or maximized (e.g., revenue) is most often done for one and not for all stakeholders of the whole chain, and even if the costs or revenues could be optimized there are different shares of savings or profit growth between WSC stakeholders during the planning horizon [58]. Further, optimizing is most often done either from the sight of the wood-buying organizations or wood harvesting and transport organizations. However, WSC optimization also differs a lot if it would be done either for forest harvesting or for transport organizations. A recent study reported that if forestry, transport, and industry optimize (e.g., using MOLP) operations at equal rights by collaboration, it provided the most efficiency to a WSC [54]. However, if one partner optimized the WSC in its specific favor, the total costs increased considerably. Furthermore, by considering simulation as an approach to the same problem, the solution becomes technically impossible at equal weights of parameters distributed between WSC stakeholders.

Nearly, all WSC optimizations (and simulation models) neglect the simple fact that wood quality parameters (e.g., freshness, coloration) change with time and in most cases result in considerable loss of value, especially in the case of sawlogs. On the other hand, there can also be benefits from log drying in the logistics network, which can be considered together with the losses by using time-varying parameters in optimization models [59]. Furthermore, according to dimension and quality parameters (e.g., knottiness, discoloration), freshly harvested wood logs qualify as sawlogs, pulp logs, or energy wood, but quality can deteriorate during lead time (e.g., by blue stain infection or bark beetle infestation) according to weather. Controlling saw wood quality changes from the date of harvesting and integrating weather-based quality forecasts in the transport allocation decisions (e.g., by prioritizing picking-up of sawlogs facing downgrading within the next two weeks) significantly reduces the amount of downgraded wood and value losses based on the case study in Austria by 57% and 42%, respectively [35•].

Reducing Inaccuracies in Dynamics by Right Model

Theoretically, sound dynamic models of DSSs support effective management of the WPC [4•], but before modeling, solution method should be selected suitable for different WSC problems. The methodology determines the model structure and reduces solution inaccuracy. Figure 3 presents a modeling guide for data-driven decision-making problems for the management of WSCs and WPCs. The guide utilizes the ERP system which includes a database for the needed information, which is collected about dynamics, number of criteria, and number of decision variables, which also may affect later data analytics. Figure 3 gives examples for deterministic DDMs of the WSCs in the IMEI. These methods and models simulate or optimize WSCs in the ERP or DSS. If only one criterion and few decision variables are in the decision base, an ordinary calculus system may provide an accurate solution. If one criterion and more than four decision variables are in the decision space, which needs both elements of dynamics for deriving a solution, a dynamic linear programming (DLP) model provides the most accurate solution. If multiple criteria are involved in the decision problem, either goal programming (GP), multiple objective linear programming (MOLP), or some heuristics solutions can be used in the application, which improve the decision support needed by the IMEI [8••]. However, heuristics solutions are out of any standardization aims in general.

In Finland, WSC's wood resources are initially and usually managed by buyers of forest industry organizations. To optimize the WSC, operations analysts need to remember that wood sellers usually contact several buyers. In addition, they may sell several times parts of their wood resource stock or sell all wood instantly. Their decisions also depend on the service WPC and WSC organizations offer. This means that there is a two-tier system for inputs and outputs in the digital marketplace (before and after buying), and organizations need to manage the situation on both side parameters and constraints in the planning model. That is because any cost wood suppliers save in selling wood materials to the buying organization will ultimately support the

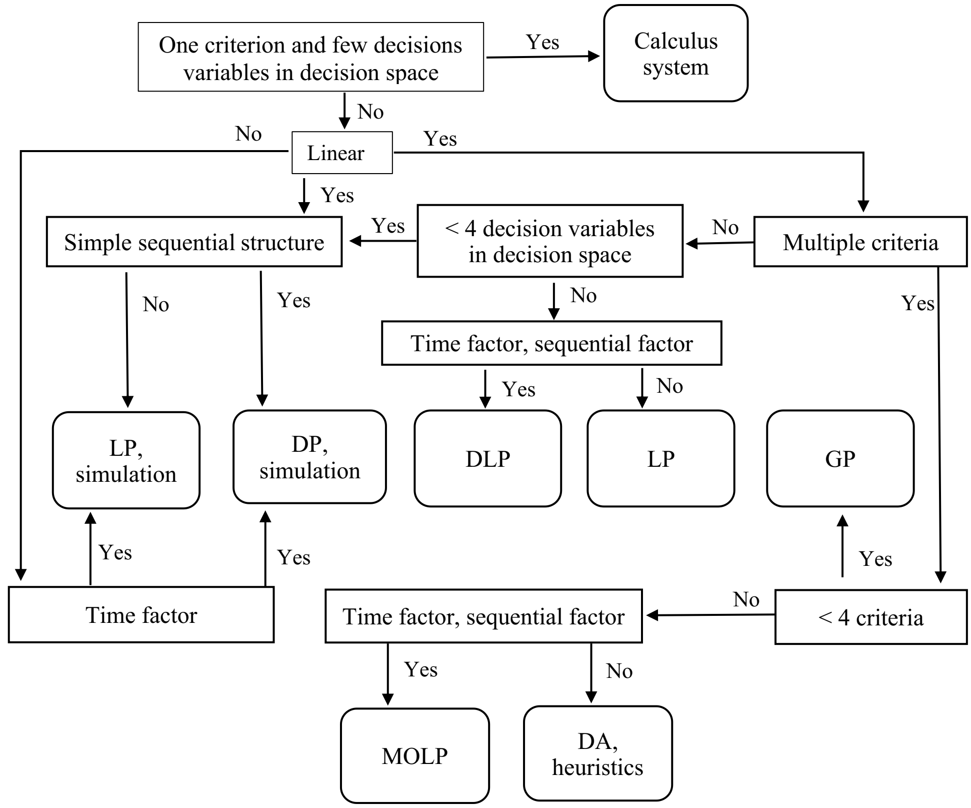


Fig. 3 Modeling guide for data-driven decision-making problems in WSCs and WPCs

organization's purchasing work in the future. Other Nordic countries as well as countries with a high proportion of buying contracts of standing timber (or better wood stock sales) face rather similar preconditions, whereas elsewhere in relation to specific terrain or wood supply market conditions, or particularly with regard to available harvesting systems before buying phase, a significant lack of digital data hinders the application of simulation/optimization.

Currently, suppliers' wood inventory is managed by WPC organizations by using strategic and tactical DSSs, while management of daily operations is controlled by outsourced WSC organizations which use operational DSSs (WoodForce, LogForce) [2•]. DSSs of the WPC organizations use a supply chain network optimization model (e.g., DLP) to balance the mills' demand with the supplier's inventory. If the supplier's inventory exceeds actual demand, storage time and potential quality losses increase. On the contrary, if there is not enough inventory for production, losses in sales and revenue occur because customer orders cannot be fulfilled in time. So, it is important to maintain an accurate balance of inventory that must be managed through DLP-specific DSSs and cloud-based ERP. In Eastern EU countries, this inventory optimization system could be applied in WPC management because the centralized ERP systems (i.e., WPC systems) are still used. For Western EU countries, Finland could provide an example for prospects about current modern comprehensive data transmission networks of WSCs which is operating well also in forest operations far from urban areas.

From the perspective of WPC, cost management is a significant issue as the cost of WSC operations is a huge factor in revenue, especially if product prices are lower in fast fluctuations. Therefore, conducting cost and benefit analysis with WSC suppliers to balance quality and affordable logistics rates is crucial. As an example, organizations may consider using third-party logistics and railway transport to optimize outsourced timber transportation, especially in decentralized wood procurement conditions with long transport distances. The ERP should include modeling parameters for this analysis if the databases are structured well for solution models. Therefore, successful modeling of WSC and effective use of DDMs relies on adequate in-house resources such as trained staff, up-to-date ICT systems, and technologies.

Accuracy of Spatial Data in GIS for WSC Modeling

Geospatial properties and quality have been discussed on many occasions. The spatial data used in digital WSC systems usually have many sources, and the datasets have varying spatial extents and resolutions. Spatial data should be as accurate and correct as possible to ensure the right solutions in optimization processes. There are many practical limitations when the digital data source is selected to be the basis for an operational planning system [24••]:

- A dataset fulfilling the requirements is not available or is too expensive,
- Collecting the required data independently is too laborious or expensive,
- Data processing capacity is insufficient with regard to the high spatial resolution, or
- The importance of spatial information is low in relation to the needs.

Still, there is the need to describe operational planning environment as realistic as possible using sufficient digital abstraction for modeling of real-life objects and events. In addition to the spatial precision of the GIS data, abstraction can refer to an operation included in the WSCs. For example, digital marketplaces (e.g., www.kuutio.fi) facilitate wood trading by providing a virtual place where wood supply and demand can meet. Temporal variations in WSCs and wood demand of IMEI will probably increase in the future, and details in abstractions require dynamic elements. When operations progress in the WSC process, time is also spent. Single trees are understood as an example of the lowest level of abstraction (Fig. 4). In wood-harvesting operation, the abstraction presented here would obviously necessitate the inclusion of wood-forwarding tracks in the transport network of forest stands, and data of this kind are not yet publicly available. Instead, it is convenient to use roadside storage locations as the starting points for WSCs, or, if the locations are unknown, to choose a spatial precision that corresponds sufficiently well to the distributions of roadside storage sites in the real world [24••].

Both vector and raster data can be used to model the transportation network in GIS, since transport distances, times, and costs can also be assessed using raster data and raster calculation tools, but it can be difficult to account for dense network areas, if a too small scale (i.e., a coarse grid) is used [60]. Also, the modeling of complex road objects will obviously be more straightforward in a vector-based system than in a set of raster layers. Raster data models are typically used in strategic analyses of the static "cost-path" type [61, 62••], while vector data are preferred for dynamic systems that call for complex connectivity and shared attributes between spatial objects [60]. Sufficient road network data is available nowadays in vector format (e.g., OpenStreetMap 2021), even free of charge [63].

Detailed tree data, including tree lists, have been collected using field measurements or airborne LiDAR. Digitalization of forest information services has opened new opportunities during the last decade, and wood procurement planning and the purchasing of timber can be expected to be conducted more in a digitalized environment in the future, without necessarily visiting all the potential stands. The multi-source National Forest Inventory database has been generated by combining field measurement-based National Forest Inventory data with data from satellite images and estimating given forest and forestland attributes in a continuous raster layer covering the entire country [64]. The resolution of the raster grid is 16 m, and a new version is published every second year. The reliability of species-specific attributes is rather poor in satellite-based map products [65]. Another important provider of public forest data is the Finnish Forest Centre, which provide GIS data on forest resources in a raster format (16 m) and as vector polygons representing either forest stands (principally in private forests) or planned cutting areas [66]. Finnish Forest Centre products are based on LiDAR data and aerial images, which are interpreted and processed to final datasets with support from field assessments. The resulting polygons contain detailed attributes describing the growing stock (tree list estimates). A canopy height model is also available as raster data with a 1-m resolution for further single-tree map products. The southern part of the country is covered every 6 years.

The road network is the most important digital data in forest logistics in Finland, as most WSCs are based on truck

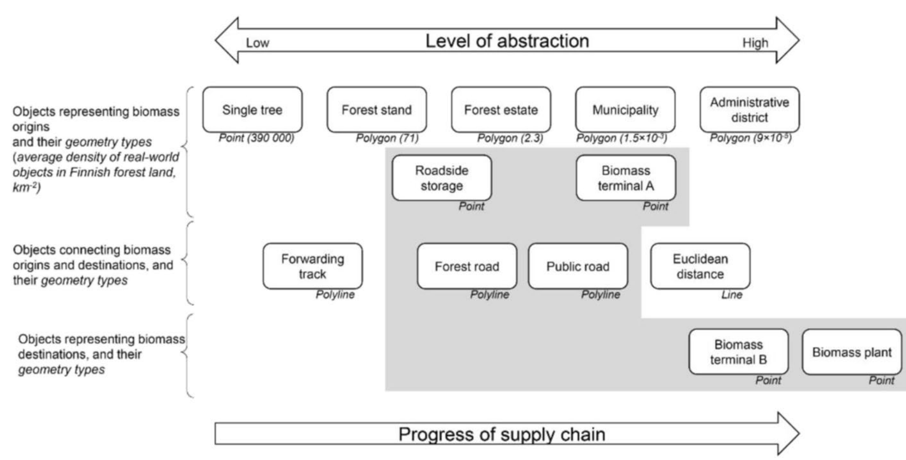


Fig. 4 An example of the abstraction possibilities in a GIS model that represents a WSC [24••]

transportation [67]. Forest road construction and maintenance are responsible for forest owners who manage private forest roads together by road associations. The National GIS database contains vector data on all roads and streets which is available free of charge [68]. Its spatial precision is high, and the geometry and attributes of the public roads and streets are checked and updated regularly. Attribute data concerning private forest roads (e.g., width, surface, obstacles, and turning points) are seldom provided at present, although improvements in this respect are currently under way [69]. As far as other transportation modes, vector lines of railways and fairways of maritime transport are also available as public data [70]. Only a small proportion of users utilize OpenStreetMap data for transportation network modeling [60], and the quality of this volunteered geographical information is not always as high as the quality of the data from national mapping agencies.

The quality of forest roads is not described in traditional national free databases. Especially in countries with huge areas of forest, manual road quality checkups are laborious and expensive to carry out regularly, but quality parameters are essential for optimizing and simulation models of WSC management. Low- and high-pulse-density LiDAR-derived data can be used here to determine various quality features of unpaved forest roads [71•]. These products can be used to classify roads in terms of various quality parameters and identify poor-quality roads—the ones that will need maintenance the most in the coming year—with a reduced need for field visits. Also, tests have been carried out to identify rut depths using unmanned aerial vehicle (UAV) photogrammetry [72] and mobile laser scanning, including both car and UAV-mounted sensors [73]. Collecting road data by crowdsourcing truck drivers' mobile phones, for example, is in the pilot phase in Finland as a means of automating and collecting road data more efficiently [69, 74, 75], and this could well reduce the need for separate road quality inventory visits and thereby save time, money, and resources.

Discussion

Prospects in the Near Future

During the past years, ICT companies have developed modern business systems, cloud, and information security solutions for WSC practice with data analytics (cf. [76–78]). In addition, WPC organizations of IMEI have been investing in data-driven business development in order to provide their collaborators with more comprehensive data-driven DSS to support forest logistics by, e.g., mutual developed digital solutions for collaborative operational management of wood harvesting and transport (WoodForce, LogForce) [2•]. However, for improving logistics, as part of the WPC's local digital development, WSC organizations (harvesting and transport organizations) are supported with ERP solutions based on standard platforms. In the future, to replace current ERP systems, IMEI needs tools to better synchronize outsourced dynamic processes of WSCs. For example, wood supply chain collaborators should have easy access to the log data of forest machines to monitor timber harvesting and transport progress in real time. In this regard, organizations of IMEI will aim to be the best digital solution provider to offer useful collaborator experience, not only by procuring wood but also by providing digital solutions for logistics systems. To achieve this, some of the identified challenges to overcome are as follows:

- Plenty of manual work in different ERP systems,
- Scattered data in separated parts of WSC and not easily available for analysis and actions,
- Lack of resources for the development of WSC and its DDMs of DSS in ERP systems,
- Old and rigid standards, codes, and network platforms.

To improve digital services, provided to WSC organizations, WPC's ERP should also handle separate logistics processes for supporting external stakeholders such as harvesting and transportation companies and forest owners through application programming interfaces (API). Additionally, modeling requirements for real-time data export to standard platforms (e.g., to Microsoft Azure Data Platform) should be fulfilled, to easily enable reporting, analytics, and digital applications powered by cloud computing (e.g., Microsoft Azure). Recently, a forest machine producer selected Annata 365 as their ERP that has been designed originally for the manufacturing and distribution industry of vehicles and heavy machinery. Applying standard platforms and software packages ensures that the platform is continuously being developed and there are also plenty of global commercial partners as well as a large developer community for dialogue and innovative development.

The digital API ERP solution can be efficiently used for the implementation of several DSS types in WPC organization. It can be used for wood harvesting and transport management, wood purchasing, sales of harvested wood, deliveries to terminals and mills, monitoring and control of operative work, invoicing, reporting, etc. Currently, the API ERP solution is already used in the wood-purchasing process, because forest owners as wood sellers regularly need aftersales services. With the API solution, WSC organizations also attain better transparency throughout the entire WSC, reducing manual work and utilizing local data on WSC operations. The main results achieved include among others:

- Faster collaboration through better access to standardized data,
- Local data is easier to use than before,
- Many of the manual tasks have been automated,
- User experience has been improved through user-friendly solutions,
- Communication is more efficient by mobile tools,
- International standardized data format is comparable for additional analysis.

With the above-described digital WSC management solution, the entire life cycle of the WSC process is managed on one unified digital platform. For example, if the API ERP is based on the Dynamics 365 environment, WSC operations may contain a serial number throughout the WSC's life cycle enabling a structured process for tracking. ERP solutions have already been successfully implemented at global stakeholders and collaborators because standards ensure that platform functions can be used on any mobile tool and device making the daily work of the WSC collaborators more efficient and easier. ERP solutions enable continuous development and provide better transparency of WSC operations, so collaborators can be served even better in the future.

There have been literature reviews on digitization which aim to identify challenges and opportunities of Industry 4.0 in the forest supply chain [79, 80]. It is good to remind that WSC is the upstream part of these supply chains, while Industry 4.0 focuses on the middle or downstream parts of the forest supply chain. According to definitions, Industry 4.0 is the current trend of automation and data exchange in the integration of digital technologies into manufacturing and industrial processes. It encompasses a set of technologies that include big data, industrial IoT networks, artificial intelligence (AI), and robotics. However, WSC delivers only raw material to the forest industry satisfying dynamic demands of production. Therefore, there would be a need for decision support by Industry 4.0, which develops quality and logistics issues of WSC for faster and more accurate. So far, big data and IoT are used in digital platforms of WPC by API ERP, but only minor improvements have been reached by AI and robotics, which have increased productivity of production remarkably as the elements of Industry 4.0. On the other hand, AI and robotics are applied effectively in digital platforms of WSC both in forest harvesters and trucks. For example, the automatic optimization of tree's log bucking and the intelligent boom control 3.0 have been used in harvesters as operator assistance technology, which have made forest work more productive and cost-efficient [81]. Furthermore, these machines produce standard data which could be at more open use in DDMs and DSSs of collaborators in the WSC network, which would increase remarkably efficiency of forest logistics and the profitability of the forest industry.

Cloud Platform–Based ERP and DDM for Collaboration and Group Decision-Making of WSC

Since various collaborators are responsible for the activities in the WSC, dynamic interdependencies between different operations may result in inefficient WSCs due to several, partly conflicting objectives. Collaboration between stakeholders will provide opportunities to improve WSC efficiency, but they can hardly be realized without MOLP models for sharing objectives and/or resources. Formulation of the MOLP model requires a seamless data flow to foster collaboration in the WSC.

From this literature review, the authors have identified a variety of optimization models concerning the planning in WSCs. However, ordinary optimization alone may not sufficiently support collaboration between the stakeholders in the WSC. In addition to using standard single-criterion models or MOLP, multiple objective dynamic linear programming (MODLP) can also be formulated as DDM on specific dynamic WSC problems, which should be used especially in the context of WSCs. Usually, dynamics issues appear more often in WPC problems than in WSC problems. Therefore, it is necessary to develop supply chain planning with separate DDMs addressing the planning problems either on strategic, operational, or tactical levels. Although results are preliminary, added value of modeling can be reached by ITOA in combination with DDSE technologies to provide effects of local data and operational optimization tools for collaborators.

The literature revealed DDM and ITOA methods to optimize the WSC by applying DDSE into ERP systems for WSC management. After developing previous DDM elements, it is possible to share local data in a specific DSS between the stakeholders involved. For improving the coordination of collaborators in the WSC, group decision-making methods could be utilized in the formulation of DDM based on local data parameters providing an accurate digital representation of the specific WSC situation, which can be achieved with the help of collaborators participating in ITOA analysis.

The proposed cloud platform–based ERP system architecture can be used for planning and control of WSCs, which allows the combination of DDM elements with the cloud platform. In Finland, this platform already serves [82, 83] as the basis for the collaboration between the stakeholders of the WSC and for analyzing and sharing data over the WSC network in both vertical (sequential operations) and horizontal dimensions (time-varying) of dynamics. Such a platform not only advances the existing group decision-making process but also provides new collaborative opportunities and support for digital implementation. In addition, the modules of the system platform allow fast and safe updating of DDMs with standardized code architecture without huge additional costs, without changing the foundations of the ERP and DSS systems.

Conclusions

The selection of a data-driven dynamic optimization model is guided by using decision base, criteria, dynamic elements, measurements, and local data to describe forest logistics that align with supply chain management goals. Since the amount of local data has increased in organizations, they have been able to develop better data-driven models. However, this has not been achieved only by choosing the appropriate data analytics technology to identify the opportunities. Organizations have created a culture of digitalization that encourages collaboration for improving data-driven modeling. Accordingly, stakeholders of WSC at every management level collaborate based on WSC data and develop enhanced data skills through practice. The establishment of standards for cloud-based platforms at time-related and sequential dynamic measures increasingly enables successful spatial forest logistics through the planning and monitoring of WSCs. This requires an ongoing automation of self-service modeling that provides collaborators digital data access. It also requires security solutions and know-how to develop specific opportunities for outsourced harvesting and transport organizations to learn data skills for investigating WSC information in order to discover powerful insights to improve WSC operations. To accelerate this process, WPC organization of the forest industry should apply more data-driven modeling in ERP to encourage WSC organizations in developing new DSS. Furthermore, establishing support capabilities for collaborators would help the implementation of systems.

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Declarations

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- • Of importance
- •• Of major importance

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