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Expert-Based Ten-Year Forecast for Logging Machines and Systems in Sweden

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Abstract: The forest sector is a significant contributor to Swedish society but requires continuous improvements in logging operations. Implementing innovations in operations is dependent on advances in other sectors, since forest machine manufacturers have only a fraction of the development capacity of, e.g., car or truck manufacturers. The aim of this study was to identify the most promising logging-machine systems, with different innovations, for implementation within ten years. The Delphi method was used to gather expert views on the importance of criteria in their decision making, their expectations regarding developments in external factors, and the most promising machine systems. Environmental and social criteria were ranked higher than economic criteria, but the rankings were relatively close. A future with greater and more stringent regulation was expected, but with scope to improve operations through technological developments such as automation and remote control. There was interest in new machine systems, but the established system dominated. Of the expected innovations, renewable energy sources were ranked highly, along with the automation of the work elements that are easiest to automate. The study provides stakeholders with a basis for decision making regarding which technologies to evaluate and test in the future.

Keywords: Delphi method; forest operations; final felling; prognosis; preferences; machine systems; scenarios; technology development

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1. Introduction

The forest sector’s production of biobased, renewable, and recyclable raw material is a significant contributor to GDP, employment, and exports in Sweden [1]. Maintaining the sector’s role on the global market is highly dependent on continuous improvement in relation to goals and regulations [2]. The goals are commonly set on financial values, whereas social and environmental demands are set through legislation and certification schemes [3]. The produced raw material originates typically from one of two types of operation: thinning, where around 30% of the trees are removed from a medium-aged stand to improve the qualitative development of the remaining trees, or final felling, where the majority of the trees are removed from a mature stand.

The sector’s contribution to society is dependent on efficient forest operations. Logging operations in Swedish forestry use the cut-to-length method with fully mechanised machine systems, which are used for about 33% of the annual harvest globally [4]. Despite this, the number of forest machines produced per year is relatively small, compared to, e.g., the numbers of cars or farm tractors produced. It is, therefore, challenging for forest machine manufacturers to lead technological development, and easier to implement solutions from other sectors. Regardless of origin, new technology is considered an important driving force in technological innovations, together with demand for new products and new legislation [5].

The machine system most commonly used for fully mechanised cut-to-length harvesting consists of two machines: a harvester that fells the trees and delimbs and crosscuts them into logs at the harvesting site, and a forwarder that transports the logs from the harvesting site to roadside landings for onward transport to industries with timber trucks. This two-machine system is a well-developed and well-established machine system for logging operations [6]. Machines used for final fellings in Sweden weigh around 20–25 metric tonnes, with a loading capacity in the forwarder of approximately 20 tonnes.

When developing machine systems, external factors can have a strong influence on their potential for adoption by the market. For example, today's machines use fossil-based diesel as energy source, so the future availability of diesel is a significant factor when choosing energy sources for future machine systems. Similar examples can be provided for environmental and economic factors.

The possibilities of implementing innovations in forest operations is dependent on developments in other sectors, so the evaluation of these is important in terms of potential for forest operations. Three areas of particular interest are automation and remote controlling of machines, as well as the development of new energy sources/carriers instead of fossil diesel. Automation has been used in robotics for industrial purposes for a long time [7], but is being increasingly used in less structured environments, such as trucks in mines or even buses on public roads [8,9]. Some first steps regarding automation in forestry have also been taken [10–13]. Remote control has been used for mining machines, thereby increasing profitability while simultaneously removing the social consequences of working underground. There have also been trials with remotely operated excavators [14] as well as forest operations [15]. Biodiesel has been used as an energy carrier for some time [16], electricity use has increased significantly recently [17], and liquid hydrogen has been used for several applications [18,19].

Machine systems, other than the two-machine system, can be used for cut-to-length logging operations. The most common commercially tested options have been based on using a single machine. With the so-called combi-machine system, one machine is used to harvest the trees, and then some of its equipment is changed to enable the transport of the logs, like a forwarder. Another one-machine option is the 'harwarder', which is able to both harvest and transport logs without substantial equipment changes. Harwarders have been manufactured in series with a certain focus on thinning operations, but have also been produced at concept level for final fellings. There have also been evaluations of a system in which several forwarders took turns to remotely control a harvester that directly processed the tree into the forwarder's loading space [20]. However, none of these systems have been able to compete with the standard two-machine system [2].

Innovations from other sectors may seem promising for the forest sector. However, to make well-informed decisions about which technologies to focus on, it is essential to evaluate how these innovations can be integrated into forestry operations. Consulting expert opinions and forecasting future innovations based on their views can provide a strong foundation for making strategic decisions. Forecasts have been made previously, but not recently [21–24].

The aim of this study was to identify the most likely innovations in logging machine systems expected to be introduced on a concept level by 2033. These are based on the insights from a panel of experts representing forestry and forest research. The Delphi method was used to assist experts in generating their forecasts.

2. Materials and Methods

2.1. Delphi

The Delphi method takes its name from the Greek Oracle of Delphi, where inquiries about future events were directed to divine entities through the mediation of temple priestesses [25]. The origins of this method can be traced back to 1948 and the beginning of the Cold War, when the US military intelligence branch, represented by the Rand Corporation [26], developed the Delphi method to predict the nuclear weaponry capacity and targeting strategies of the USSR. Developed in the realm of national security, the Delphi method was treated as a classified secret, and no information about it was revealed until fifteen years later [25,27].

Its design aims to harness the advantages of collaborative interactions, such as tapping into various knowledge sources and fostering creative synthesis. Simultaneously, it seeks to mitigate the potential drawbacks that can arise in group settings, often stemming from social, personal, and political conflicts.

According to Rowe and Wright [26], a Delphi procedure is characterised by four essential features: anonymity, iteration, controlled feedback of responses to all participants, and statistical aggregation of individuals' responses.

Anonymity is achieved through self-administered surveys, allowing experts to share opinions privately. This reduces social pressure from dominant individuals or majority views, encouraging evaluations based on merit rather than the status of the idea's source. Multiple questionnaire rounds allow experts to revise their judgments without fear of losing face [26]. After each questionnaire round, the facilitator shares a summary of the group's anonymous responses, often as a mean or median. This feedback reflects all members' views [26,28]. The ore confident experts tend to hold their stance, while the uncertain ones often adjust toward the median [29]. At the end of the polling process, the facilitator calculates the group judgement using a statistical average, typically the mean or median of the experts' final estimates [26]. According to Rowe and Wright [26], the Delphi method involves using diverse domain experts (5–20), providing statistical feedback, and continuing rounds until responses stabilise, with clear, balanced questions. While structured, the Delphi method is adaptable [30]. For this study, it helps forecast technological, economic, ecological, and social changes driven by future machine systems in Swedish logging operations. We implemented a two-round Delphi approach [28,31], as detailed in later sections.

In the preparation phase, selecting appropriate experts was crucial, as expert selection is often considered a key challenge in Delphi studies [31–33]. Experts are typically identified based on traits such as experience, education and/or training, social recognition, and relevant skills like creativity, self-confidence, and strong communication [34–39]. For our study, we prioritised experience, education and/or training, and recognition within their field.

There is no fixed rule for the number of experts in a Delphi study [25,40–43]. Smaller panels are sufficient when experts share similar backgrounds, while more diverse panels, especially international ones, may require larger groups. However, adding too many participants can reduce accuracy if their expertise is imbalanced. Ultimately, Delphi relies on the quality of expert responses rather than quantity, ensuring valid and reliable outcomes [29,44,45].

2.2. Participating Experts

The views were gathered from experts from an existing collaboration group (Table 1), the (Swedish) Reference Group for Future Logging Technology. All had sufficient domain knowledge and substantial experience from strategic, tactical, and/or operational forest operations. They held various roles, such as staff manager, project leader, or specialist. Their organisations were active in Swedish forestry, some of them with large coverage of Sweden's forests, whereas some had more extensive operations in specific areas. Five of the organisations were forest companies, and one was a forest owners' association. Together, they harvested around 36 million cubic metres of solid stem wood under bark (m^3 solid under bark) in 2022, representing 48 percent of the total volume harvested in Swedish forestry [3]. To ensure honest responses, the questionnaires were sent out and responses collected during a one-day workshop with all experts in one room. A total of eight people in the group participated throughout the workshop, and one person participated only during the ranking of criteria and external factors. When responding, they were instructed to focus on their own questions and were seated in such a way that they could not see the other experts' responses.

Table 1. Criteria for selection and description of the experts' background and experience.

Category	Description
Criteria for selecting experts	(1) Experience of R&D at a forest company, FOA * or research institution (2) Experience from working in the Reference Group for Future Logging Technology
Number of experts	5 from forest companies, 2 from FOA, 2 from a research institute
Current roles of experts	Staff manager, project leader or specialist
Education of experts	Upper secondary school or university degree in forestry, engineering or similar.
Experience in the forest sector, years	11–40

* FOA = Forest owners association.

2.3. Workshop and Questionnaires

The experts responded to questionnaires about the following: (1) criteria that are influential when choosing a future machine system; (2) changes in influential external factors expected by 2033; and (3) description of the features and/or innovation considered to be the most promising contributions to a new machine system by 2033. The experts responded to each set of questionnaires in two rounds (Figure 1). A third round would have been time-consuming and three long questionnaires could have led to a loss of focus Additionally, inviting the busy experts might not have been as successful. The results from the second round are presented in the Results section.

The following procedure was applied:

1. The experts received a link from the lead author to the first-round questionnaire and were given a certain amount of time in which to respond.
2. The lead author presented the experts' responses as mean values with no information revealing identities, i.e., the responses were anonymous. They were shown figures like those presented in the Results section.
3. The experts received a new link with the final-round questionnaire and the same time to respond.
4. The lead author presented the final results in the same way as in Step 2.

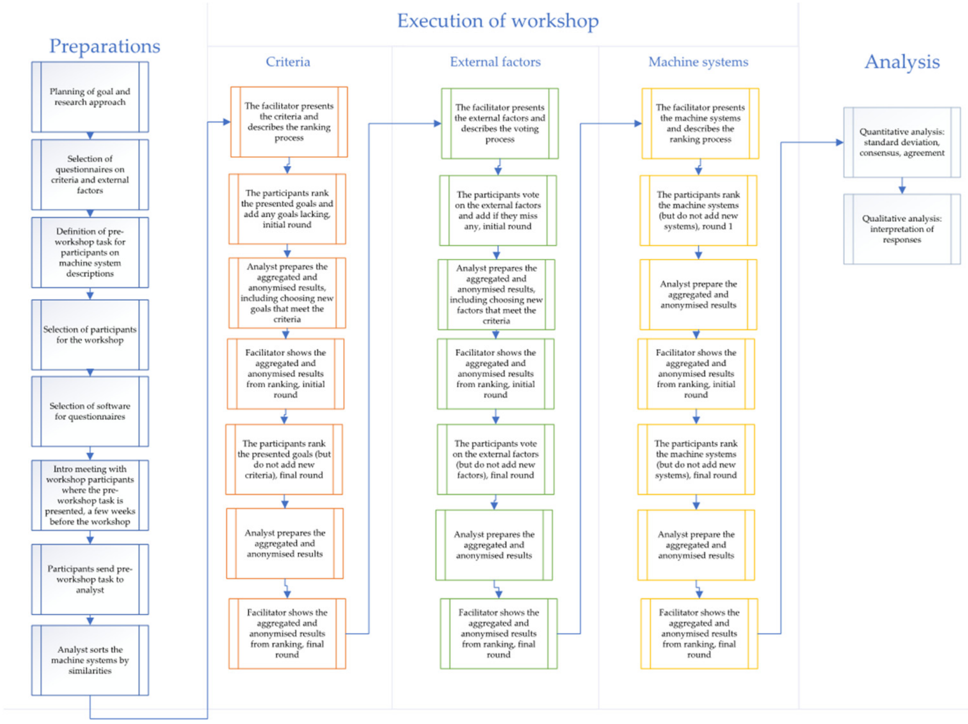

Figure 1. Flowchart showing the planning, execution, and analysis of the study.

When designing questionnaires and alternatives, we used the principles for Delphi as defined by Rowe and Wright [26].

2.3.1. Criteria

The experts were asked to rank a set of criteria according to their impact on decisions regarding future logging machine systems, with the highest impact given the lowest ranking point. The criteria were inspired by those in Jonsson et al. [3], which involved representatives from forest companies and a FOA. Notably, the same forestry organisations represented in Jonsson et al. [3] also participated in our study, linking the two studies in terms of organisational profile and expert focus on forestry technology development and decision-making processes. The criteria connected to one of the sustainability perspectives were social (S), environmental (En), or economic (Ec). Only criteria that were non-divisible, necessary, measurable, concise, and understandable [46] were added to the questionnaire. The chosen methodology did not allow the experts to indicate whether any criteria were not deemed necessary.

The criteria were presented during the workshop in the following randomly chosen order:

- Safer working environment, incidents, and accidents per 1000 working days (S);
- Higher wood value, goal achievement % (Ec);
- Lower carbon dioxide emissions, kg CO_2-equivalents per m^3 solid under bark (En);
- Lower total costs (logging, relocation, travel), SEK per m^3 solid under bark (Ec);
- Lower soil compaction, kg per m^2 (En);
- Lower vibration exposure, m per s^2 (S).

The experts could not indicate whether any criteria lacked significance in their decision-making. During the voting in the initial round, the experts could add criteria from their decision-making they thought were missing in the first round. Their suggestions were added on the same premises as the original criteria. It was not possible to add criteria in the final round of ranking. During the final round, the criteria were listed in the order of the experts voting from the initial round, with any added criteria at the end. The experts had five minutes to respond in each round. The criteria were ranked using Microsoft Forms™.

2.3.2. External Factors

External factors with direct influence on the ability of possible future machine systems to compete by 2033 were chosen. The goals from Jonsson et al. [3] were used as a basis for mapping factors with influence, which were connected with energy, technology, legislation, or wood products. To clarify the experts' views, the factors were presented as statements about their status in 2033. The experts then stated whether they strongly agreed, agreed, disagreed, or strongly disagreed with each statement. The factors were randomly stated as a positive or a negative change, and randomly ordered as follows during both rounds:

- Diesel price has decreased (energy);
- Better technologies for automation are available (technology);
- Fewer and less stringent demands regarding continuous cover forestry (CCF) methods (legislation);
- Higher tolerance for carbon dioxide emissions (legislation);
- Better technologies for remote control (technology);
- Increased demand for wood products with lower quality (wood product);
- Decreased accessibility of energy sources other than diesel (energy);
- Higher tolerance for soil rutting (legislation);
- Decreased demand for wood products with higher quality (wood product).

The factor concerning CCF methods was included to reflect potential shifts toward more regulated forest management practises, where there are more stringent requirements regarding CCF methods. Factors for both high- and low-quality wood products were included to cover the range of demand. The experts could add external factors they thought were missing in the initial round. If the factors were clear and understandable, they were added in the final round. The experts had five minutes to respond in each round. As with criteria, the voting was conducted through Microsoft Forms™.

2.3.3. Machine Systems

Ahead of the workshop, all experts were given an oral introduction and the possibility to ask questions during a one-hour online meeting 13 or 14 working days before the workshop. Following the lead author's instructions during the introduction, each expert submitted at least two suggestions to the lead author the day before the workshop. These suggestions outlined the experts' predictions on what the most competitive machine systems at the concept level might be like by 2033. All descriptions had the standard of the established two-machine system used in 2023 as a reference. As further description of the two-machine system, and as inspiration, they received detailed information about the time per working sequence [47] and costs distribution between the categories of cost for capital (investment costs), variables (personnel, fuel, oils, maintenance, and repair), relocation, and travel [48].

Introducing a new series-manufactured machine is a relatively long process, which is why we chose to ask about machines at the concept level, i.e., a test-level machine that can be used operationally but has not yet been adapted for series production or tested for compliance with legislation requirements.

Each suggestion contained a description of the following:

- The external factors that had changed (if any), and how they had changed;
- The machine(s) included in the new machine system, and what each machine does;
- The automation level and the working tasks that had been automated (if any);

- The energy carrier used, its transfer in the machine(s) (power train), and how the issue of energy supply to the forest sites has been solved;
- The machine(s) that are remotely operated, if any, and where the operator is located.

To maintain anonymity during the workshop, the lead author presented all suggested machine systems. To ease the cognitive challenge of keeping all systems in mind, the suggestions were presented in an order based on their similarities. The experts had ten minutes to rank the systems. In contrast to the previous two questionnaires, the experts could not add any new machine systems to this questionnaire's final round. The machine systems were ranked using Typeform™ to accommodate the large number of alternatives.

2.4. Analysis

The overall ranking, from most to least preferred per round, was presented by sorting the average ranking of the criteria or machine systems from low to high. Voting on external factors took the form of responding with agreement/disagreement on statements, so the responses were analysed based on the following translation:

- Disagrees strongly = 1;
- Disagrees = 2;
- Agrees = 3;
- Agrees strongly = 4.

The responses were presented, both at the workshop and in Section 3 of this paper, as a percentage for each response, such as "25 percent strongly disagree".

The external factors that were stated as a negative change during the workshop were translated, together with their responses, into a positive change to ease interpretation and comparisons between factors. The words in each factor that were changed are listed below with underscore, followed by the new word(s):

- Decreased accessibility of energy sources other than diesel -> Increased;
- Decreased demand for wood products with higher quality -> Increased.

The machine systems were grouped as a part of the analysis, based on their characteristics.

Suggestions regarding the automation of machine systems were categorised as either operator support or the automation of specific work sequences. For automated sequences, the systems were further categorised on the basis of the type of work being performed and the equipment used. The work types were divided into harvesting or transporting. Harvesting encompassed all tasks where trees are processed, such as felling, delimbing, cross-cutting, sorting (either onto the ground or directly into a load carrier), and relocating the machine between the harvest of individual trees. Transporting referred to tasks related to moving logs from the harvest site to the roadside landing.

The equipment was classified into two categories: crane operations and driving. A transport machine could be driven during or between crane work sequences, such as felling or processing trees, or unloading logs. It could also involve moving with either a full or empty load carrier between the harvesting site and the landing. However, when both crane and driving tasks were involved in a sequence, it was classified as crane work, as crane operations are typically prioritised in time studies [47]. This classification resulted in potential combinations, such as harvesting crane work, harvesting driving work, transport crane work, transport driving with full or empty load carrier, or transport driving work during loading or unloading (i.e., crane work).

If the descriptions of the energy sources contained several alternatives, they were categorised according to the order in which they were mentioned, i.e., interpreted as the order of dominance.

Finally, Delphi studies are often conducted with the aim of achieving consensus or increasing agreement among experts. We, therefore, calculated two indices—the DeMoivre Index and the Strict Agreement Index—used to measure agreement among experts in Delphi studies [41].

Indices Used for Measuring Agreement Among Experts

In a Delphi round, experts evaluate a number of items or objects using some sort of rating scale, and agreement is expressed per object by calculating the percentage of experts that evaluate an item in a certain way (e.g., the percentage of experts that give an item the highest rank) [41]. The standard deviation is also often used as a measure to express agreement among experts, although this measure should not be used when objects are rated on an ordinal scale [41].

There are other ways to measure agreement among experts, and here we used two: the DeMoivre Index (DM_t) for measuring consensus, and the Strict Agreement Index (SA_t) for measuring agreement (Table 2).

Table 2. List of indices used for measuring agreement among experts.

Name of Index (Denotation)	Index Type	Minimum Value	Maximum Value
DeMoivre Index (DM_t)	Consensus	0	1
Strict Agreement Index (SA_t)	Agreement	0	1

In a Delphi study, consensus on an object only occurs if all experts attribute the same rating to that object, which means that it is very difficult to achieve consensus [40,41]. Hubert [49] formulated DeMoivre's definition of agreement (after the French mathematician Abraham de Moivre) in the following way: "an agreement occurs if and only if all raters agree on the categorisation of an object" [41]. According to the previous definition, consensus between two experts, r and r', regarding the rating x of object i in round t ($t = 1, \ldots, T$), is defined as follows:

$$c_{irr't} = \begin{cases} 1 \text{ if } x_{irt} = x_{ir't} \\ 0 \text{ otherwise} \end{cases}. \tag{1}$$

When there are m experts, consensus on an object is achieved when there is consensus within all possible expert pairs ($m(m-1)/2$). Consensus on object i in Delphi round t was therefore defined as follows:

$$c_{it} = \begin{cases} 1 \text{ if } \sum c_{irr't} = m(m-1)/2 \\ 0 \text{ otherwise.} \end{cases}, \tag{2}$$

where $c_{it} = 0$ or 1 (0 denoting no consensus, 1 denoting consensus). For all n objects taken together, the DeMoivre Index,

$$DM_t = \frac{\sum_i c_{it}}{n}, \tag{3}$$

denotes the number of objects that received the same rating from all experts as a proportion of the total number of objects in Delphi round t.

The concept of agreement is less strict than the concept of consensus, and it occurs if at least two experts in a group attribute the same rating to an object. Consensus can, therefore, be considered a special case of agreement [41]. In addition to the DeMoivre Index, an agreement index was developed that matches the concept of agreement as mentioned above. Meijering et al. [41] defined the percentage of equal ratings of object i in round t over the m experts in Delphi round t as follows:

$$a_{it} = \frac{\sum_{r'>r} c_{irr't}}{m(m-1)/2}, \tag{4}$$

where $0 \leq a_{it} \leq 1$ (0 denoting total disagreement, 1 denoting consensus). For all n objects taken together, the index

$$SA_t = \frac{\sum_i a_{it}}{n}, \tag{5}$$

denotes the mean proportion of equal ratings across experts and objects in Delphi round t.

To enable presentation in percentages, the results from Equations (1)–(5) were multiplied by 100. For examples of the calculation process, we can recommend reading, e.g., Meijering et al. [41].

3. Results

3.1. Criteria

The experts' ranking placed the criteria in two distinct groups, with five criteria considered as more important (receiving lower values) and the remaining two considered less important (Figure 2; Table 3).

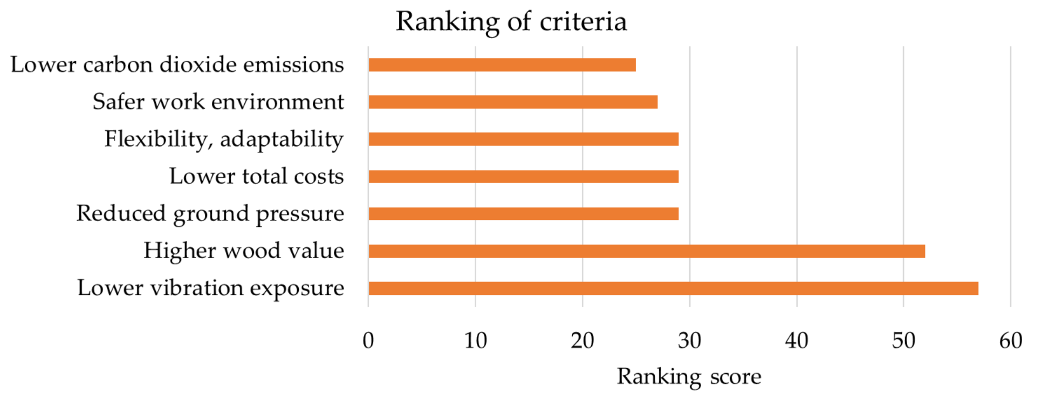

Figure 2. The experts' ranking of criteria importance when making forest technology decisions. A low value indicates high importance. The criteria are sorted with the lowest value at the top.

Table 3. Experts' rankings of criteria. The criteria were connected to one of the sustainability perspectives: social (S), environmental (En), or economic (Ec).

Criteria	Average Ranking *	Standard Deviation	Agreement Index (%)
Lower carbon dioxide emissions (En)	2.8	0.6	36.1
Safer work environment (S)	3.0	1.7	16.7
Flexibility, adaptability (Ec)	3.2	1.3	11.1
Lower total costs (Ec)	3.2	2.2	16.7
Reduced ground pressure (En)	3.2	1.4	19.4
Higher wood value (Ec)	6.2	0.6	36.1
Lower vibration exposure (S)	6.3	0.9	36.1

* The maximum and minimum values are 6.3 and 2.8, respectively.

The overall consensus index was 0%, and the overall agreement index (SAt) was 24.6%. The highest agreement among experts was for the following criteria: "*lower carbon dioxide* *emissions*" (a_{it} = 36.1%), "*higher wood value*" (a_{it} = 36.1%), and "*lower vibration exposure*" (a_{it} = 36.1%) (Table 3). The least agreement was for "*flexibility, adaptability*" (a_{it} = 11.1%). Note that "*flexibility, adaptability*" was added as a criterion by an expert. The criteria with the highest agreement index were either ranked as the most or the least important.

3.2. External Factors

The experts agreed that the technological factors were expected to improve, except for the factor "*decreased demands for high machine utilisation, because of less variation in spare parts supply*", which was added by an expert (Figure 3). The statement was added as increased demand for high machine utilisation, because of larger variation in spare parts supply, and to ease interpretation, it was changed in the analysis to "*decreased demand for high machine utilisation, because of less variation in spare parts supply*". The energy factors were expected to increase, but with different impact on the possibilities to choose future machine systems. "*Ruralisation, easier to recruit operators to work in the countryside*" was added by an expert and expected to decrease. The factor was sorted as a new category. The legislation-related factors received relatively clear responses, signalling expectations of a more regulated future.

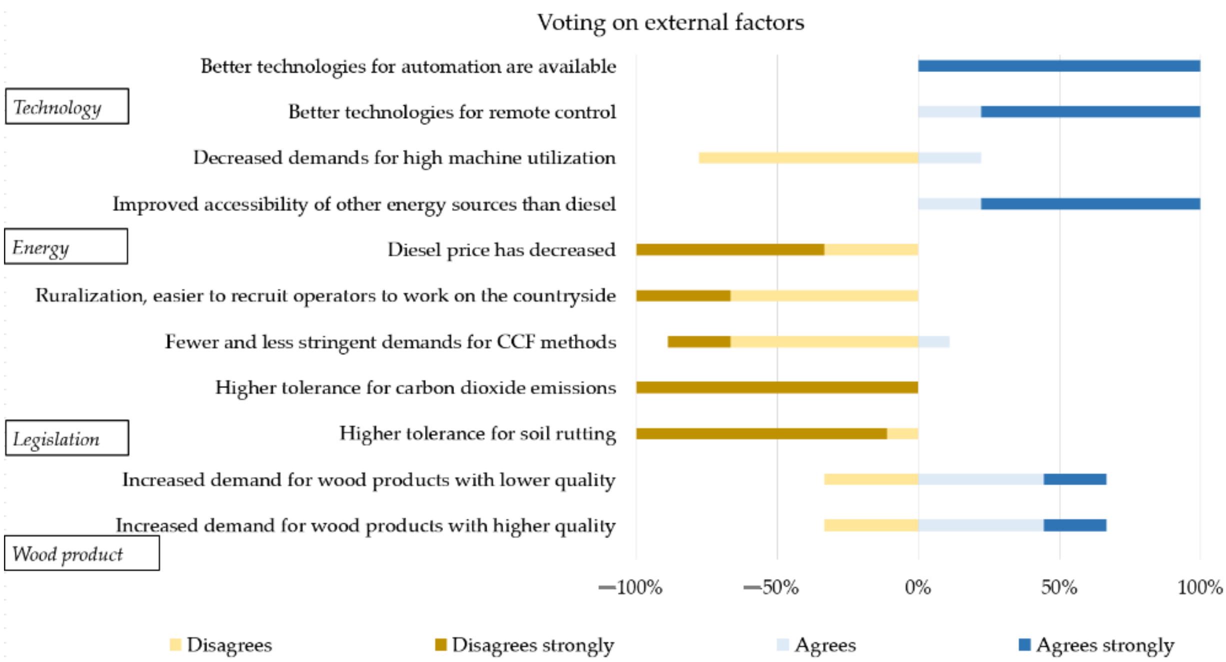

Figure 3. The experts' voting on statements about expected changes in external factors in ten years' time. The factors are sorted into categories, which are shown in italic and grouped, as indicated by the black boxes. The ruralisation factor is presented as a separate category. If an entire horizontal bar is on the same side of zero, it means that all experts had the same general opinion, but it could vary in strength (as indicated by different colours in the bar). Continuous cover forestry is abbreviated as CCF.

Full consensus was observed for two external factors—*higher tolerance for carbon dioxide emissions* and *better technologies for automation are available* (Figure 3). The first signal that legislation and demand are expected to be tougher, and the second indicates the experts' expectations regarding technology development. The same factors have full agreement index values (Table 4).

Table 4. Experts' opinions on external factors in both rounds and sorted by categories.

Categories and Factors Within Categories	Average Voting *	Standard Deviation	Consensus (%)	Agreement (%)
Technology				
Better technologies for automation are available	4.00	0.00	100	100.0
Better technologies for remote control	3.78	0.42	0	61.1
Decreased demand for high machine utilisation, because of less variation in spare parts supply	2.22	0.42	0	61.1
Energy				
Improved accessibility of other energy sources than diesel	3.78	0.42	0	61.1
Diesel price has decreased	1.33	0.47	0	50.0
Ruralisation				
Ruralisation, easier to recruit operators to work on the countryside	1.67	0.47	0	50.0
Legislations				
Fewer and less stringent demands regarding continuous cover forestry methods	1.89	0.57	0	44.4
Higher tolerance for carbon dioxide emissions	1.00	0.00	100	100.0
Higher tolerance for soil rutting	1.11	0.31	0	77.8
Wood products				
Increased demand for wood products with lower quality	2.89	0.74	0	27.8
Increased demand for wood products with higher quality	2.89	0.74	0	27.8

* The maximum and minimum values are 4.00 and 1.00, respectively.

After the two factors with full agreement, the highest agreement among experts concerned "*higher tolerance for soil rutting*" (a_{it} = 77.8%), "*better technologies for remote control*" (a_{it} = 61.1%), "*improved accessibility of other energy sources than diesel*" (a_{it} = 61.1%), and "*decreased demand for high machine utilisation, because of less variation in spare parts supply*" (a_{it} = 61.1%) (Table 4). The least agreement concerned "*increased demand for wood products with lower quality*" (a_{it} = 27.8%) and "*increased demand for wood products with higher quality*" (a_{it} = 27.8%). Note that the external factors "*urbanisation*", "*easier to recruit operators to work on the countryside*", and "*decreased demand for high machine utilisation, because of less variation in spare parts supply*", added by the experts, showed high levels of agreement (a_{it} = 50% and 61.1%, respectively). This shows that it was a good decision to let experts add external factors.

The standard deviation for the four environment-related factors—"*fewer and less stringent demands regarding CCF methods*", "*higher tolerance for carbon dioxide emissions*", "*improved accessibility of other energy sources than diesel*", and "*higher tolerance for soil rutting*"—varied from zero for "*higher tolerance for carbon dioxide emissions*" to 0.57 for "*fewer and less stringent demands regarding CCF methods*".

The standard deviation for the two statements regarding wood quality was relatively large. Several experts signalled that they expect the demand for wood products to increase, but no clear pattern emerged.

The standard deviation for the four economic statements—"*diesel price has decreased*", "*better technologies for automation are available*", "*better technologies for remote control are available*", and "*decreased demands for high machine utilisation, because of less variation in spare parts supply*"—was neither high nor low. "*Decreased demands for high machine utilisation, because of less variation in spare parts supply*" was added, and the experts appeared to agree that the demands for high utilisation will probably increase. However, the standard deviation was relatively high.

In summary, the experts appeared to think that a tougher future awaits, with more and tougher legislation on soil rutting, carbon dioxide emissions, and forest management methods. The demand for forest products may increase. Simultaneously, the availability for energy carriers other than diesel, and better technologies for automation and remote control were expected to increase (Table 4).

3.3. Machine Systems

3.3.1. Raw Data

A total of 23 machine systems were proposed by the experts before the workshop. Two of the systems used airborne machines (unmanned aerial vehicles, UAVs), while the rest used ground-based machines (Table 5).

Table 5. Description of the machine systems, sorted as they were presented during the workshop. Note that all systems with hybrid energy carriers/power trains used electricity.

Number	Machines	Automated Work Elements	Energy Carriers/Power Trains	Remote Control
MS1	Harwarder with shuttles	Driving empty and full	Diesel hybrid	Yes, cabin
MS2	Harwarder	Harvesting, driving empty and full, crane movement out and in during unloading	Electricity	No
MS3	Harwarder	Processing	Biodiesel hybrid	No
MS4	Extra small harwarder	Fully autonomous	Electricity	Yes, trailer
MS5	Harvester and shuttles	Fully autonomous	Liquid hydrogen hybrid	Yes, trailer
MS6	Rubber-tracked harvester and UAVs	Harvesting except relocation	Biodiesel hybrid	Yes, cabin or trailer
MS7	Rubber-tracked harvester with two cranes, and UAVs	Partially automated harvesting, autonomous UAVs	Electricity	Yes, UAV monitoring from another place
MS8	Harvester and shuttles	Relocation of harvester, shuttles fully automated	Liquid hydrogen hybrid	Yes, operating station by the owner's base
MS9	Rubber-tracked TMS	Felling, processing, sorting in the load carrier	Diesel hybrid	Yes, trailer
MS10	Harvester and shuttles	Harvester crane out, crane in, and relocation, autonomous forwarding	Electricity	Yes, trailer
MS11	TMS	Both machines: crane out, crane in, driving at main road	Biodiesel hybrid	Yes, trailer

Table 5. *Cont.*

Number	Machines	Automated Work Elements	Energy Carriers/Power Trains	Remote Control
MS12	2-grip harvester and forwarder	Crane in, processing	Diesel hybrid	Yes, trailer
MS13	TMS	Processing, driving empty and full	Electricity	Yes, trailer
MS14	Harvester and rubber-tracked forwarder	Partially automated loading, driving empty, during loading and full	Diesel hybrid	Yes, trailer
MS15	TMS	Several harvesting work elements, driving empty and full	Biodiesel hybrid	Yes, harvester cabin or trailer
MS16	Harvester and shuttle	Harvesting and relocation of harvester, fully automated forwarder	Biodiesel hybrid	Yes, harvester cabin
MS17	TMS	Harvesting, forwarders crane out and crane in	Liquid hydrogen hybrid	No
MS18	TMS	Crane out and crane in	Electricity	Possibly from the trailer
MS19	TMS	Driving empty and full	Diesel hybrid	No
MS20	Harvester and rubber-tracked forwarder	Driving empty and full	Biodiesel hybrid	No
MS21	TMS	None, only operator support	Diesel hybrid	No
MS22	TMS	None, only operator support	Electricity	No
MS23	Rubber-tracked TMS	Processing	Diesel hybrid	No

Shuttle—a transport machine without a local operator, i.e., an operator in another location or autonomous operation.

Hybrid—electricity in combination with diesel, biodiesel, or liquid hydrogen.

Cabin—the machine can be operated from the cabin of a manned forest machine at the forest stand.

Trailer—the machine can be operated from a mobile control room/ construction trailer by roadside.

UAV—unmanned aerial vehicle.

TMS—two-machine system.

3.3.2. Ranking and Indices

There was no consensus (DMt = 0%) on rankings of machine systems among experts, but this was expected because there were a total of 23 machine systems. The value of the overall agreement index was high (12.6%).

The group of two-machine systems (TMS) was ranked as having the highest potential, as well as the highest number of suggested machine systems (17), but it also had the highest standard deviation (Table 6). *Harwarders* received the lowest potential, relatively low standard deviation, and the highest agreement index (a_{it} = 27.7%). Interestingly, the TMS-based MS5 used direct-loading, which is one of the bearing principles of harwarders. *UAVs* were ranked in the middle of the machine system groups.

Table 6. Results for the machine system ranking. The ranking was carried out for a full machine system but grouped into categories in the analysis. The categories are sorted from highest ranking (i.e., lowest value and highest potential) to lowest ranking. Note that all hybrid machines under "energy carriers/power trains" use electricity.

Categories And Groups Within Categories	Number of Systems	System Numbers in Table 5	Average Ranking	Standard Deviation	Agreement Index (%)
Machine systems					
TMS	17	5, 8–23	9.6	5.7	9.3
UAVs	2	6–7	15.5	3.5	10.7
Harwarders	4	1–4	20.5	2.3	27.7
Automation					
Operator support	2	21–22	9.5	4.5	13.0
Crane work for harvesting machine	3	3, 12, 23	14.7	5.0	16.7
Driving of transport machine with empty and full load carrier	3	1, 19–20	7.3	6.9	10.7
2–4 categories automated	11	2, 6, 8–11, 13–15, 17–18	12.0	5.8	10.4
Fully automated, i.e., all categories automated	4	4–5, 7, 16	14.8	7.9	17.0
Energy carriers/power trains					
Liquid hydrogen hybrid	3	5, 8, 17	5.0	3.6	8.3
Biodiesel hybrid	6	3, 6, 11, 15–16, 20	10.7	6.0	12.5
Diesel hybrid	7	1, 9, 12, 14, 19, 21, 23	9.6	3.6	9.2
Fully electric, i.e., no other energy source than electricity in the machine(s)	7	2, 4, 7, 10, 13, 18, 22	18.6	3.6	18.0
Remote control					
Yes, from office	1	8	3.0	0.0	7.0
No	8	2, 3, 17, 19–23	10.5	7.1	17.0
Yes, different places or not defined	3	6–7, 15	12.7	4.9	7.0
Yes, from trailer by roadside	9	4–5, 9, 10–14, 18	13.2	6.6	12.0
Yes, from the cabin of another forest machine	2	1, 16	16.0	1.0	7.0
AVERAGE					**12.6**

Regarding the automation of work elements, "*Driving of transport machine with empty and full load carrier*" received the highest potential, with standard deviation close to average but low agreement. "*Fully automated*" and "*Crane work for harvesting machine*" received the lowest potentials, high standard deviations but high agreements.

The groups within energy carriers/power trains received relatively similar potential, except for "*fully electric*", which was ranked as low potential. However, the standard deviation for *biodiesel hybrid* was high, showing the diversity among the experts' rankings. Despite that, the agreement index was quite high for biodiesel (a_{it} = 12.5%) and electricity (a_{it} = 18.0%).

Remote control from the office was ranked as having the highest potential among the remote control groups, but this was based on only one system. The other groups were given similar rankings, but the standard deviation was clearly lower for remote control from the cabin. The agreement was the highest for no remote control (a_{it} = 17%) (Table 6).

4. Discussion

4.1. Experts' Views on the Future

The results showed that "*lower carbon dioxide emissions*" was ranked as the most important criterion for the choice of future machine systems, followed by a "*safer work environment*". In contrast, Jonsson et al. [3] saw that economic criteria often serve as goals, while passing threshold values sufficed for environmental and social criteria. There can be many explanations for the differences. For instance, the work of Jonsson et al. [3] was a qualitative analysis based on interviews. Our study was based on pre-defined questions, where the experts had no opportunity to differentiate whether a criterion was to be maximised, minimised, or used as a threshold.

Three criteria had the same final ranking, namely "*lower total costs*", "*reduced ground pressure*", and "*flexibility*, *adaptability*". The closeness of the ranking for the three criteria signals the challenge to weight them in forest operation decision-making and the complex decision environment in general. "*Higher wood value*" and "*lower vibration exposure*" received the lowest importance, which may indicate that the performance on those in relation to the other criteria is expected to be satisfactory ten years from now.

Expressed through the external factors, the experts appeared to expect a more challenging future with more and tougher regulations. Such concerns can easily be understood, based on the changes in regulations, certifications and public opinion in recent decades [50]. The experts were reasonably in agreement that the tolerance for carbon dioxide emissions and soil rutting will decrease in the future, indicating that most experts expected more and tougher regulations, but there were exceptions. Regulations demanding greater use of CCF methods were expected. Questions about how to manage forests are prominent in the public debate in Sweden, and experts may think that it is uncertain about where the debate will lead, since there is far less knowledge about CCF methods than the current set of practises with rotation forestry.

The expected demand for wood products varied, but it appeared to lean towards an increased demand both low- and high-quality wood products in the future. However, the disagreement does correspond to the relatively low ranking for increased wood value. This suggests a potential future with demand for forest products in operations with more and tougher restrictions. Expectations regarding technology development, mainly remote control and automation, are high and may compensate, at least partially, for the expected restrictions if they are met.

Machine systems suggested by the experts included 17 two-machine systems (TMS), which were considered to have high potential on average, but with a large variation between the individual machine systems. This may be explained by familiarity with the system. It may also be perceived as less risky to invest resources in developing remote control and automation alone, without also changing the basic machine system. On the other hand, some of the experts expressed disappointment to the lead author just after the workshop, highlighting that no bolder ideas were presented during the workshop. Such expectations have also been expressed previously [3], but it can be of interest to note that the lack of bold ideas clearly indicate that the disappointed experts did not expect such a development themselves either.

The *harwarders* received low potential, possibly due to prior limitations when competing with TMS [48,51,52]. Since the ranking ended with a dominance of two-machine systems, it may have been perceived as risky for the experts to express their faith in the harwarder system. Nevertheless, the anonymous data-gathering procedure should have protected against that risk. However, one of the bearing principles of the harwarder is the rationalisation through direct loading while processing, which was used for a two-machine system ranked number two. The same kind of system, but with direct loading on a forwarder from a remotely operated harvester, was tested about two decades ago, but this failed mainly because of the waiting times resulting from high machine interdependence in the system [20]. Less common systems, such as UAV-based transport and the whole-stem method, face significant challenges and are unlikely to advance within the scope of the study.

There were several systems presented with remote control, where the views on potential varied depending on the operator's location. The highest potential was given to a system with an "*office*" location, but since there was only one system with that solution, the high potential may have been for other reasons. "*Trailer by roadside*" was the most promising and clearly defined solution, involving several systems. This may be related to the flexibility of working with multiple machines, while still being able to do maintenance work and planning on-site in the stand. In contrast, there was little interest in "*cabin of another forest machine*", which may be perceived as a half-step, since a machine cabin will still be needed and the operator's work environment will not be as improved in terms of vibrations as when the operator controls machines from a trailer. Remote control has been encouraged as a step enabling further automation [15].

The potential for automation varies among the forest machines' work elements, depending on complexity. The easiest element to automate is probably "*driving of transport machine with empty and full load carrier*", which also was considered having the highest potential. Automating the driving entails reading the environment and planning where to drive, something that can already be achieved in some modern cars [15]. Even though forests are more difficult environments to describe than public roads, trials have been performed with a forest machine automatically following a pre-defined route [53]. Crane work is probably the most challenging to automate, since more information must be gathered and processed in preparation for more complex decision-making. "*Crane work for harvesting machine*" was ranked the same as "*fully automated* systems", suggesting that it will probably be the last element to be automated. However, some crane automation has been successfully developed recently, suggesting that the potential may be higher than expected [13].

The perception that fossil-based diesel will be less available, more regulated, and replaced by other sources appears clear between the questionnaires for criteria, external factors, and machine systems. The systems with *liquid hydrogen hybrid* and *biodiesel hybrid* showed high potential, low standard deviation, and high agreement. The reasons behind the ranking may be that the step from fossil-based diesel to diesel based on renewable sources is quite short and is associated with relatively low risk. In fact, there are already operational systems that only work with biodiesel [54]. The shift from diesel to electricity, however, appears to be regarded as more of a leap, perhaps with low potential, since the systems were given low potential and showed low standard deviation, despite as many as seven "*fully electric*" systems being suggested. Electricity as an energy carrier has been used for series-manufactured cars for quite some time and is being increasingly tested for trucks [55]. If electricity is to be used for forest machines, high-energy consumption demands, similar to those of trucks, must be met, but simultaneously supplied to the remote logging sites. Those challenges must be solved before electricity can become an interesting energy carrier.

Full consensus was attained for factors regarding the availability of better technologies for automation, lower tolerance for soil rutting, and lower tolerance for carbon dioxide emissions.

The criterion "*lower carbon dioxide emissions*" was given the highest importance. We also see indications of this in the machine system ranking, especially when we simultaneously look at the expectation that carbon dioxide emission regulations will become stricter. The systems with energy carriers that may reduce net carbon dioxide emissions were perceived as most potential, whereas "*fully electric*" showed low potential, probably not because of its potential during operations, but because its implementation is challenging. "*Safer working environment*" is clearly important in forest operation decision-making, but maybe not as clearly reflected in the machine system ranking. However, we argue that it is a natural consequence of established testing procedures that already have a high security level [56]. The criterion of "*lower total costs*" is expressed in the systems, since, for instance, many of them aim to decrease time consumption and/or costs through automation. "*Reduced ground pressure*" is not necessarily captured clearly but, as an example, some systems had tracks on the transport machine or all machines, which are known to decrease ground pressure [57].

The potential worries about future regulation and hopes for improved technology may be interpreted through the machine system ranking. We see environmentally friendly energy carriers at the top, in response to unanimous expectations of decreased tolerance for carbon dioxide emissions and, of course, the criterion "*lower carbon dioxide emissions*".

There are systems with more automation and remote control than today's machines, which may be a natural consequence of expectations of better availability of such technologies. The experts expected more regulations related to CCF, which can be connected to the additional and important criterion of "*flexibility*, *adaptability*". Systems more flexible than those in use today are likely to compete well, but this is not clearly shown in the machine system ranking. One-machine systems as harwarders, for instance, are more flexible in terms of faster response time from updated bucking instructions to wood products delivered to roadside.

This study focused on the mechanised cut-to-lengthharvesting method as applied in Swedish forestry. The same method is used in many other countries and regions [4], so the findings should, therefore, also be relevant for many other parts of the world, but with adaptations to local contexts.

4.2. Strengths and Weaknesses

Forest operations in Swedish forestry are mainly performed by contractors. The experts were representative of machine buyers on the market, since all but one buy machines or substantially influence the purchases made by their contractors. The experts, therefore, primarily serve as proxies, but this is suitable for the purpose of this study.

The experts' organisations were all active on the same Swedish market for forest raw materials and forest products. As competitors, their openness may be expected to be limited. Thanks to the anonymity of the voting procedures, we did not expect this to have any substantial impact. Neither did we expect or could note any impact by strong individuals or organisations, which is a general advantage with the Delphi method. The voting was conducted in two rounds each for all parts. The experts could add criteria and external factors during the initial round, but relatively few were added. Our interpretation is that the most relevant criteria were already defined and included in the initial round.

Simultaneously, the experts did not take any actual decisions during the workshop, so it was possible to rank something that was not fully in line with their preferences or those of their organisation. The risk for discrepancies is probably the largest for criteria. The total costs were the most important criteria in the study by Jonsson et al. [3], a conclusion reached through a more thorough study design. It is, therefore, possible that, e.g., the total costs would be given higher importance, which would be natural for the profit-making organisations participating. Another possibility is that the higher importance criteria have grown in significance to such an extent that the organisations would not wish to continue their operation if carbon dioxide emissions are not reduced, and so on.

The study design of machine systems was that the experts sent suggestions to the lead author before the workshop, which helped them to think through future possibilities. Among the suggestions, there were several systems with great similarities, not surprising in view of the open study design. Because of the overlap and the large number of systems, it was a challenge for the experts to grasp the unique characteristics of each system before ranking. This could have been solved either by interpreting the suggestions, which would compromise the uniqueness of each system, or simply by adding time to the ranking process. Also, the study could have been designed for experts to rank the potential of specific characteristics (i.e., the categories used in the analysis), rather than focusing on relatively well-defined machine systems.

4.3. Future Studies

The experts could not state whether they wanted to maximise or minimise a criterion, or apply a threshold value. Such choices would be interesting to add in future studies.

The results for machine systems were interesting and relevant for the forestry research field. The ranking concerned predefined specific machine systems, with overlap among several of them. If the ranking had instead been on the categories from which the experts defined their systems, the interpretation could have been easier to understand.

The supply of electricity to forest stands is a challenge that would be interesting to investigate. A power supply could open for electricity where the available technology is relatively good and improving in performance thanks to developmental advances in the car and truck industries.

The study focused on final fellings; conducting a similar study with an emphasis on CCF operations would be interesting.

This study provides forestry organisations, research and development organisations, and machine manufacturers active on the Swedish market with ideas for further evaluations and trials. What we expect to see is an increased materialisation of the most promising ideas, such as analysis through simulations, and time study analyses of virtual machines and/or physical concept machines. The steps may lead to improved technologies for Swedish logging operations.

5. Conclusions

The experts' predictions of future machine developments until 2033 can be concluded as follows:

- A clear expectation of further automation, with the greatest potential in automating easier working elements within a given time frame.
- A strong emphasis on electricity as an energy carrier/power train, with the greatest potential seen in hybrid technologies that combine electricity with other energy carriers.
- The continued dominance of the established two-machine system, with no significant alternatives expected to challenge its position.

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