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New technological solutions for waterlogged forests by cable yarding

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Abstract: The article proposes new technological techniques for clear cutting in swampy areas using standing skylines, new construction of yarder and the technology of its operation. As a result of the research on using the Larix 3T-500 cable yarder in winter and summer, the operational negative peculiarities of tower yarder in waterlogged forests were identified. Analysing data on experimental comparative time studies, some measures to reduce the negative effect of the identified features on yarding, felling, lateral yarding were worked out. General recommendations for work performance in swampy logging areas were developed. Based on the initial data for each bundle (yarding distance, lateral yarding distance, average volume of the bundle, etc.) the calculation in the MathCad program was performed and a regression dependence of the yarder performance was obtained. Obtained numerical data on comparative time studies of the working cycle operations were summarized in bar charts, taking into account the loss of time on operations.

Keywords: logging; productivity; swamp; special techniques

According to the official data in the Republic of Belarus from 2003 to 2019, the volume of wood in final felling, growing on waterlogged felling areas, is 1–1.3 million m^3 per year. The development of this volume is in the range from 60% to 90%. However, the use of harvester-forwarder technology does not result in developing the swampy forest areas. Cable yarding is a possible solution for waterlogged forests in the Republic of Belarus.

Wood harvesting in the swampy forest areas of the Republic of Belarus is a serious problem of the industry scale. At the moment, in the logging structure of the whole country, CTL-System is used in more than 95% of cases using harvesters and forwarders (option 1), gasoline-powered saw and forwarder (option 2), gasoline-powered saw and skidder (option 3). Less than 5% of the total volume of logging is carried out using the tree-length system. This smaller group also includes the harvesting of wood in swampy logging areas. Here the tree-length system is used.

The existing system of usability typification provides 4 groups (STB 1360-2002) depending on the bearing capacity, the type of forestry equipment, the groundwater level and the development season (Table 1).

There is no term “slope” in this typification, since Belarus is a flat country. The total area of forest areas with a slope of more than 15% is 2.9%. When working with slopes up to 10%, there are no restrictions on the use of any forestry equipment. When working on a hillside with a slope of 10–15%, the traction force and engine stability of the machines

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Table 1. Forest logging typification

Indicators		Types of soil: with low bearing capacity (peat-bog soil wetlands)	with weak bearing capacity (clay-loam and clay soil)	with medium bearing capacity (sandy and sabulous with increased moistening)	with high bearing capacity (sandy, sabulous of normal moistening)
Groundwater level from the cutting area surface (m)		0–0.5	≥ 0.5	0.5–2.5	≥ 2.5
Development season		dry summer, cold winter	summer, winter	summer, winter, dry autumn	throughout the year
Average unit pressure of wheels or tracks, maximum (kPa)	crawler-type vehicles	30	45	65	80
	wheeled tractors vehicles	–	100	140	180

are limited. With slopes of more than 15%, only crawler-type vehicles are allowed to work, the use of special skidding means is allowed.

In the documents regulating logging in the Republic of Belarus there are no items directly dedicated to skylines. These installations have not been used in the country for more than 30 years. The only yarding system that is used for the development of swampy cutting areas has been operating for only a few years and the results of its work are not currently known to a wide mass of loggers. Experimental studies were carried out on this yarder.

Swampy forest areas, in accordance with the operational typification in the Republic of Belarus, belong to the most difficult type for operation – type of locality IV, where the use of wheeled vehicles is not allowed, only crawler-type vehicles are allowed. The specific ground pressure constraint on soil is 30 kPa. However, in addition to the low bearing capacity of soils in this area, the output of groundwater to the soil surface is also a serious problem, which makes it almost impossible to effectively use crawler-type vehicles. A mobile skyline system is the only effective and cost-effective option for wood harvesting in such conditions.

Cable yarding is used in countries with mountain areas, such as France, Italy, Czech Republic, Slovakia, Switzerland, Slovenia, Austria, Turkey, USA, China, Croatia, Germany, etc. (Horek 2007; Spinelli et al. 2010; Lindroos, Cavalli 2016; Štollmann et al. 2017). It is also known that in Europe contract rates are higher for cable yarding than for ground-based logging. The application of such systems often starts to be used when the slope exceeds 40% (Spinelli et al. 2015).

The effect of various factors on the productivity of cable yarders was studied by various authors (Ghaffariyan et al. 2009; Spinelli 2010; Talbot et al. 2014; Huber, Stampfer 2015; Spinelli et al. 2015, 2017; Enache et al. 2016; Hoffmann et al. 2016; Lindroos, Cavalli 2016; Proto et al. 2018).

All of these works were based on experimental data. According to their results, productivity functions of cable yarders by the factors such as yarding distance, lateral extraction distance, piece size (m^3), logs per turn, etc. were formed. Moreover, due to a certain dissociation of the directions of the research sample, it was quite difficult to combine their results into one common system. In the studied sample, there is no research on the productivity models for cable yarding in waterlogged forests. In all diversity of factors, the authors did not take into account the seasonal variations, such as the type of soil, forestry restrictions that primarily affected the harvesting technology in each case, the proximity of waterways (rivers, lakes, swamps), workloads in described productivity models.

In contrast to other logging equipment, the operation of the standing skyline is more sophisticated, thus, more complex thinking is required for designing workplaces. Specific physical load of operators is typical – during delay times, pulling the main line into the stand, working at heights, etc. (Tsioras et al. 2011; Allman et al. 2017, 2018).

Air logging by helicopters minimizes the negative impact of the technology on the environment.

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Even though, this way of extraction is used only to a minimal extent, especially in mountain areas. High costs associated with forest harvesting, much higher compared to ground technologies can be regarded as the main reason (Akay, Bilici 2016; Grigolato et al. 2016).

Cable yarding is also used for site works after wind calamity, forest fires (Bilici et al. 2019). Tower yarders are used for clear as well as selection cutting (Enache et al. 2016), whereby the price of 1 m^3 of the timber cut in this way in mountain areas is several times higher than in the case of technologies when tractors or harvesters are used. Their application under these conditions is determined by the ecological impacts.

Forest harvesting using forest cableways is usually more economically beneficial in flat terrain than in mountain areas (Schweier, Ludowicy 2020). Therefore, the use of this equipment under the conditions of flat terrain is prospective.

In the case of logging in waterlogged forests, cable yarding is used significantly less often and, as a result, the study of the primary transport process in such areas is not completely covered. The practice of using a tower yarder in waterlogged forests has shown that the experience of using cable yarding in mountain-like conditions cannot be drawn on the flat swampy logging sites without changes (Erber, Spinelli 2020; Schweier, Ludowicy 2020).

Following the above-mentioned facts, it can be said that extensive research on the operation of cable yarder has been carried out, wherein technological schemes and working methods adopted for the use under the conditions of swampy cutting areas have not been developed yet. Therefore, the logging using a cable yarder was studied in more details and subsequent recommendations on the exploitation were made.

MATERIAL AND METHODS

The initial data for this work were obtained by conducting the research on cable yarding by Larix 3T-500 in summer (Figure 1A) and winter (Figure 1B) conditions in the base of SEI Berezinsky biosphere reserve, SFI Uzdensky forestry, SFI Gluboksky experimental forestry. Black alder was the predominant species in the studied stand and to a lesser extent at an approximately equal ratio, there were birch, spruce, or pine occasionally.

It is widely known that when logging in swampy logging sites, it has to be dealt with serious natural features. Low bearing capacity of the soils, groundwater discharge (Figure 2A, B) and high stumps, rhizomes of several trees (Figure 2C, D) remaining after felling, with the height of up to 1.5 m, are the most important of them.

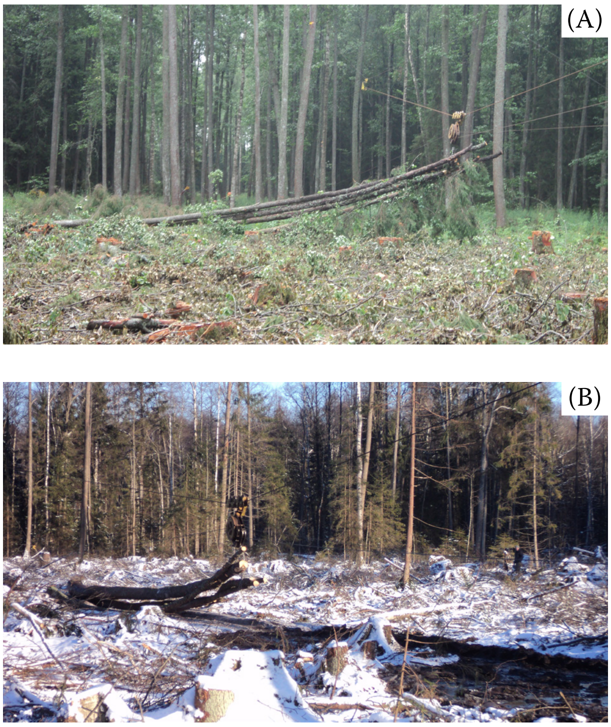

Figure 1. Yarding by Larix 3T-500 (A) summer conditions; (B) winter conditions

The explored Larix 3T-500 cable yarder was modified according to the Belarus 1525 agricultural tractor (Minsk Tractor Works, Belarus Republic). The maximal traction force of the installation was 3 t, the maximal skidding distance along the skyline was 450 m, the tower height – 7 m, lateral extraction distance – 80 m. The yarding crew consisted of 1 feller, 1 choker setter, 1 chaser man, 1 crosscutter. Skidders and forwarders were used to transport. The results of the researches performed are shown in Table 2.

For the three cutting areas given below, stopwatch studies were carried out and empirical functions of hourly productivity were obtained for P_h of the inquired installation Larix 3T-500. Performance equations were obtained by compiling a matrix of values of each studied factor (yarding distance, lateral yarding distance, etc.) in the MathCad program (Version 15, 2010) and then solving the matrix using the “solve” tool. The combined dependency looks like this:

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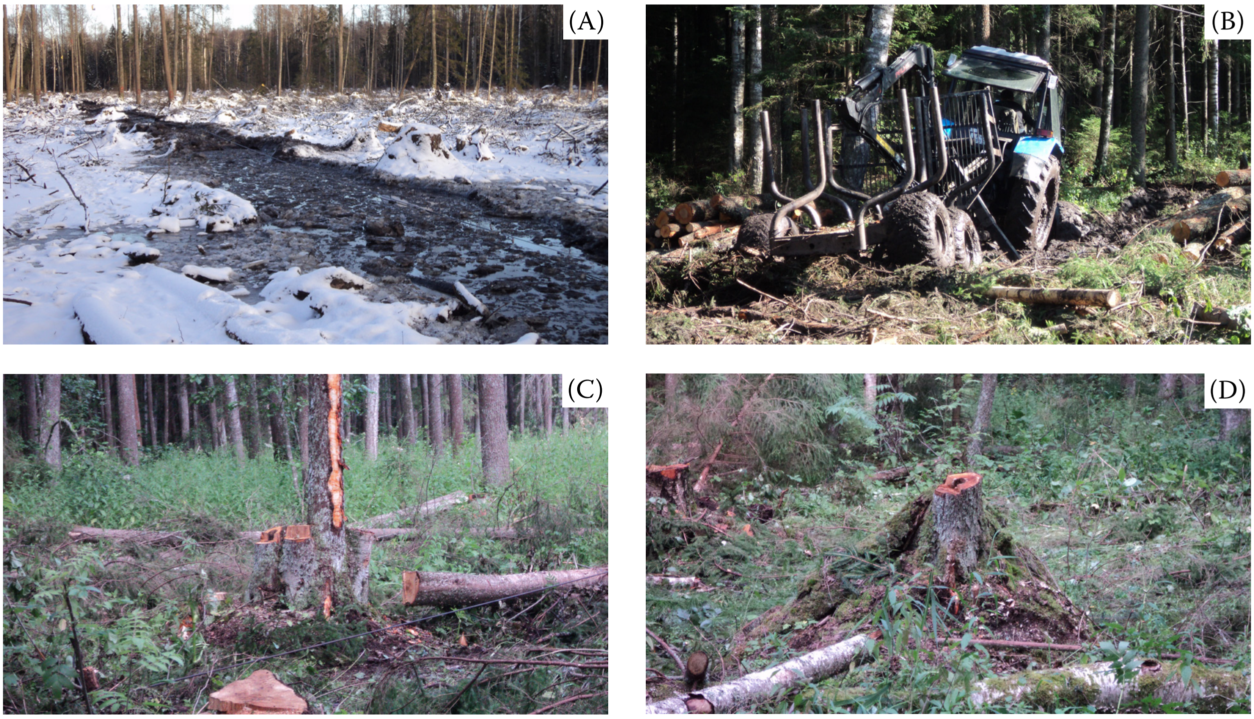

Figure 2. Natural-production features of waterlogged forests in Belarus (A) winter conditions; (B–D) summer conditions

Table 2. Main indicators of research of the operation of cable yarder in conditions of waterlogged forest

Indicator	Berezinsky biosphere reserve	Uzdensky forestry	Gluboksky experimental forestry
Machine		chainsaw, cable yarder	
Extraction direction		flat terrain	
Season of extraction	winter	spring	summer
Number of spans		100	
Total volume extracted (m^3)	2 356	1 412	1 753
Measurement cycles	130	154	161
Stand structure		*Alnus glutinosa*, *Betula pendula*, *Pinus sylvestris*	
Stocking (m^3·ha^{-1})	298	281	269
Crew		1 feller, 1 choker-setter, 1 operator carriage	
Operations		felling, hooking, delimbing	
Age (years)		60	
Treatment		clear cut	
Harvest intensity, volume (%)		100	
Harvest intensity, trees (%)		100	
Number of stems	4 925	2 450	2 988
Yarding distance (m)	0–500	0–340	0–420
Lateral yarding distance (m)		0–80	
Stems per turn	4.4	3.8	4.2
Stem size (m^3)	0.49	0.61	0.54
Average volume per cycle (m^3)	2.2	2.3	2.3
Productivity without delays (m^3·h^{-1})	6.5	7.7	7.4
Cost (EUR·m^{-3})	7.3	7.5	7.9

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$$P_h = -0.046 \times yd - 0.002 \times ly + 0.053 \times st + 19.672 \times \times ss - 35.002 \times avt - 4.622 \times sn \quad (1)$$

where:

P_h – total time productivity (m^3);
yd – yarding distance (m);
ly – lateral yarding (m);
st – stocking ($m^3 \cdot ha^{-1}$);
avt – average volume per turn (m^3);
ss – stem size (m^3);
sn – stems per turn (number).

It is apparent that the data did not turn out to be identical, despite the fact that the conditions for the three cutting areas were very similar. It happens due to the variation in forestry parameters of each specific cutting area. These empirical relationships for P_h are consistent with the data obtained by other scientists (Ghaffariyan et al. 2009; Spinelli 2010; Spinelli et al. 2015, 2017; Hoffmann et al. 2016; Lindroos, Cavalli 2016; Proto et al. 2018; Schweier, Ludowicy 2020). So, in most of the learned techniques, the main factors which have an influence on the process are yarding distance, lateral yarding, average piece size (number of stems), average piece size, terrain slope, etc. In our work, we did not aim to research all existing factors, but it was decided to focus on the most characteristic ones: yarding distance, lateral yarding, average volume per turn, stem size, stems per turn. The "stocking" parameter has also been set up. Together with the "average piece size/stem size" parameter, it determines the average number of trees per ha.

RESULTS

In the study of the harvesting process on three waterlogged cutting areas, measurements of the time spent on each operation of the working cycle were carried out, taking into account time delays and without them. The resulting graphs (Figures 3–5) allow us to compare these costs and determine the most complex operations by selecting the operations with the greatest difference between the costs of time.

The bar charts (Figures 3–5) were created in MS Excel (Version Professional, 2016). In their construction the data from comparative time studies performed on the three described cutting areas were used (Table 2). The values of the time spent were obtained in natural conditions by visual observation of the Larix 3T-500 yarder operation using a stopwatch.

The term "delays" designates the loss of time on the release of the clamped bundle, rechoking (repeated hook up), repeated transitions of the choker man to a safe distance, etc., which affected the cycle time increase. To eliminate these time losses, the worker needs to perform additional actions that increase the cycle time. The sum of "delays" and productive time was combined by the term "with delays". The net productive time was called "without delays".

The analysis of the graphs (Figures 3–5) allowed us to identify both the obvious labour-intensive operation (lateral in – because other authors have the same results), and, at first glance, not obvious operation (hook, carriage in, partly lateral out). Comparison of the data in the graphs and visual observations of timber harvesting when measuring the time spent allow us to draw similar conclusions for all three studied cutting areas. For some operations, such as carriage out and unhook, the difference in the cycle time is negligible. In the first case of carriage out it is caused to a greater extent by the inconsistency of actions between workers when taking control between the consoles of the operator near the installation and the hook in the cutting area. For the unhook operation, situations were observed when, after lowering the bundle, chokers did not spontaneously open when lowering, there were cases of entanglement of chokers, traction rope and whips. The time delays occur when manually pulling the lateral out, which depended on the complexity of the terrain: a waterlogged forest in which the legs of the workers bogged down. When carrying out a pull-up of a lateral out in winter in such areas, it is even more dangerous to move than in other periods of the year, since wetlands freeze with water coming to the surface and it is visually difficult to determine the degree of freezing depth and the water level under the ice. There were cases of a worker falling through the ice.

The biggest delays were observed when performing the operations of carriage in, lateral in, hook. The delays during the skidding operation were mainly associated with the contact of the skidded bundle and the trees of the intermediate supports (main and reserve), less often with the still standing trees. The lateral in process was complicated by a whole complex of factors: contact with high stumps, friction of a bundle or individual whips against stumps, growing trees, trees of intermediate supports, as a result of which the process

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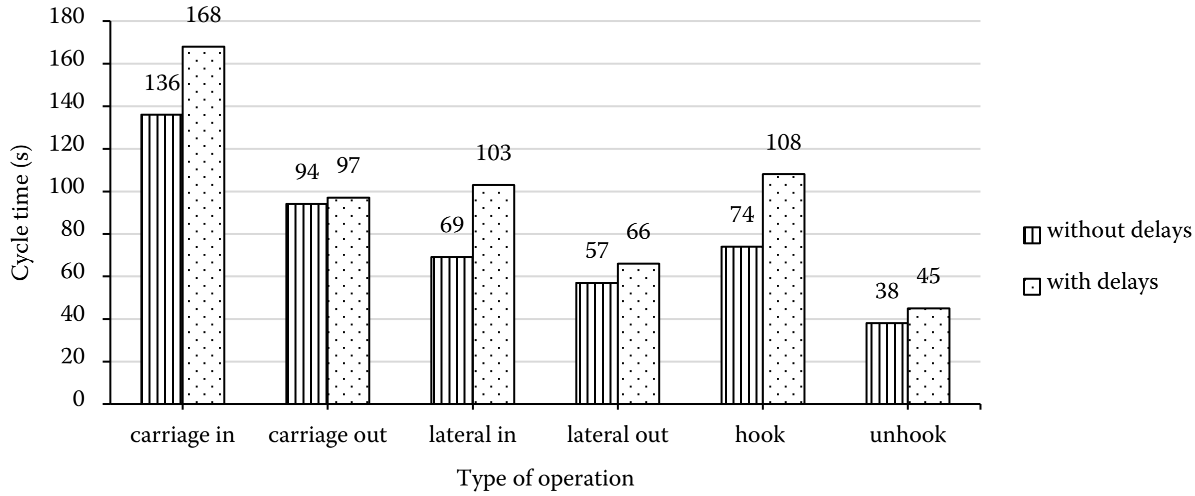

Figure 3. Comparison of mean cycle time with and without delays (Berezinsky biosphere reserve)

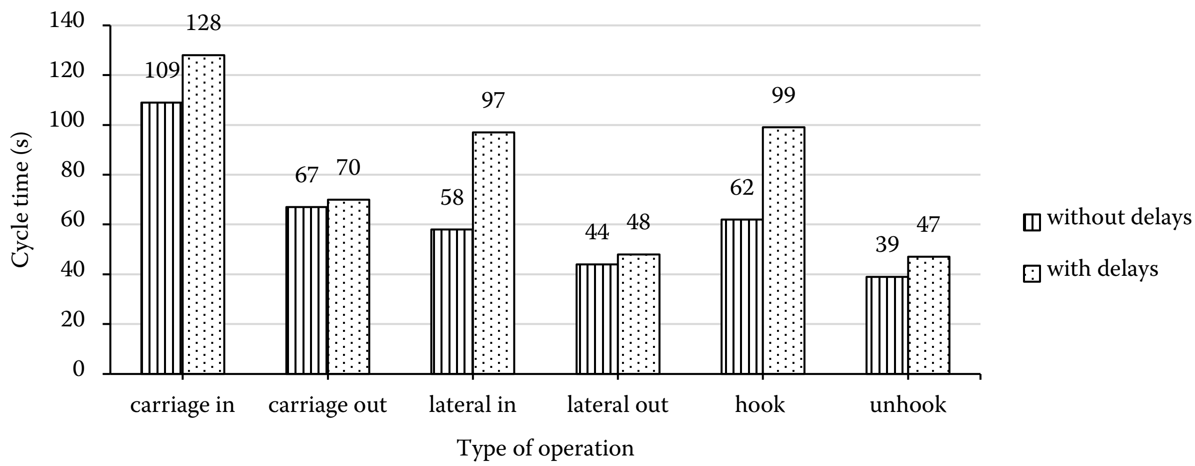

Figure 4. Comparison of mean cycle time with and without delays (Uzdensky forestry)

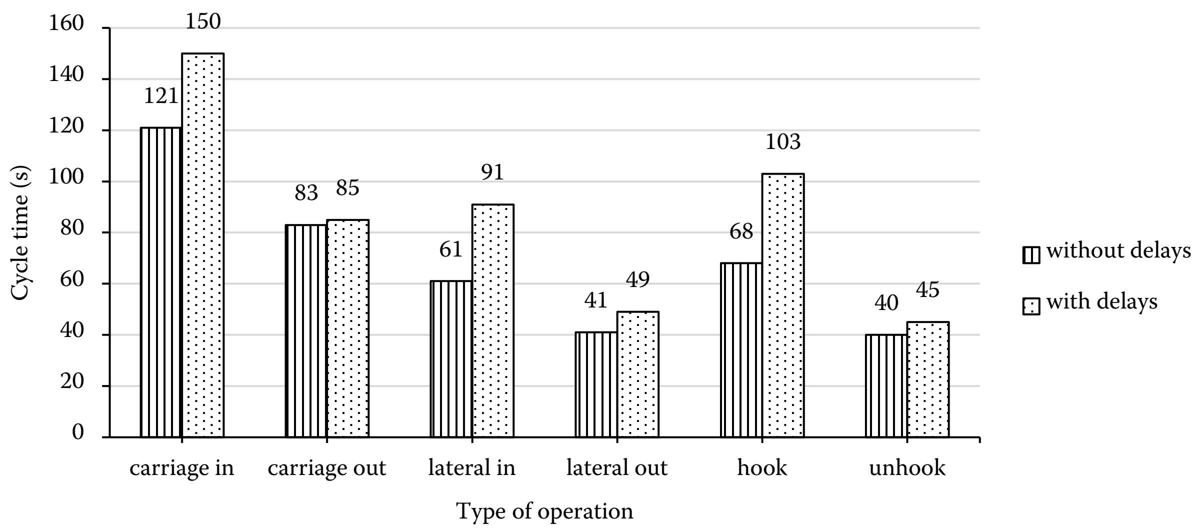

Figure 5. Comparison of mean cycle time with and without delays (Gluboksky experimental forestry)

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often stopped and was carried out in an intermittent rhythm with a reduced speed. The time spent on hooking stems has been increased by repeat this operation.

Based on the analysis of data obtained as a result of the research, the number of additional features related to the yarding in swampy conditions was determined (Figure 6).

Feature 1. The contact of moveable bundles and trees of intermediate supports during lateral yarding. It is a technological feature caused by the fact that the bundle does not manage to twist completely and starts to break out the intermediate supports during the lateral yarding (Figure 6A).

Feature 2. The clamp of the stump by the bundle. It is a forest growing factor to a greater extent, appearing not due to unskilled operations by the feller, but because of the impossibility of safe and efficient felling in coppice as the butt part of such trees is a cone-shaped formation with a high earthen hill or stump sitting on the roots and root flows (Figure 6B).

Feature 3. The resistance of moving bundle from stumps. It arises due to the structure of stumps on swampy logging sites. Frontal yarding resistance in the form of stumps (Figure 6C) is a common problem for the swampy logging site. A tear of the mainline is not common when trying to overcome such an obstacle using a bundle.

Feature 4. The low bearing capacity of access road soil. A considerable part of the area with groundwater discharge does not allow the use of both

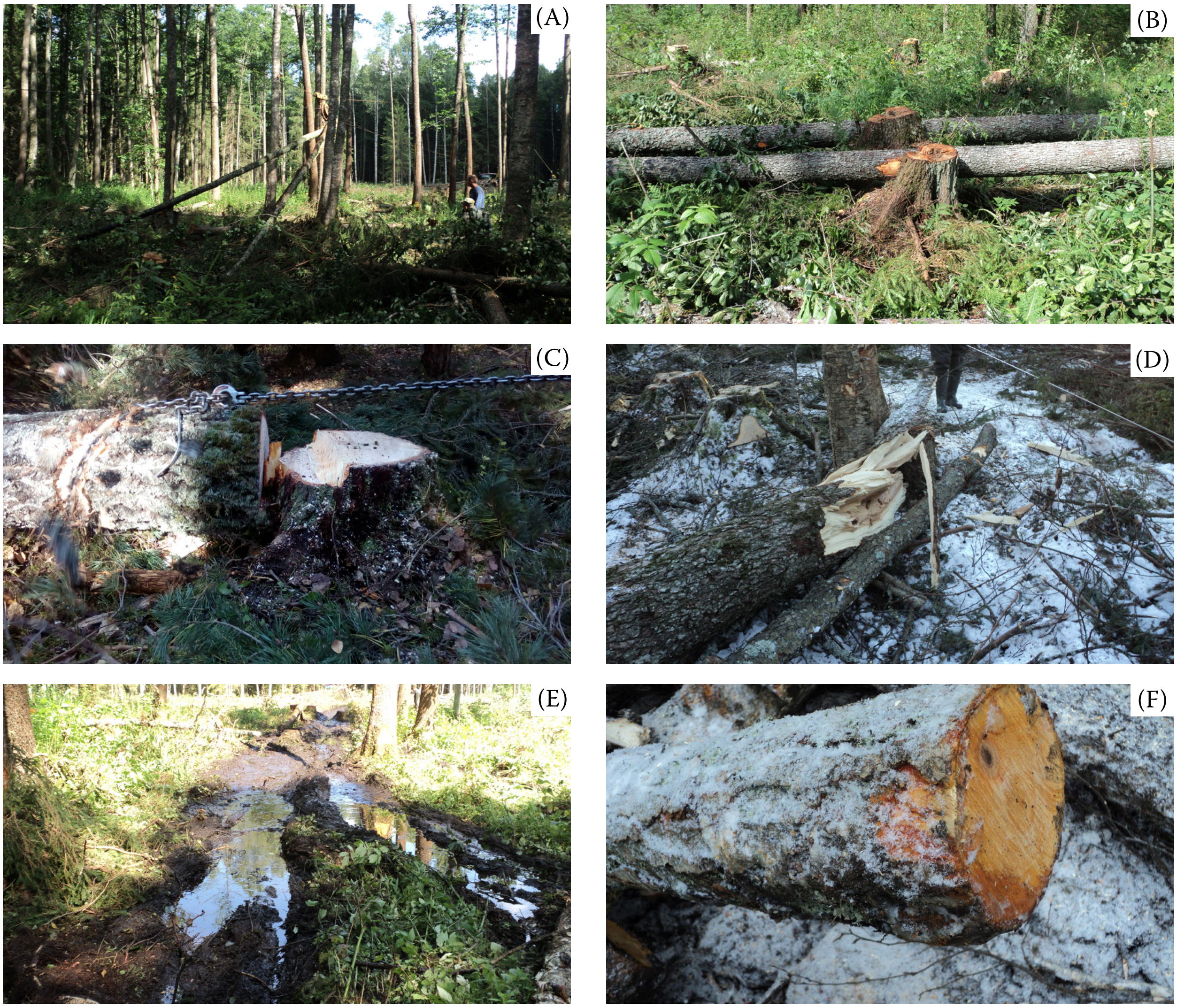

Figure 6. Difficulties of yarding (A) contact of the bundle of stems and trees of intermediate supports; (B) clamp of stump by bundle; (C) thrust of timber into the stump; (D) broken trunk of an alder; (E) swamp surface of the cutting area; (F) ice forming on timber

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wheeled and tracked vehicles or those with the combined type (Figure 6E).

Feature 5. The increased amount of residues due to the fragility of black alder wood. When conducting the research it was noted that during tree felling and processing with chainsaw, more waste is generated (Figure 6D). It is caused by the fragility of black alder making up more than half of swamp stocking. Some cases of trunk breaking into 3–4 parts when falling were observed.

Feature 6: Difficulty in accurate felling of coppice species (alder, birch) due to multiple root felts consisting of several trunks (2–5), as well as the brashness in timber of black alder when falling. The presence of stumps standing on buttress flares and root felts consisting of several trunks, as well as the need to orient the tops of the stems perpendicular or at an angle to the skyline, creates a difficult situation for the safe and effective work of a feller.

Feature 7. The work of the personnel becomes significantly more complicated due to ecosystem features of swampy cutting areas. In summer, the work of fellers and choker setter becomes more complicated due to a large amount of mosquitoes in wetlands. At any time of the year, the movement of the personnel around the logging site is limited due to the low bearing capacity of soils (Figure 6E).

Feature 8. Mud sticking (in summer) and forming ice on timber (in winter). The high level of mineral particles in the timber bark leads to an increase in the consumption of chains during cross-cutting. Forming ice on timber in winter also makes the process of bucking and moving near the stack as well as the process of collecting assortments by forwarder (Figure 6F) more complicated. In some cases, the freezing of timber to each other can occur.

As a result of studying technology experience of the cable yarding in the Czech Republic, Slovakia, Ukraine, the USA, Norway, etc., as well as the analysis of regulatory documents (Samset 1985; Horek 2007; Štollmann et. al. 2017) no specialized technological schemes and recommendations to eliminate the above-described features were identified. At the moment, assessment of the degree of an impact of all the above complicated situations on the productivity of cable yarder is a reasonable time-consuming task. However, the significant negative effect of these features on the safety of workers, the reliability of facility design, and the efficiency of logging when using this technology is absolutely obvious.

The figures shown in the diagrams (Figures 3–5) characterize the average execution time of each operation without time delays and with delays. In cases with time delays, additional time was required to release the clamped bundle, rechocking, repeated transitions of the choker setter to a safe distance, etc., which affected the increase in the cycle time. The cases when no such actions were required were called "without delays".

The above-described eight features complicate cable yarding in waterlogged forests. Recommendations for the logging of swampy cutting areas using cable yarding (mainly standing skyline) were consolidated and include:

Proposal for feature 1: Yarding in cutting areas directly adjacent to trees of intermediate supports, new methods of work were proposed (Figure 7A–D).

These techniques enable to exclude inefficient and labour-intensive features of stem yarding observed in cable yarding just when lateral yarding is done near intermediate supports. The development of the zone behind the intermediate support was one of the most responsible stages. If the methods of work in this area are not followed, the risk of injuries and breaking trees of intermediate supports increases sharply. This can be caused by rubbing between the bundle and the tree of intermediate support or incision of the bundle into a tree.

Scheme A (Figure 7) was applicable to the yarding of stems which were choked in close proximity to the skyline (trees growing in the zone of 0–10 m from the skyline). Tops felling towards the landing led to their fall on the trees of intermediate support or flanking mainline. Felling was carried out in the opposite direction from the landing. Stems in the bundle were chocked behind the butt and when lifted, they partially unfolded relatively to the tops to a position parallel to the yarding corridor and moved to the landing.

Scheme B (Figure 7). Felling was carried out with the tops in the direction opposite to the upper landing in such a way that at the first stage the bundle was yarded to the carriage and when yarding to the landing, there was a time when the bundle twisted completely to a position parallel to the axis of the skyline position.

Scheme C. Trees located on an additional half-swath 10 m wide were recommended to develop according to Schemes C and D (Figure 7). The difference between these schemes is that Scheme C was used in the cases when the top of the trunk

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after felling did not fall behind the anchor of the intermediate support in the direction of yarding, and Scheme D was used in the case when 1/3–1/2 of the trunk turns out to be behind the anchor of the intermediate support.

When applying scheme D, the trees moved in the area between the anchor and the tree of intermediate support. To apply this scheme, high precision of felling was not required, since the direction of yarding could be adjusted by the movement

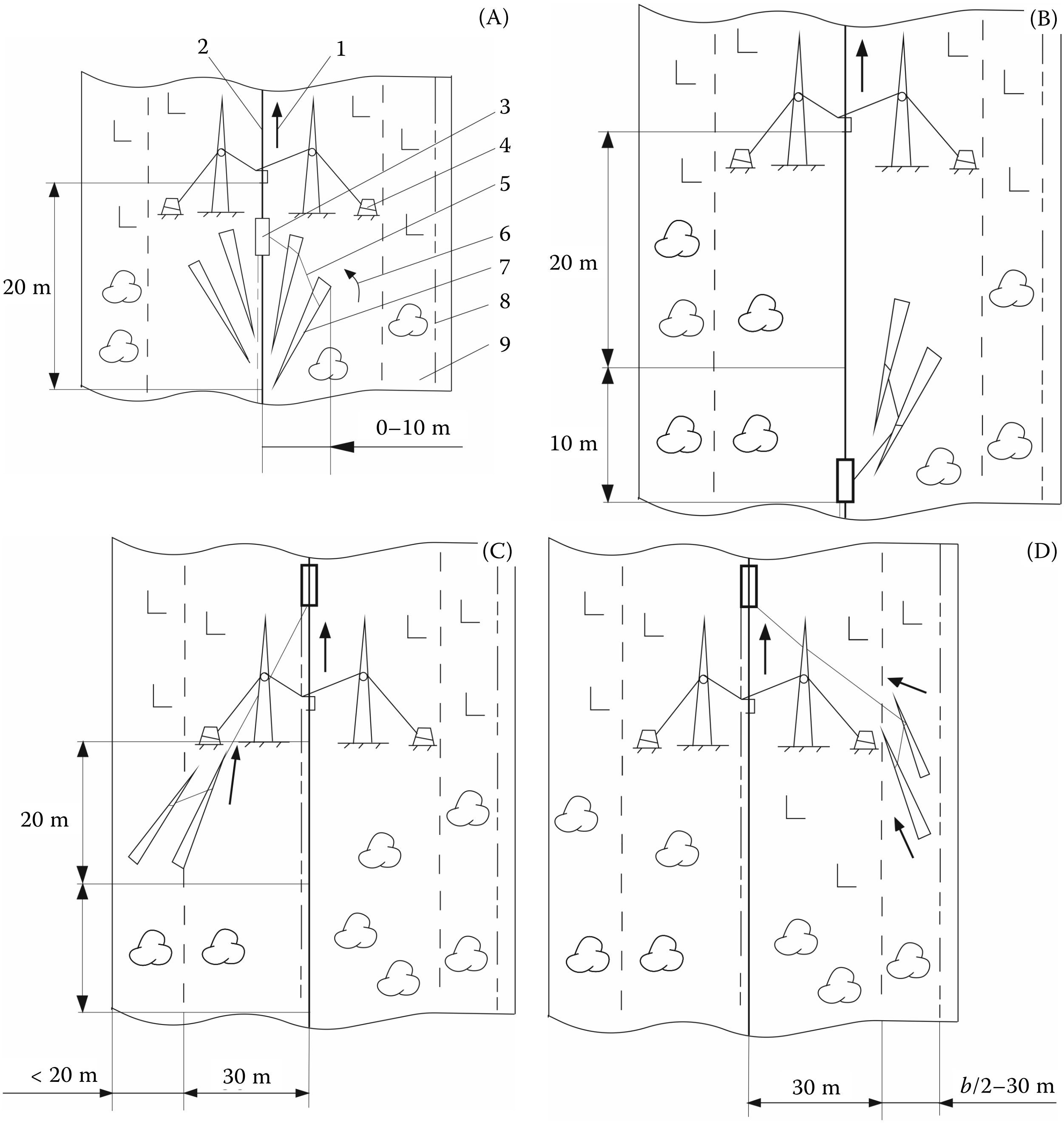

Figure 7. Scheme of the development of section behind intermediate supports (A) development of the main half-swaths; (B) development of a section up to 20 m long after an intermediate support; (C) the top part of the stems after felling is located on the main semi-apiary between the anchor and the tree of the intermediate support; (D) a bundle of stems is pulled up at an angle to the carriage, bypassing the anchor and trees of the intermediate support

1 – skidding direction, 2 – skyline, 3 – carriage, 4 – intermediate support anchor, 5 – mainline, 6 – the direction of the bundle reversal, 7 – chockered bundle, 8 – haul-back line, 9 – additional half-swath

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of the carriage along the linking skyline behind the intermediate support. In the case of applying scheme D, the contact of bundles and intermediate support was completely excluded.

Proposals for feature 2: To reduce the number of bundle clamps of stumps, it is necessary to conduct exact felling with laying the required number of trees with minimal spread over the tops in the perpendicular direction to the skidding corridor. In the situations close to the clamp around the stump, it is necessary to work consistently and to drag stems separately to the skyline. In some cases, these two features can be overcome by applying the developed technology (Figure 7).

Proposal for feature 3: To minimize the negative effect of the frontal contacts of the bundle with the stumps, the dragging has to be performed making short pauses (1–2 s) at the minimal speed using the choker and dragging schemes. There are generally accepted methods described in the paper of Samset (1985). Chocking is done in a special way to redirect forces in order to overcome obstacles. It is also possible to use skidding cones to reduce any negative impact of frontal contact (Figure 6C) (Schlaghamerský, Roško 1964).

However, the use of techniques (Figure 8A) is an extreme measure as long as it involves lines loading to a greater extent in comparison with standard operations. The use of a skidding cone is often preferred.

Proposal for feature 4: The issue of the increased ground moisture of access roads can be solved by their reinforcement:

– use of logging residues to make forest roads more durable;

– using the panels;

Proposal for feature 5: This problem is afforestation and there have been no possibilities to solve it so far. Partially, this problem can be solved by the directed felling of a tree on the "pillow" made of branches and twigs.

Proposal for feature 6: This feature, as well as feature 5, is unavoidable and, if such situations arise, it must be solved by performing special felling techniques specified in standard documentation – felling of such trunks is performed at the angle of 90° to the plane of the trunk inclination in the root felt.

Proposal for feature 7: To improve the quality of yarding crew work, it is necessary to supply workers with means for protection against insects, such as clothing and aerosols, laying the slab boards on the ground at the upper landing.

Proposal for feature 8: For this feature, like for feature 5, it has been difficult to provide an effective solution so far.

General recommendations for cable yarding in waterlogged forests:

– implementing the stem yarding mainly over the tops;

– consistent chocking during lateral yarding of stems through stumps;

– adding local soil when reinforcing access roads;

– lateral yarding from distant parts of the swath, it is recommended to form a bundle of no more than 2–3 stems at the maximum distance when hauling-in the bundle. As it nears the skyline, this number can be increased to 4–5 in close proximity to the skyline (up to 10 m).

The proposed cable yarder and technology. The proposed construction based on an automobile chassis and its operational technology (Figure 8A) can be considered an option to increase the wood procurement effectiveness in wetlands using cable yarding. The installation under working conditions includes two natural main supports and artificial main supports, natural rear supports with blocks suspended on them, six-drum winch, two flanking and one linking skylines, one central and two flanking mainlines, two support yarding carriages and one main yarding carriage (with its autonomous diesel engine), hydraulic manipulator with a hydraulic manipulator operator cabin and harvester head, real-time video camera on the main yarding carriage and clamp (Figure 8B). Using the system, the swath can be developed without labour-intensive operations: lateral yarding and hooking.

The main yarding carriage movement along the swath is performed using the central and two flanking mainlines. The central mainline is around the block in the main yarding carriage and it is connected to the grapple through which the grab of the bundle is carried out. The movement of three carriages to the landing at once is provided by the synchronic inclusion of the drums of all three mainlines.

The main yarding carriage moves around the swath along the linking skyline connecting support yarding carriages. The construction ensures timber collection anywhere on the swath.

The cutting area is developed parallel to the forest road (Figure 8). Felling is carried out by the feller perpendicularly to the road. For the convenient bundle capture, the direction of felling is selected

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to be able to capture the entire bundle with the grapple.

The grapple is operated using the video camera by the operator from the basic automobile chassis of cable yarder. After the release of the mainline drum, the lowering of the grapple into the bundle due to its weight occurs. When grapple tongs come into contact with the bundle, the sharpened edges of the tongs move apart and slide along the generatrix of the stems. Then the drum of the mainline is activated, which sets into motion the grapple tongs, which rise up and under their own weight connect under the bundle of stems, gripping them and lifting them till the contact with the stop on the carriage.

When the main yarding carriage reaches the landing, equitable stacking is performed. Sorting the stem bundles in the landing along the forest road by moving the main yarding carriage along the flanking mainline using its transmission and hy-

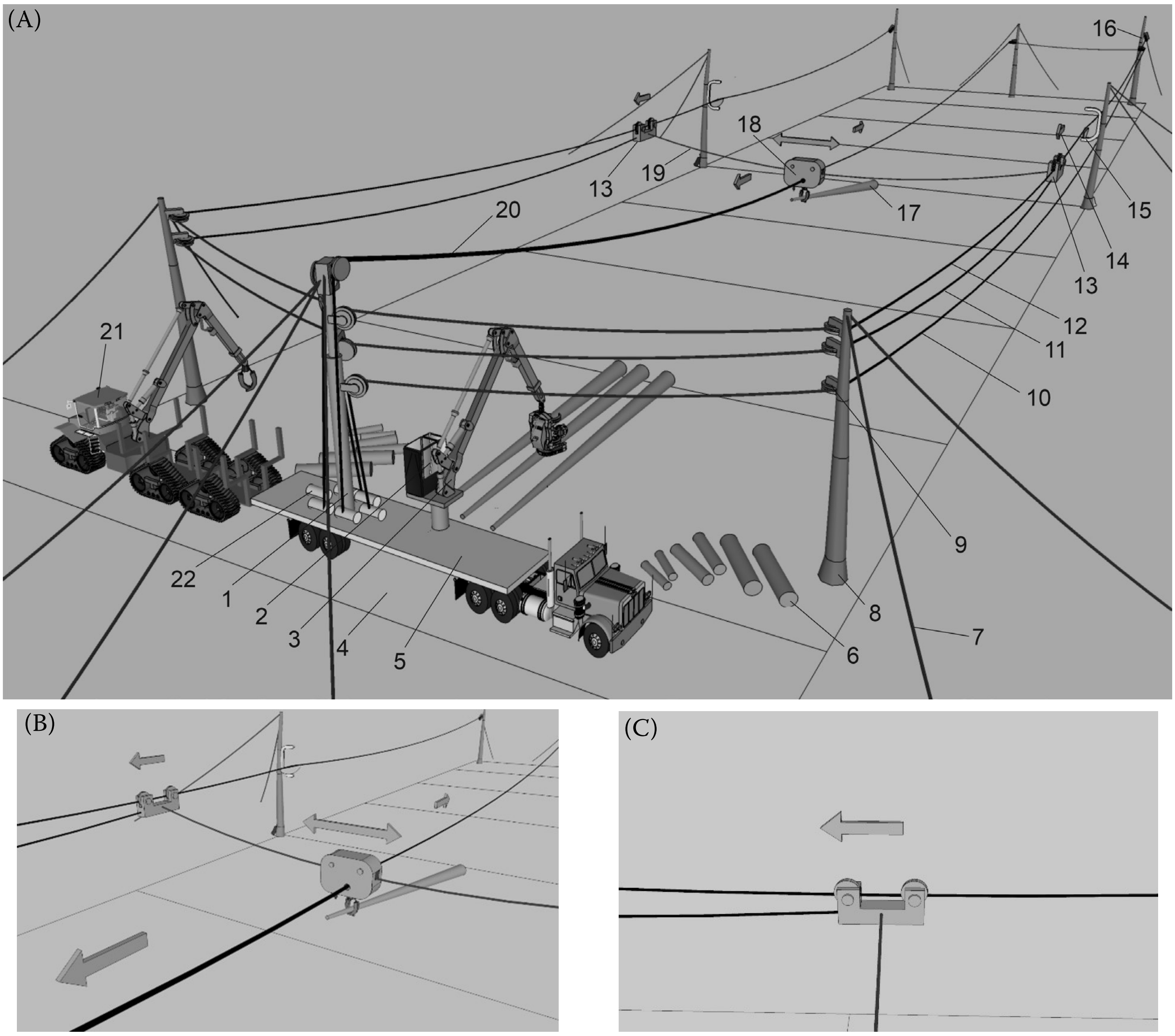

Figure 8. The proposed construction of cable yarder (A) general view; (B) main yarding carriage with video camera and grapple; (C) support yarding carriage

1 – metal headspar, 2 – cabin of the hydraulic manipulator operator cabin, 3 – hydraulic manipulator, 4 – forest road, 5 – basic automobile chassis of mobile cable system, 6 – sorted bundles of tree lenghts, 7 – guyline, 8 – tree headspar, 9 – tailblock, 10 – haul back line, 11 – flanking mainline, 12 – flanking skyline, 13 – support yarding carriage, 14 – direction of carriage movement, 15 – jack, 16 – tree tailspar, 17 – stem, 18 – main yarding carriage, 19 – linking skyline, 20 – central mainline, 21 – forwarder on tracked chassis, 22 – six-drum winch

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Table 3. Technical characteristics of the proposed system

Parameter	Measure
Corridor length (m)	500
Lateral yarding distance (m)	50
Lifting capacity (kg)	3 000
Distance between side supports in width (m)	70–100
Line speed without load (m·s^{-1})	5
Line speed with a load (m·s^{-1})	2
Tower height (m)	6
Crane lifting force (kNm)	150
Basic unit/power (HP)	400
Skyline – linking, flanking and central (m·mm^{-1})	550/20
Mainline (m·mm^{-1})	550/12
Weight main yarding carriage (kg)	500
Weight support yarding carriage (kg)	30

draulic manipulator controlled by the cab worker takes place if it is necessary.

Carriage out is provided by the inclusion of the haulback line returning to the logging site both main yarding and two support yarding carriages connected to it using the linking skyline. Yarded bundles are crosscut in the landing and sorted into several groups. Harvested timber is transported using a forwarder on the tracked chassis (when transported to the loading point). However, at the present time, this system is only tested. In the future there is a possible option without central and two flanking mainlines and haulback line. When using all three carriages with a separate autonomous engine, such a system is possible.

For the proposed system, the following technical characteristics are provided (Table 3). These technical characteristics are indicative and may change during the design and manufacture of the proposed cable yarder.

DISCUSSION

As can be seen from the dependencies [Formula (1)], the factors that most affect P_h are stem size, average volume per turn, stems per turn. This pattern completely coincides with similar studies for rope installations in mountainous areas (Ghaffariyan et al. 2009; Spinelli 2010; Talbot et al. 2014; Huber, Stampfer 2015; Spinelli et al. 2015, 2017; Enache et al. 2016; Hoffmann et al. 2016; Lindroos, Cavalli 2016; Proto et al. 2018).

Regression analysis of the performance of the proposed system was not carried out. Another approach to the issue based on identifying the key problems following the chronometric measurement when pulling the load from the land under skyline and during its yarding to the landing (in total 8) was used. The mentioned approach seems to be well-founded. Formulas dealing with the dependence of time necessary for individual operations of timber extraction were mentioned in a large number of already published works (Ghaffariyan et al. 2009; Spinelli 2010; Talbot et al. 2014; Huber, Stampfer 2015; Spinelli et al. 2015; Lindroos, Cavalli 2016; Proto et al. 2018). The effect of all relevant technological factors (mean yarding distance, mean stem volume, extraction distance, etc.) is expressed by them. Other works show the development of individual times after specific operations: carriage out, lateral out, hook, lateral in, carriage in, unhook and others (Hoffmann et al. 2016; Spinelli et al. 2017). Following the mentioned approaches, the time consumed during each operation with the corresponding range (the difference between the minimum and maximum measured values) can be evaluated. However, factors affecting individual time intervals cannot be determined. In most cases, measured data are statistically processed and the correlations and true-like values are provided. Specific manufacturing processes, rope systems used (ways of installing the lines) and the technological processes are taken into consideration only partially or they are completely ignored. The results obtained in this way do not allow the detection of several factors covered in the total time consumed. Main factors (in total 8) affecting the time consumed during cableway skidding, even though with no exact numerical assessment, are synthetized in the article. The effect of the factors was evaluated following the lengthening of the time necessary for yarding in comparison with the standard time consumed and not affected by disruptive factors. At the present time, the issue dealing with the effect of the factors on forest cableway productivity and effectiveness has not been discussed yet.

Comparison of regression dependencies for determining productivity (Ghaffariyan et al. 2009; Spinelli et al. 2015; Hoffmann et al. 2016; Lindroos, Cavalli 2016) with the obtained dependency for swampy felling areas showed that the coefficients for the same variables in the expressions for P_h are close values. At the same time, there are also distinctive patterns. The coefficients for *ss* (stem size) and *sn* (stem number) are the largest of all the studied works. This is caused by a combination of factors. An increase in the number of tree-length logs in a bundle directly affects the number of hang-ups of the bundle during lateral yarding. These two indicators are closely related and mutually affect each other. On the one hand, an increase in the volume of tree-length logs leads to a decrease in the number of tree-length logs in a bundle (fewer hang-ups). On the other hand, an increase in the volume of a tree-length log leads to an increase of a tree-length log itself in the geometric dimensions, which also leads to an increase in resistance when moving. The coefficients in front of the *yd* and *ly* are an order of magnitude larger (1–2 times and 2–3 times, respectively) in comparison with data (Ghaffariyan et. al. 2009; Spinelli et al. 2015; Hoffmann et al. 2016; Lindroos, Cavalli 2016), which indicates a more close interaction between performance from skidding distances and lateral yarding for swampy cutting areas.

It was difficult to take into account the long-term statistics of harvesting with a cable yarder, since it has been working for only a few years and data collection for each cutting area was not carried out. It was also difficult to take into account the level of staff training (Schweier, Ludowicy 2020), since there are no specialized training courses for such equipment in the country, there is also a "staff turnover" in the forestry of the Republic of Belarus.

Higher towers, artificial anchors, mechanized bunching before extraction and un-guyed yarder-systems can also be a temporary solution, along with the proposed solutions (proposals) in adaptation of yarder performance on flat marshy cutting areas (Erber, Spinelli 2020). The proposed solutions are already being applied one by one or in groups by a number of manufacturers of cable yarding systems. Combining them with the proposed solutions can increase the degree of efficiency of the use of such systems in swampy lowland cutting areas. However, further research is required to select the most effective solutions from among those proposed in this paper and in the source (Erber, Spinelli 2020) so that the resulting adapted installation with upgraded technology does not become a set of many ways and means that restrain each other.

Modification of operation processes (by using the pulleys to change the line direction) can result in reducing several adverse factors and damage in the remaining stand (Picchio et al. 2012). Manual transmission, installation, and dismantling of directional pulley causing the lower labour productivity are required in the case of the given procedure.

Assessment of cost effectiveness of the proposed yarding system is a little bit complicated as no similar equipment has been used in the practise yet, either in mountain areas or in wetlands. It is supposed that this system will be more effective than the modern cable yarders, because of no lateral yarding and manual work associated with load movement. Therefore, the time consumption is reduced as well as the number of yarding crews (Devlin, Klvač 2014).

Procedures mentioned in Figure 8 followed the research on the process of yarding in wetlands using standard forest cableways. Reducing the effect of eight specified adverse factors is the aim of the proposed procedures. The procedure from Figure 8 reduces the manual operations of choker setter and chaser man and thus, the safety in the workplace can be improved.

Nowadays, the use of helicopter air transport of timber (Akay, Bilici 2016; Grigolato et al. 2016) in wetlands is not effective. It can be used only in specific stands at the environmental protection area, biosphere reserves, in the areas with poor road network, in the case of difficult manufacturing conditions where standard equipment cannot be used – under conditions when the cost effectiveness is not a parameter of primary importance.

Manufacturers of cable yarders offer technological solutions of forest cableways allowing the yarding in mountain as well as in flat areas. They are proposed for the use on hard surfaces with high bearing capacity (Erber, Spinelli 2020). On the market with forest cableways, there is a lack of the cableways proposed for the work in the flat wetlands.

In the waterlogged forests a modern standing skyline can be used in terms of technology, but it is not cost-effective. They are preferred in the areas where the emphasis is put on an ecological aspect.

CONCLUSION

The work technology proposed in the article as well as special working methods applied in waterlogged forests were tested under winter and summer conditions at SEI Berezinsky biosphere reserve, SFI Uzdensky forestry, GLHU Gluboksky experimental forestry. The use of new technology

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made it possible to exclude the loss of time for bundle rechoking, and to prevent situations with the threat of trees causing intermediate support breaking. At the same time, a significant step forward in the development of special cable skidding systems and their technology when working under the conditions of swampy cutting areas can be made.

The proposed yarder and technological equipment should be used especially in the waterlogged forests. They can be also used for cutting areas with difficult conditions – after wind calamity, forest fires, along the electric power transmission lines, etc.

As a result of the study it was found out that when logging using cable yarding under the conditions of flat swampy logging sites, the number of features reducing the effectiveness of logging using such systems arises. To overcome the difficulties caused by these eight factors (the contact of a moveable bundle with trees of intermediate supports during dragging, clamp of stump by the bundle, resistance of moving bundle from encountered stumps, the low bearing capacity of access roads, the increased amount of cutting waste, difficulty in precise felling of coppice species, complicated work conditions of the personnel), special solutions were proposed. Tested in practice was one of the solutions (the methods to eliminate the contact problem between the moving bundle and trees of intermediate support when dragging were tested in the research). Rational solutions were proposed to eliminate the negative impact of most of the features, however, part of them, such as ice formation, mud sticking, the low bearing capacity of access roads require the creation of new technological methods during skidding.

Currently, a wide range of cable yarding can be used in the waterlogged forests. The most commonly used is standing skyline based on the developed methods to eliminate the difficulty of contact between the bundles and supporting trees. Other recommendations were also developed primarily for this system.

However, the transition to the proposed system allows the improvement of the operations in the logging site as compared to existing systems. The number of workers in the yarding crew can be reduced to three (if there is a feller) or two (when using the felling carriage). This way, the time of performing the primary transport of timber to the upper landing can be reduced significantly and the job safety of workers can be improved as well.

The working conditions of mobile cable logging systems in lowland swampy cutting areas are quite different from the mountain conditions of logging. In this case, it is necessary to work on a new technology, or on a traditional one, but with working methods and technical and technological solutions that reduce the negative effect of the forest-growing features of swampy cutting areas. However, this solution will be only partially effective, since the existing installations were developed primarily for mountain conditions. It will be more rational to create a design of a new cable yarding system, which will be adapted primarily for work in lowland swampy areas, and can also be effectively used, if necessary, in mountain forests.

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