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APPLICATION OF TERRESTRIAL LASER SCANNING MEASUREMENTS FOR WIND TURBINE BLADE CONDITION SURVEYING

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Abstract

Wind turbines are among the key equipment needed for eco-friendly generation of electricity. Maintaining wind turbines in excellent technical condition is extremely important not only for safety but also for efficient operation. Studies indicate that defects in the external structure of a turbine blade reduce energy production efficiency. This research investigated the potential of the terrestrial laser scanning technology to examine the technical conditions of wind turbine blades. The main aim of the study was to examine whether terrestrial laser scanning measurements can be valuable for wind turbine blade condition surveying. The investigation was based on the radiometric analyses of point clouds, which forms the novelty of the present study. Condition monitoring focuses on the detection of defects, such as cracks, cavities, or signs of erosion. Moreover, this study consisted of two stages. The next objective entailed the development and examination of two different measurement methods. It was then identified which method is more advantageous by analysing their effectiveness and other economic considerations.

Keywords: Terrestrial Laser Scanning (TLS), intensity parameter, measurement methodology, wind turbine blades, condition surveying, defects detection.

1. Introduction

Global warming is among the most significant global problems. In this regard, the development of *renewable energy sources* (RESs) is important in protecting the environment. First, given the excessively high CO2 emissions, the presumption is that any electricity generation method that has low dependence on coal is profitable and beneficial. Second, fossil fuels are finite and their deposits are being depleted. Developing countries become energy-independent through RESs because their energy security improves. Moreover, RESs may be highly relevant when countries with gas or oil resources are involved in armed conflicts because such situations may lead to energy crises.

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Environmentally friendly energy generation can be implemented through various means, such as producing biomass and biogas as well as operating hydroelectric, photovoltaic, and wind power plants. The last two are typically associated with RESs and are the most popular methods for generating green energy. According to a report published by WindEUROPE [1], Europe currently has 236 GW of installed wind power capacity. In 2021, Europe's wind farms generated 437 TWh of electricity covering 15% of the demand in EU-27+UK. The expectations for the next few years are even greater. The International Energy Agency expects wind to be the foremost power source in Europe by 2027.

Given the ongoing progress concerning the technologies for wind turbine construction, these expectations will likely be met. The increasing demand for wind energy has led to the development of increasingly large wind turbines, in terms of blade sizes, and in large numbers. A larger wind turbine blade size increases the amount of energy produced. Wind turbines are towers built up to 160 m above ground [2]. Unfortunately, this results in difficulties in inspection and maintenance. Accordingly, various technologies to reduce the costs associated with the periodic technical inspections of wind turbine blades are undergoing investigation. Methods for accurately and efficiently detecting defects are invariably in demand. The lifetime, dependability, and efficiency of an entire system are considerably dependent on the periodic monitoring of its technical condition. As with any other technical devices, the technical condition and exploitation characteristics of wind turbines deteriorate in time.

A minor defect occurring at a critical point of the blade (*i.e.*, at the hub or in the vicinity of the *leading edge* (LE)) may exponentially increase the extent of damage. The initial effects of erosion processes on blades may appear 2–3 years after commissioning the turbine for operation [3]. Many studies have proven that erosion degrades turbine performance [4, 5]. Sareen *et al.* [5] revealed that LE erosion is significantly detrimental to aerofoil performance. They proved that the increase in drag, resulting from light erosion to heavy erosion, reaches 6%–500%. Based on the foregoing, the researchers estimated that an 80% increase in drag due to a relatively small degree of erosion may result in an annual energy production loss of approximately 5%. If the drag increases to 400%–500%, coupled with the loss in lift (moderate-to-heavy erosion cases), an approximately 25% loss in annual energy production may be observed. This state indicates that an effective and well-organised technical diagnosis of minor defects can prevent critical damage to wind turbine blades.

Owing to the nature of objects that may constrain measurements, technologies that enable the remote collection of metrics are optimal for diagnosis. Moreover, currently, measurement techniques that do not interfere with the structure and surface properties of objects are highly preferred (non-destructive testing or non-destructive examination). Evidently, the intactness of an object under examination is among the most significant factors affecting the choice of measurement method. Prior studies indicate that the following non-destructive methodologies that can be used in the context of the diagnostic testing of wind turbines [6]: ultrasonic testing techniques [7], photogrammetric methods, acoustic emission [8], thermography [9], performance monitoring, radiographic inspection [7], and *terrestrial laser scanning* (TLS) [10, 11]. Nowadays, the photogrammetric method is the typical one used to examine the condition of wind turbine blades, as well as terrestrial photogrammetry and using unmanned aerial vehicles (UAVs) [12]. The major advantage of UAV photogrammetry is definitely the wide-ranging cost reduction, without losing data quality (images from a lower distance than conventional land-based photogrammetry). The aforementioned cost reduction is associated with various aspects. Firstly, this is due to the lack of need to use specialized equipment; to construct scaffolding and use elevators. Secondly, the relatively short time required for inspection, thus minimizing turbine shutdown time and minimizing financial losses. Despite the important advantages of this technology, it should be kept in mind that it is not fully effective. Taking photographs is possible only under favourable atmospheric conditions, especially one must be mindful of the wind. The same cost-reduction advantages are ensured by the TLS technology. However, an additional advantage, compared to photogrammetry, is the ability to perform measurements under more windy weather conditions. Besides, the automatization of data processing is nowadays an important issue. Advances in technology have made *computer vision* (CV) an accurate methodology for assessing the condition of structures. Satisfactory quality, combined with reduced human effort, causes the CV technology to be highly desirable. Nowadays, the CV is successfully finding its application in structural health monitoring, including crack detection [13, 14]. Methods such as machine learning or deep learning have found application in defect detection [15, 16]. Guo *et al.* [17] presented damage identification of wind turbine blades with deep convolutional neural networks.

So far, the studies on the TLS technology, with regard to wind turbines, have been limited to object deformation verification (*i.e.* deformation and torsion of blade and tower as well as tower verticality) based on three-dimensional (3D) coordinates. A literature review indicates that the research on the possibility of using the TLS technology, especially that based on the analysis of radiometric point cloud information, to detect defects on the surfaces of wind turbine structures is limited. Accordingly, the present study entailed a thorough investigation and analysis of this technology.

To the authors' best knowledge, the TLS technology has the potential for defect detection. It enables remote measurements with a large information package (more than 1 million points per second) and considerably high resolution. In addition to spatial coordinates, TLS records the power of the laser beam reflected from a scanned surface. The radiometric power of the laser beam can provide information regarding any changes in the physical and chemical properties of the scanned surface. Such information is extremely useful in the technical diagnostic measurement of construction objects. Thus far, the TLS technology has been applied to many research fields [18–27]. The application of TLS ranges from the simple modelling of building structures to the detailed monitoring of the technical conditions of building walls. A recent survey showed that this technology enables the diagnosis of building structures and detection of wall cracks with a size even of a few millimetres [28]. Given the tremendous potential that TLS has exhibited thus far, it is reasonable to argue that its application to the technical condition examination of wind turbine blades must also be investigated. Any surface change on the blade (possibly a defect) can be detected based on radiometric point cloud analysis. However, the proposed technology also has limitations. Many factors affect the quality of TLS data. The knowledge of the potential and limitations of a measurement method is significant in planning to attain specific objectives. For instance, measurement involving wind turbine blades is especially challenging.

The main aim of this study was to explore the potential of the TLS technology to examine the technical conditions of wind turbine blades. The possibility of detecting blade's defects was based on the analysis of radiometric point cloud information, which forms the novelty of the present study; similar studies are not found in the literature. Condition monitoring focused on the detection of turbine blade defects, such as cracks, cavities, or signs of erosion. The study consisted of two stages. The next objective was to develop a measurement method for examining the technical conditions of wind turbine blades using the TLS technology. Two different methods (approaches) were compared so as to determine which one is more beneficial. The main criteria were the effectiveness of the methods and economic considerations. The tests were conducted under field conditions for various research objects.

2. Theoretical background

2.1. TLS

Terrestrial laser scanning is a non-destructive and remote sensing technology that enables the generation of a high-precision 3D model of the scanned object. After appropriate post-processing, the final product of TLS measurements is a huge information package called a point cloud. A point cloud is a set of data consisting of spatial points (XYZ coordinates) positioned relative to each other with user-selectable scanning density. The coordinates of each point are defined in relation to the centre of the scanner (polar coordinates). They are determined by the horizontal and vertical angles as well as the distance to the object as measured by a rangefinder. In addition to geometric information (XYZ), radiometric information (the so-called intensity parameter) is derived. Intensity is simply defined as the ratio of the power of the received energy to the power of the energy emitted by the TLS device.

The TLS technology is based on measuring the distance between the TLS sensor and tested target. Manufacturers of TLS scanners use two techniques for distance measurements. One scanner type uses the time of flight and the other scanner type uses phase shift. In summary, the phase-shift technology is characterised by speed, high accuracy, and medium range, whereas the time-of-flight technology has a longer range, slightly lower accuracy and speed than the former [29]. Therefore, choosing the right type of scanner in the context of expected measurement results is necessary.

The broad application of this technology indicates its interdisciplinary nature. Therefore, its implementation to resolve the research problem in this study is anticipated to yield satisfactory results. The key aspect in the context of using the TLS technology for wind turbine blade defect detection is the intensity of the laser beam. In this investigation the results were analysed based on the intensity parameter. Intensity is an additional parameter recorded by the TLS detector [30] that provides information regarding scanned objects. It is defined as the backscattered energy of the laser beam. In addition, in the scientific community, intensity is commonly considered as the fourth coordinate next to XYZ. Intensity represents a mathematical relationship between *emitted* (PT) and *received* (PR) TLS signals [31]. For a Lambertian surface, the relationship is described by a simplified version of the laser equation [32]. Reflectance is a highly problematic parameter due to its dependence on multiple physicochemical characteristics of the scanned surface. The most significant effect on the power of the received signal comes from properties such as colour, roughness, and moisture. Many researchers have described the influence of these properties on the absorption and dispersion of laser beams (*e.g.*, [33–35]). In contrast, from the perspective of blade defect detection, the absorption and dispersion of the laser beams can be regarded as an advantage. This is because blade defects are typically characterised by changes in colour and structure (smoothness). Based on the studies conducted thus far (*e.g.*, [34,35]), dark colours have been found to absorb a greater amount of the laser beam than light colours. Therefore, the intensity values in blade sections with defects are expected to be lower. Moreover, rough surfaces cause more beam scattering than smooth surfaces. Consequently, bigger scattering occurs at defect locations, causing changes in intensity values.

Notably, the change in intensity may also be caused by a change in the angle of incidence of the laser beam. This occurs because as the angle of incidence increases, the size and shape of the laser spot are significantly modified [36,37]. Studies have shown that as a rule, intensity values decrease as the angle of incidence of the laser beam increases. However, data can be normalised, and the effect of a change in the angle of incidence can be reduced. Solutions for minimising this effect have been presented in literature, *e.g.* [32, 38]. The problem resulting from a change in the angle of incidence in relation to wind turbine blade measurements is presented in Fig. 1. The red line depicts the laser beam, the black line is perpendicular to the surface at the point of incidence (called the normal), and α is the angle of incidence at the point of incidence.

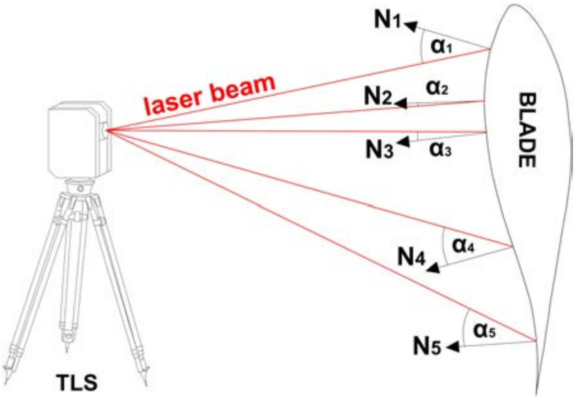

Fig. 1. Effect of the angle of incidence on intensity values.

2.2. Wind turbine

The blade, one of the key components of turbines, is the object of this study. A typical wind turbine blade, along with the common names of its various edges and sides, is presented in Fig. 2.

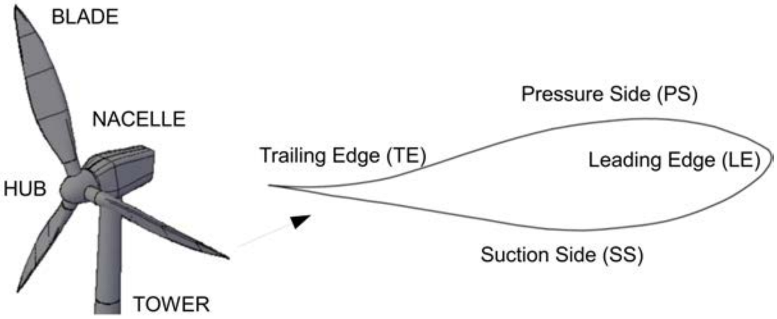

Fig. 2. Wind turbine main components and a cross-section schematic of a wind blade [39, 40].

Damage to the external surface of a wind blade during its lifetime is an everyday phenomenon; hence, defects are undesirable but normal. The formation of defects mainly depends on various environmental conditions under which turbines operate and that are completely beyond the control of turbine users. The most fundamental types of wind turbine blade defects and their corresponding causes (according to a literature review and knowledge verification through interviews with companies working on wind turbines) are listed in Table 1 [39].

Table 1. Typical structural damage and its causes in wind turbine blades [39].

No.	Condition/Cause	Damage/Defect type
1	Precipitation	Droplet impact/LE erosion
2	Dust	Particle impact/LE erosion
3	Low temperature	Icing on surface/LE erosion
4	Precipitation + low temp.	Hail impact/LE erosion, structural damage
5	Foreign object impact	Bird strike/LE structural damage
6	Lightning strike	Local heat exceedance/structural damage
7	Salt formation	Salt formation on surface/drag increase
8	Overspeed	Design load exceedance/structural damage
9	Manufacturing anomalies	Propagation of manufacturing error by load structural damage

3. Research and results

To investigate the possibility of using the TLS technology for measuring wind turbine blade defects, the research was divided into two stages. These stages were both implemented as a result of a partnership with one of the wind farm operators. All tests were performed in an outdoor environment using a phase-shift scanner (a Z + F 5016 IMAGER). This scanner is characterised by a maximum data acquisition rate of 1 100 000 pixel/s, operational range of 0.3–365 m, and range error of ≤ 1 mm +10 ppm/m. For the Z + F 5016 IMAGER, the laser beam spot size and divergence were 3.5 mm (at the exit) and 0.3 mrad, respectively. The open-source CloudCompare software was used for the post-processing of datasets and mapping of results. Raw data were used in this study. Moreover, data normalisation considering the effect of the laser beam's angle of incidence was ignored because surface changes in a relatively close vicinity were considered. A general scheme of the research programme is shown in Fig. 3.

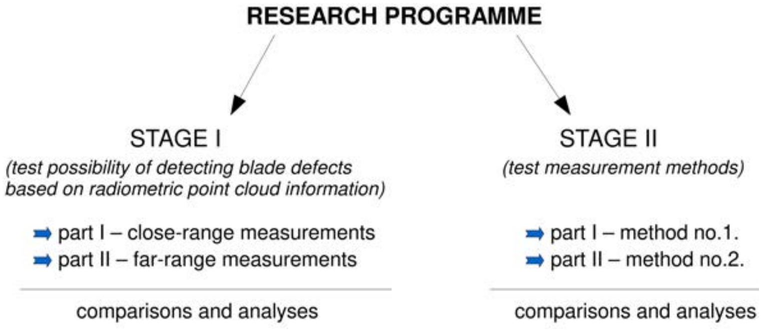

Fig. 3. General scheme of the research programme (stages and parts of study).

3.1. Scheme and objects of the research programme

The first stage of this study entailed laying the groundwork for the next stage of the research programme. Because no previous work that directly confirmed the utility of the TLS technology for blade defect detection could be found in the literature, a test study was conducted.

The first stage consisted of two parts. The first and second parts were conducted close to and at a distance from the measured blade, respectively. The close-range measurements were approximately 5–7 m, and the far-range measurements were approximately 60–70 m from the tested blade. Close-up measurements were performed because the wind farm operator dismantled the blades of one of the turbines (Turbine EW-18, Location I) for maintenance. The dismantled blades were 20 years old. The blades laying on the ground surface were surveyed for defects. A photograph of the scanned blades is shown in Fig. 4.

Fig. 4. Photograph of the scanned blades.

The measurement process described above is crucial to the overall study. It had two primary purposes. First, the direct access to the defects enabled the comparison between the visual assessment of blade defects and the obtained point clouds, providing knowledge on how a particular type of defect affected the change in the intensity value of the point cloud. Second, it enabled the comparison between the point clouds obtained by far-range and close-range measurements, facilitating the determination as to whether defects were detectable using the TLS technology. Because of the increased distance to the measured object, the size of the laser spot was increased, affecting the efficiency of measurements. These comparisons are crucial because in typical situations wherein the blades are attached to the turbine, the measurement distances are least 50 m. The results of this stage of the research programme are reported in Section 3.2.

The second stage entailed the development of an optimal method for evaluating wind turbine blade defects. This stage had two parts, each of which corresponds to an examination using a specific measurement method.

In the first part of Stage II, Turbine EW-8 in Location II was measured. Parameters of the wind turbine: 2 MW turbine, tower height – 80 m, blades age – 24 years. A schematic of the measurement method (referred to as Method No. 1) is shown in Fig. 5a. The method proceeds as follows. The turbine blades remained stationary while the scanner locations were positioned relative to the turbine. Five measurement positions were identified (labelled as 1–5 in Fig. 5a). Special artificial Z + F profi targets were used in this measurement session (labelled as t1–t6 in Fig. 5a). Based on these targets, all obtained point clouds were registered to the same coordinate reference system to generate a complete 3D model of the turbine. The results of this part of the research programme are reported in Section 3.3.

In the second part of Stage II, Turbine EW-1 in Location III was measured. Parameters of the wind turbine: 2 MW turbine, tower height – 100 m, blade age – 15 years. The measurement procedure, referred to as Method No. 2, was opposite to that of Method No. 1. In this second method, the turbine blades were in motion, and the scanner remained in one position. In Method No. 2, the cooperation of the operator is essential as it includes operating the turbine during

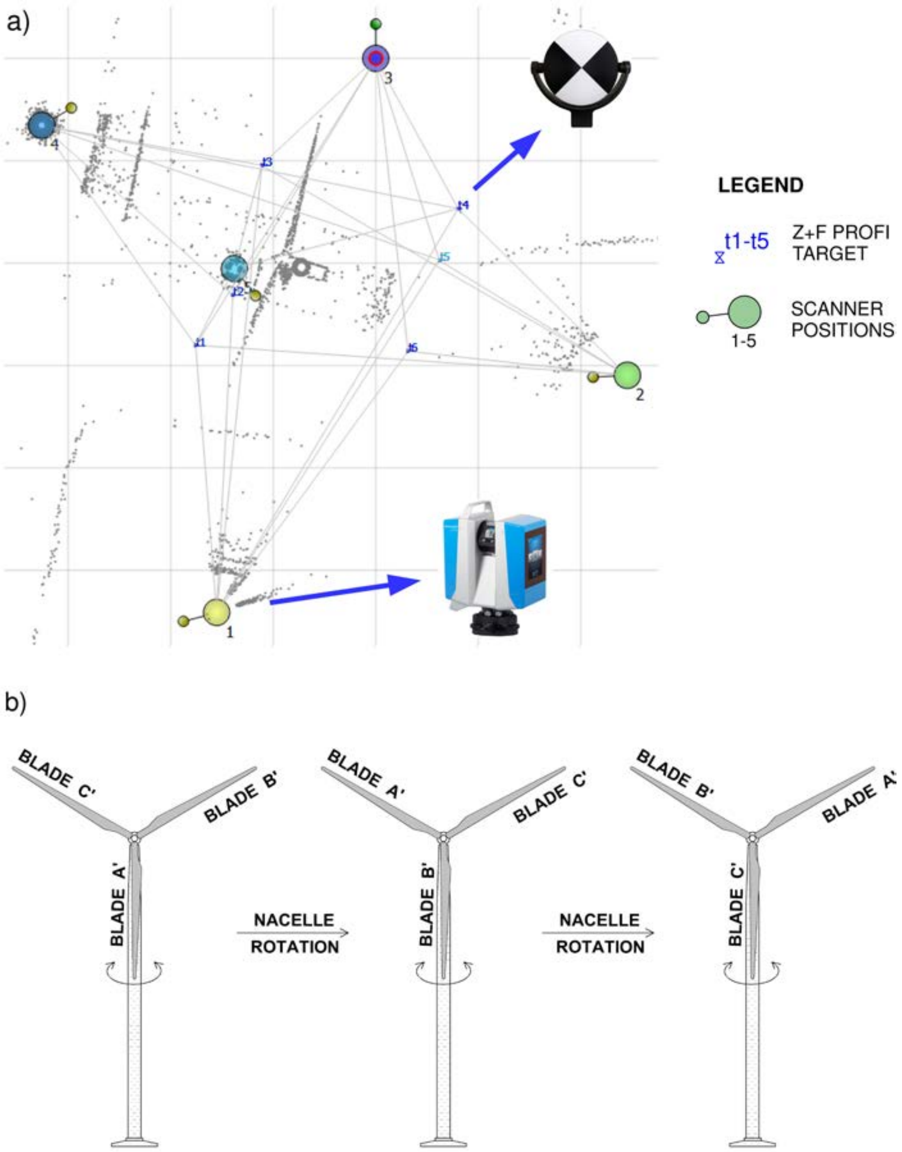

Fig. 5. Schematics of the methods: a) Method No. 1 and b) Method No. 2.

the measurements. Turbine operation refers to the rotation of the blades. In the first step, the blade faced downward; positioning the blade parallel to the turbine to the extent possible was preferred. Then, the blade was positioned so that the *suction side* (SS) faced the scanner. The first measurement was then conducted. Next, the blade was rotated by approximately 90°, and measurements were obtained. Rotations were performed until all four sides of the blade were measured. Subsequently, the rotor was moved, and the measurements of the second and third blades were conducted analogously to that of the first blade. The schematic of Method No. 2. is presented in Fig. 5b. The results of this part of the research are reported in Section 3.4.

3.2. Measurement results for Turbine EW-18 in Location I: Stage I

As mentioned in the previous section, in Stage I of the research programme, the capabilities of the TLS technology in the context of blade defect detection were verified. It was determined whether blade defects can be effectively detected with TLS and how these defects were presented as point clouds. Specific sections of the three blades were tested. However, only a few snippets were selected for presentation and analysis because certain defects were similar.

As expected, the TLS technology enables effective detection of blade defects. The comparison of the actual appearance of damages with the point clouds obtained from the close-up measurements (see Fig. 6a and 6b) lead to the conclusion that the point clouds well reflect the blade condition; the distribution of the change in intensity values considerably approximates the damage shapes.

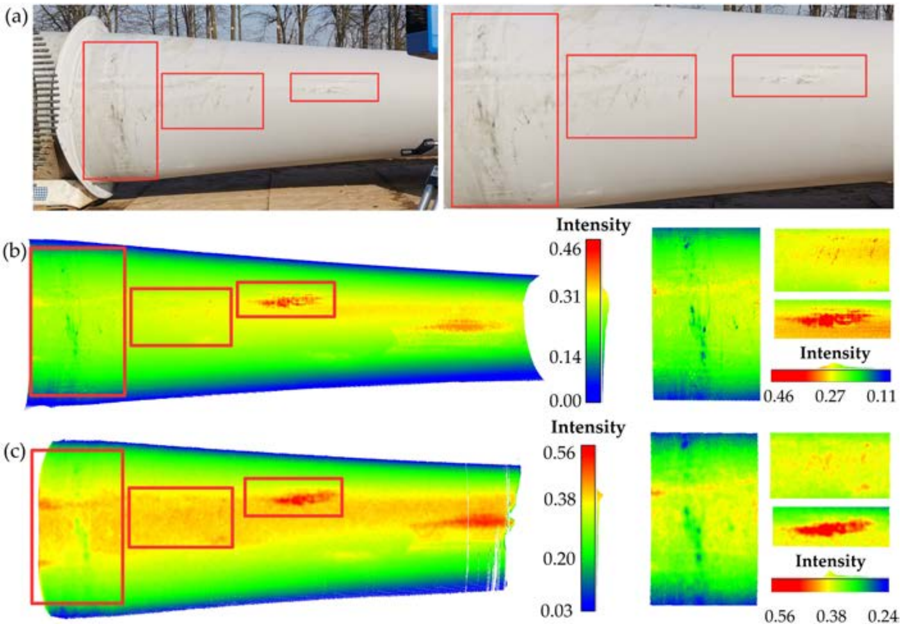

Fig. 6. Tested blade: (a) photographs, (b) close-range measurements and (c) far-range measurements.

The second objective of this research stage was to determine whether the long-distance detection of blade defects was possible (as planned for the succeeding stages). Due to this purpose, the same three damaged sections scanned at a close-range were scanned at a distance of 60–70 m. The point clouds obtained by close-range and far-range measurements including the areas selected for analysis are presented in Fig. 6b and 6c, respectively. An initial comparison reveals some similarities between the selected point clouds. However, an examination of small sections provides more accurate results. Thus, the sections selected for analysis are shown on the right side of Fig. 6.

In addition, four snippets were selected from the second blade. The fragments of the blade that were apparently the most suitable in the context of analysis were selected for examination. The selected sections enabled analyses of different situations (see Fig. 7): detection of defects from both distances (red area in Fig. 7 and Fig. 8); detection of repairs from both distances (black areas in Fig. 7); detection of defects only from the close range (purple area in Fig. 7).

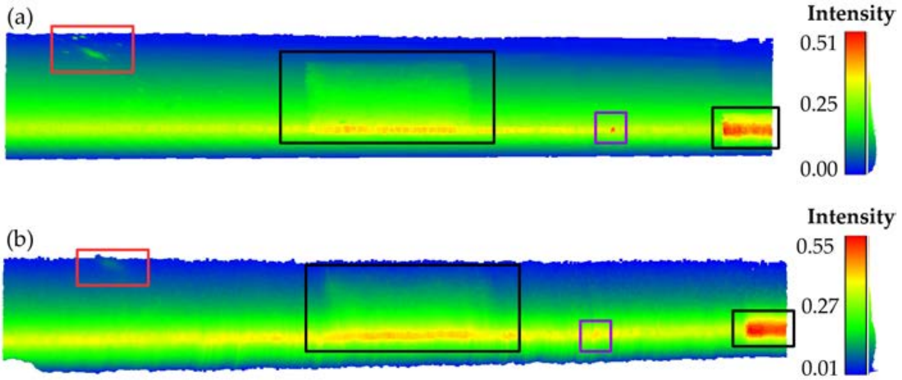

Fig. 7. Obtained point clouds with the marked areas selected for analysis: (a) close-range and (b) far-range measurements.

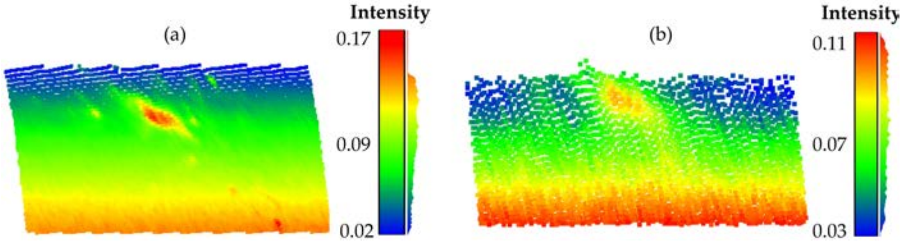

Fig. 8. Area selected for analysis (red area in Fig. 7): (a) close-range and (b) far-range measurements.

More extensive analyses were performed focusing on the defects that were not detectable from a certain distance (purple area shown in Fig. 7). This issue was directly related to the size of the laser spot, which increases with the scanning distance. The aforementioned defect was extremely minor so it was barely visible in the photograph. The defect was dimensioned using the CloudCompare software based on the point cloud obtained by close-range measurements. Its dimensions were approximately 10 mm × 5 mm (Fig. 9). The detection of such minor defects is difficult because the size of the laser spot at a scanning distance of approximately 70 m is approximately 24 mm. If the defect is smaller than the laser spot, then the possibility of detection

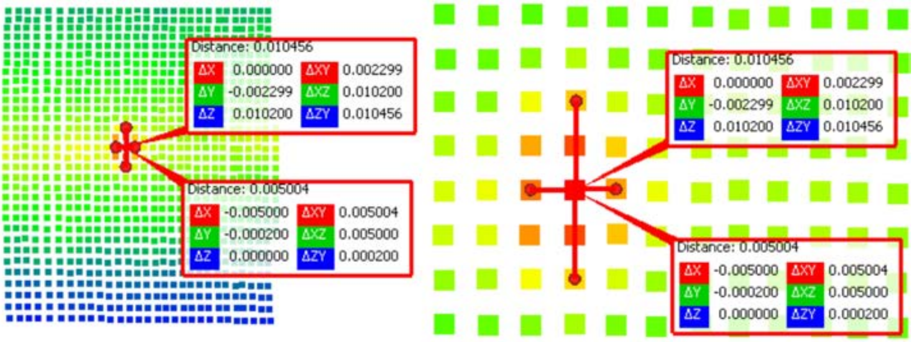

Fig. 9. Area selected for analysis (purple area in Fig. 7).

decreases. Although this can be regarded as a disadvantage, it leads to an important conclusion: if the damage can be detected with TLS, it is probably at least 20 mm in size.

The investigation results indicated the possibility of using the TLS technology to measure the technical conditions of wind turbine blades. Defects in the external structure of blades, such as cracks, cavities and erosion can be detected. For this to be possible, turbine operation must be stopped to immobilise the blades. However, every minute of turbine operation is extremely expensive considering economy and energy generation. Therefore, the development of an optimal measurement method is crucial. Accordingly, the next two sections of this paper present the analysis results of the measurements obtained using two different methods.

3.3. Measurement results of EW-8 turbine in Location II: Stage II, Part I (Method No. 1)

This part of the research programme was first implemented on a functioning turbine. This was possible because the wind farm operator had to stop turbine operations to implement repairs. This turbine downtime was leveraged to conduct the surveys in this study. Technical operations require the turbine to remain stationary at all times. Therefore, the first measurement method assumed changes in the position of the measurement station (scanner). After analysing the field situation (*i.e.*, turbine blade arrangement), five scanner locations were deemed sufficient. The inspection of each blade to the extent possible (*i.e.* scanning the four surfaces of each blade) was preferred. Moreover, the choice of the number and location of the scanner positions to achieve measurement efficiency was crucial. Section 4 *(Discussions and Conclusions)* further elucidates the foregoing.

The blades were labelled as A, B, and C in accordance with the nomenclature established by the operator. The obtained point clouds (from five measurement positions) indicate that Method No. 1 enables scanning:

- Position 1: A fragment of PS of blade A, SS of blade B, and a fragment of PS of blade C.
- Position 2: SS and TE of blade A, fragments of TE and PS of blade B, SS and TE of blade C.
- Position 3: TE and fragments of PS and SS of blade A, PS of blade B, and SS of blade C.
- Position 4: PS of blade A, LE of blade B, and SS of blade C.
- Position 5: TE and PS of blade A, a fragment of SS of blade B, a fragment of SS of blade C.

In the foregoing, PS denotes the pressure side, and TE denotes the trailing edge; SS and LE are as previously defined.

Unfortunately, complete measurements were not obtained. The blade arrangement only resulted in the satisfactory scanning of the SS of blade C. The PS, LE, and TE sections were scanned; however, the results were insufficient for analysis in terms of defect detection. Obtaining a scan of the LE of blade A was also impossible. Another conclusion that can be drawn is related to the scanning of the blade TE. Studies show that the direct measurement of this edge may be supplanted/replaced with another approach. The point cloud of blade TE can be created during the post-processing stage by accurately scanning the SS and PS surfaces. This is possible using the special targets mentioned above and combining the point clouds of SS and PS. The prerequisite is to scan these two sides in a favourable arrangement such that they are scanned up to their ‘edges’.

However, in cases of successful measurement, the obtained point clouds can be used to evaluate the technical conditions of the blade and locate the defects. By analysing the complete obtained point cloud, no defects are clearly visible; therefore, only those sections with blades are excluded for the analyses. Consider Fig. 10 as an example. The figure shows the point cloud of blade B at the first scanner position (SS of blade B). Such a point cloud provides a better representation of the measurement results. The change in the distribution of the intensity parameter values causes the defects in the blade to become more visible. Further subdividing the point cloud into smaller components increases the possibility of defect detection. Method No. 1 is further elucidated in Section 4 *(Discussions and Conclusions)*.

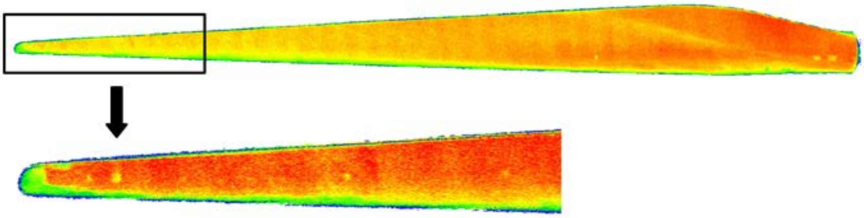

Fig. 10. Point cloud obtained for SS of blade B.

3.4. Measurement results of Turbine EW-1 in Location III: Stage II, Part II (Method No. 2)

As mentioned above, this measurement method assumes one surveying position and requires turbine blades rotations. The procedure, performed as planned by the researchers, resulted in the comprehensive measurement of each blade. The four sides of the blade (*i.e.*, PS, SS, LE, and TE) were all scanned. The blades were labelled as A′, B′, and C′ in accordance with the nomenclature established by the wind farm operator. As an example, Fig. 11 shows the point clouds of blade A′ obtained with Method No. 2. For blades B′ and C′, analogous point clouds were obtained.

The obtained point clouds indicated that this measurement method is effective for detecting wind turbine blade defects. In this method, even without splitting the obtained point cloud into

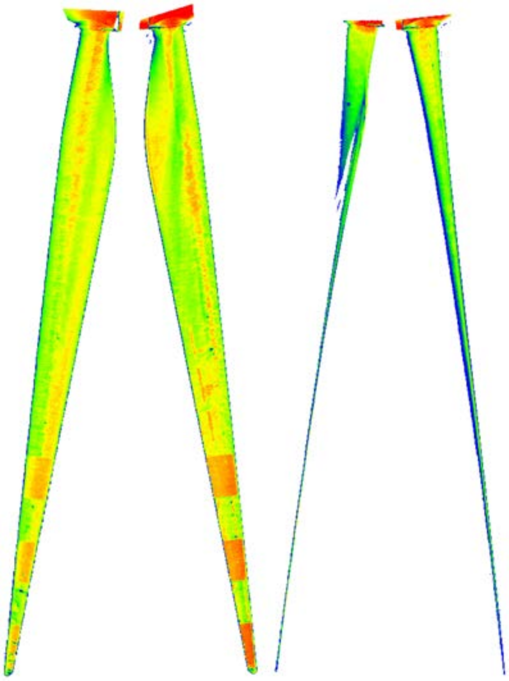

Fig. 11. Point clouds of blade A′.

smaller parts, some defects are clearly visible (see Fig. 11). Examining and analysing a small section of the point cloud provide even more effective results; consequently, the defects that are not clearly visible from the first observation can be detected (an exemplary defect presented in Fig. 12).

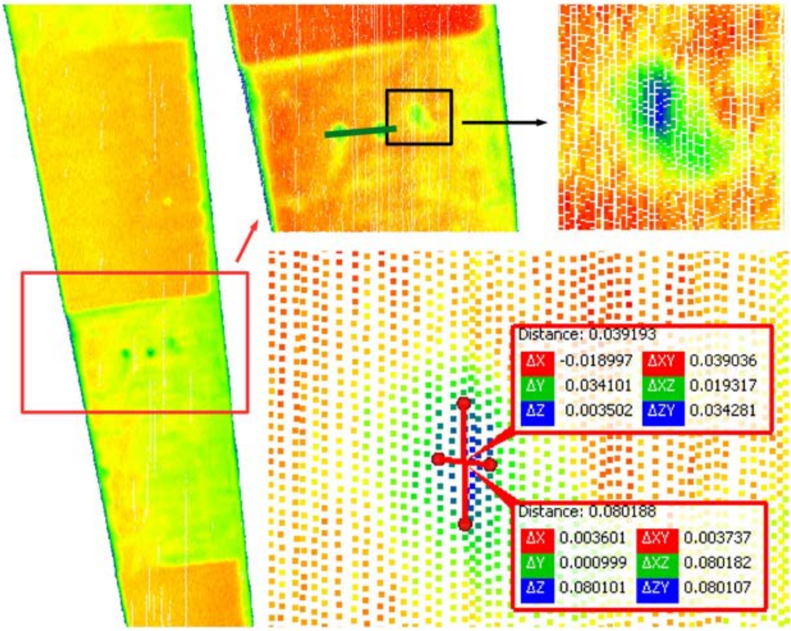

Fig. 12. Analysis result of small parts of the point cloud (a fragment from blade B′).

Additional analysis was carried out for the other two defects shown in Fig. 12. A cross-section was performed through these defects (green line in Fig. 12), and the profile was created to indicate the changes in the intensity parameter values in the damaged areas. The changes are presented in the OXI coordinate system, where I denotes the intensity (see Fig. 13). Based on the presented intensity value profile, it can be confirmed that the radiometric information is effective for detecting defects on turbine blades. We can clearly observe value deviations (decreases) in the damaged areas.

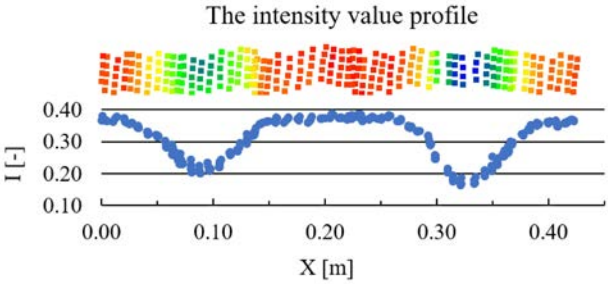

Fig. 13. Intensity value profile for damaged fragments from blade B′ (green line in Fig. 12).

Another conclusion can be drawn based on the obtained point clouds: the blade TE is undeniably the most problematic part to inspect (evidently because of its size, specifically its relatively small width). The following section further elucidates the two methods tested.

4. Discussions and conclusions

Every minute is extremely important in wind turbine operation. Shutting down the turbine for an hour results in a considerable energy loss. For example, a 1-MW wind turbine generates approximately 1000 kW in 1 h of operation. However, monitoring the technical conditions of turbine blades using the TLS technology without temporarily shutting down the turbine is impossible. The analyses of point clouds, discussed in Subsections 3.2–3.4, indicate that both methods enable the detection of defects in wind turbine blades. Accordingly, this section presents a comparative analysis of the two measurement methods with the aim of identifying the better one. Two major criteria were considered – the effectiveness of the method in relation to the value of the derived data and the economic aspect of the implemented method. Cost effectiveness was determined based on the rapidity of measurement.

First, the measurement methods are compared in terms of the effectiveness of the obtained data. At this stage, the researchers did not focus on the detailed analysis of each detected defect but on the feasibility of inspecting the blades. The optimal measurement methods developed by the researchers allowed the checking of all four sides (two surfaces and two edges) of the three blades, leading to the following results. Method No. 2 clearly ensures that the results are reproducible for all blades. In contrast, in Method No. 1, the point clouds obtained must be analysed in detail. Therefore, the first conclusion that can be drawn is that the post-processing of data (point clouds) obtained with Method No. 2 is more researcher-friendly. The analyses results are summarised in Table 2 below (‘+’, ‘−‘, and ‘+/−‘ indicate that the surface/edge of the blade has been scanned, has not been scanned, and has only been partially scanned, respectively).

Table 2. Data Obtained in terms of effectiveness (Method No. 1 vs. Method No. 2).

	Method No. 1			**Method No. 2**
	A	**B**	**C**	**A′ / B′ / C′**
PS	+	+	+/−	+
LE	−	$+^{*}$	−	$+^{*}$
SS	+	+	+	+
TE	$+^{**}$**!**	$+/-^{**}$**!**	$+^{**}$**!**	$+^{**}$

Another conclusion that can be drawn is that both methods can clearly provide the information about the conditions of the PS and SS of the blades; more thorough analyses are required for the LE and TE. Unfortunately, in the case of Method No. 1, the position at which the turbine blades were stopped rendered the measurement of the LE of blades A and C impossible. For blade B, the LE measurement was possible. In the table above, this measurement was marked with the symbol ‘*’, similarly to all the blades measured using Method No. 2. Based on the obtained point clouds, it was concluded that approximately 65% of the length of the LE (starting at the nacelle) of a blade can be effectively scanned using the TLS technology. This is because the LE width diminishes as the distance from the nacelle increases. A similar problem occurred in scanning a relatively small TE. In the case of TE, satisfactory measurement was possible by scanning approximately 25% of the blade's length (*i.e.*, at the nacelle, where the width is bigger).

Accordingly, the researchers decided to label these measurements obtained by both methods with the symbol '**'. In addition, the point clouds obtained using Method No. 1 were analysed, leading to the conclusion that in distant parts of the blade, the TE was extremely narrow so that it could be considered as a combination of the PS and SS of the blade rather than as a 'separate side' with one indispensable condition. This is denoted by the symbol '!' shown with the TE results obtained using Method No. 1. To form the point cloud of the TE, a satisfactory scan of the surfaces of the two blades is required.

In summary, Table 2 indicates that in terms of measurement effectiveness, Method No. 2 is more credible. The implementation of this method enables the controlled measurement of the entire blade surface (three blades). Unfortunately, with Method No. 1, the obtained point clouds have certain deficiencies.

The researchers conducted additional studies regarding the accuracy and quality of the obtained point clouds. With Method No. 2, the results were repeatable. For all sides of the blades, the measurement accuracy in terms of the distance of measurement and size of the laser spot was the same. This is definitely an advantage during the post-processing and analysis of particular faults and defects. Unfortunately, with Method No. 1, accuracy and quality vary because of different scanner positions and distances to the blades. Moreover, within a single scanner position, the measurement accuracy of each blade varies. In this methodology, the longest distance is between the scanner position and the blade facing upwards (blade B). Thus, these scans have the largest laser spot and the least precise measurement. When the length of the blade is assumed to be approximately 70 m and the height of the tower is approximately 100 m, the resulting laser spot becomes extremely large when the end part of the blade is scanned. A large laser spot renders the detection of small cavities difficult. In addition, with Method No. 1, because of the position of blade B, the scanner must be more distant from the turbine compared with the required distance using Method No. 2. This is because of the excessive angle of incidence of the laser beam and wide scanning area; the problem is illustrated in Fig. 14. To derive a similar angle of incidence of the laser beam for blade B in Method No. 1 to that employed in Method No. 2 the scanner must be positioned at a greater distance from the turbine. Thus, considering the distance, range of measurement, and angle of incidence, Method No. 1 had the worse geometric measurement conditions than Method No. 2.

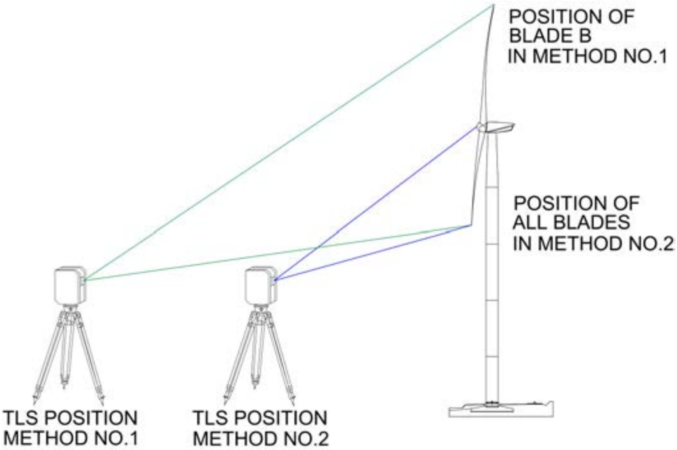

Fig. 14. Relationship between blade position, scanner position, and the angle of incidence of the laser beam.

Another consideration is the economic aspect of the two methods. Measurement time is the key element in determining the cost effectiveness of a method. Although shutting down a wind turbine reduces the amount of electricity generated, monitoring the technical conditions of blades is extremely important. From an economic perspective, this is because undetected blade defects and those that are left unrepaired reduce turbine efficiency; thus, shutting down the turbine is necessary. However, the length of time during which the turbine is not operational must be as short as possible. Therefore, the researchers analysed the two methods considering measurement time. The duration of the scanning process was mainly affected by the width of the scan area. This is because of the operation of the scanner (rotation in the horizontal plane). Thus, a wider scan area results in a greater number of rotations along the horizontal axis, consequently increasing the total scanning time.

Method No. 1 was analysed first. The measurement duration for each scanner position varied and the discrepancies were significant. The foregoing was dependent on the position of the scanner relative to the turbine because it affected the size of the scan area. For Method No. 1, blade scanning lasted as described:

- Scanner Position no. 1: approximately 15 min.
- Scanner Position no. 2: approximately 25 min.
- Scanner Position no. 3: approximately 15 min.
- Scanner Position no. 4: approximately 25 min.
- Scanner Position no. 5: approximately 45 min.

Therefore, the total duration of blade scanning was approximately 125 min. In addition to the blade scanning time, the time for the change in the scanner position must be taken into account. According to the authors, a 10-min window should be allotted for this step. More time was needed for scanning the artificial Z + F profi targets; for each scanner position it was approximately 10 min. Moreover, pre-scans are performed before the final scans and 3 min must be added for this task. Thus, accounting for the times required for blade scanning time (125 min), profi target scanning (50 min), four changes in scanner position (40 min), and pre-scans (3 min), the total execution time using Method No. 1 was 218 min.

In the case of Method No. 2, the durations of all measurements (scans) were very similar. This was because of the same blade placement during scanning. Consequently, the scanning areas were considerably similar in size. The average duration of scanning one side of the blade was 3 min; thus, the full measurement of one blade was assumed to last 12 min. In Method No. 2, considering the time for the change in the scanner position is unnecessary. However, additional time must be allotted for blade rotations. A single turn lasted less than a minute; thus, approximately 15 min had to be added to complete these tasks. In addition, each pre-scan lasted 2 min. Hence, the total execution time using Method No. 2 was approximately 53 min.

In conclusion, the entire research programme has indicated the possibility of using the TLS technology to survey the technical conditions of wind turbine blades. In this study, the authors did not focus on identifying specific defects (the number and type of defects) but on the potential of the TLS technology for this task. The authors aimed to indicate whether TLS can be used for blade defect detection and whether TLS might be competitive with the other standing methods. The conducted investigation, particularly the first stage, enabled the authors to indicate that the defects in the external structure of blades, such as cracks, cavities, and erosions can be successfully detected based on the radiometric information of a point cloud. Such a comprehensive study (report) of the technical condition of the blade is planned in cooperation with the owner of the turbines.

On the basis of the comparative analyses conducted and associated discussion, Method No. 2 was identified as more suitable for detecting defects in wind turbine blades than Method No. 1. Furthermore, the former is the optimal measurement method using the TLS technology. The obtained results were satisfactory in terms of measurement efficiency and cost effectiveness. An additional advantage of this method is the clarity of the point clouds that it provides, thus enabling researcher-friendly post-processing. Method No. 2 is also characterised by repeatability, which is another advantage. With respect to a single measurement, repeatability means that all defects on all blades are measured with the same quality. Moreover, repeatability enables periodic measurement, which is the case in turbine blade condition inspection. By properly stabilizing the measuring position during subsequent inspections, the use of the same scanner positions is possible. Consequently, reliable monitoring of defect degradation is possible. In summary, considering the greater efficiency and better quality of the data obtained, shorter measurement time, and other advantages, Method No. 2 is recommended for measuring the technical conditions of wind turbine blades.

The authors intend to expand the research and conduct laboratory investigations, *e.g.*, to analyse the effect of a specific defect based on the radiometric information of a point cloud. Moreover, the operators of wind farms have expressed their desire for further cooperation. The photogrammetric method is currently the typical one used to examine the condition of wind turbine blades. However, this study indicated the potential also of the TLS technology for this task. Thus, in subsequent studies, comparative analyses are planned. The results of applying the TLS technology will be compared with those obtained using the photogrammetric method. It is presumed that these two technologies are to a great extent complementary. Such studies will provide an insight into identifying the appropriate approach to inspecting the technical conditions of wind turbine blades.

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