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Work sampling and work process optimization in sonic and electrical resistance tree tomography

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Abstract: Using non-destructive techniques in investigating tree stem rots is a modern approach in arboriculture and urban forestry. We used PiCUS® 3 Sonic tomograph (SoT) and TreeTronic® electrical resistance tomograph (ERT) to inspect the health status of urban and park trees. The process of setting up the device and measuring is time demanding as it requires numerous delicate operations. The aim of the study was to evaluate the time needed for measurement and to propose an optimal workflow. The results of work sampling suggest that scanning of one average-difficulty tree by SoT and ERT resistance tomography takes an average approximately 52 min (when one operator measures one scan), and approx. 37 min (when two operators measure a queue of trees). Working in two-person-team is moderately more efficient. Typically, the overall costs of one scan are approximately EUR 25–30 (~ CZK 650–780), depending on many variables.

Keywords: arboriculture; job sequencing; PiCUS tree tomography; tree risk management; trunk decay; urban forestry

Tree tomography in urban forestry. The traditional tree health inspection in arboriculture and urban forestry is based on visual assessment or invasive methods like Pressler increment borer (Helliwell 2007). Recently, less invasive (probing, resistance drilling) and non-invasive approaches (static bending, ultrasonic or x-ray methods) to wood inspection started to be used (i.e. Arcigeneas et al. 2014; Ross 2002 etc.). However, these methods are suitable rather for an inspection of timber structures. For a non-invasive inspection of standing trees, tree tomography as a modern method based on electronic instruments is used (i.e. Leong et al. 2012; Gilbert et al. 2016; Nicolotti et al. 2003; Rabe et al. 2004; Deflorio et al. 2008; Göcke et al. 2008 etc.).

Tree tomography technology is used to scan trees for decay and rots and it is also verified for checking the status of wood products and structures (Oh, Lee 2013). More types of instruments from various companies were already introduced (Arciniegas et al. 2015).

The tomography technology can detect wood decay with sufficient precision. However, a rather high price of the tomography device and enormous time requirements of the measuring limit the extensive implementation of tomography in commercial forestry branch for its low cost-efficiency (Wang et al.

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2009). Its use for scientific purposes (Niemtur et al. 2014) is an exception. Therefore, the tree tomography technology is most often used by arborists in urban forestry and urban greenery management to reduce the probability of unnecessary felling a sound tree, while keeping the potentially hazardous tree standing (Heikura et al. 2008).

One of the major advantages of tree tomography, as compared to invasive methods, is that the whole cross-section image is obtained (Gilbert, Smiley 2004). Finally, tree tomography is more tree-friendly compared to invasive inspection methods like Pressler borer (Nicolotti et al. 2003).

Generally, tree tomography is applicable as a supporting tool in questionable cases when additional information of the health status inside the stem is needed to make a more informed evaluation of the tree risk potential and failure prediction (Ellis, Ellis, 2013, 2014; Koeser et al. 2017).

PiCUS tree tomograph – principles and function. In this study, PiCUS tomography system is used. The system consists of two devices – sonic tomograph (SoT) and electric resistance tomograph (ERT). Additionally, the shape of the stem is described by an electronic calliper.

SoT measures the velocity of the sound waves transiting through the wood in the stem. The velocity values are calculated based on the time intervals taken to run a sound wave from one measuring point to the others, and the distance between the sensors (the stem shape having been previously described by the electronic calliper), (Gilbert 2016). Measuring points are nails driven into the bark (reaching the wood inside) with magnetically attached sonic sensors. The sound wave is generated by tapping an electronic impact hammer ("radio hammer") on the tapping pin (part of the hammer) which is attached on the nail instead of the sensor. All the measuring points are tapped stepwise.

The outcome is a tomogram – a coloured image ("distribution map") that depicts the sound velocity distribution in the stem cross-section (Ellis, Ellis 2013; Argus Electronic 2016). The values of sound velocity are depicted by a colour scale with relative ranges. The image is compiled automatically from the partial data by the software.

The sound waves velocity in wood correlates significantly with modulus of elasticity, density and moisture content of wood (Unterwieser, Schickhofer 2011). Depending on the type of decay, the modulus of elasticity and density of wood can decrease (Brazee et al. 2011). That corresponds with higher sound velocity in healthy wood and reduced velocity in the wood struck by a disease. If the decay is in incipient stages (hard decay), the sound velocity might remain unchanged. An interpretation of tomograms can be complicated by an occurrence of caves, seams and swollen (bulbous) stem (Kazemi-Najafi et al. 2009; Wang, Allison 2008). Experience suggests that the size of a zone of decay can be determined more accurately than its position (Rabe et al. 2004). The accuracy of damaged area determination increases with the area of decay; it depends on the tree species but not on the diameter of tree trunk (Ostrovský et al. 2017).

The **ERT** device measures the electrical resistivity (reciprocal to electrical conductivity) of the wood in a tree stem. The electrical resistance between the sensors is calculated from the values of voltage and current and the distance between the sensors (Argus Electronic 2013; Göcke et al. 2008).

The outcome is a tomogram – an image where the distribution of values of electrical resistance in the stem cross-section is depicted by a colour scale. Evaluation of ERT tomogram can be complicated by each tree species' specific resistance distribution that may even change between seasons (Göcke et al. 2008). Therefore, electrical resistance tomography requires even more practice in the field to correctly interpret the image (Ellis, Ellis 2013; Argus Electronic 2013).

The electrical resistance correlates closely with the wood moisture level and with the ions' concentration in the tissue solution. It is presumed that colonization by pathogenic fungi increase moisture and elements content in wood, therefore the conductivity of the diseased wood tissue increases (Brazee et al. 2011; Göcke et al. 2008). Therefore ERT is able to detect decay in the initial phase when moisture (or ions content) is affected, not the sound velocity. The moisture level can also indicate if rain water leaks into the trunk. ERT is usually able to distinguish the peripheral and internal wood in urban royal palms (Lin, Yang 2015) or the sapwood and heartwood in coniferous or broadleaved trees (Humplík et al. 2016). This can be further applied for the improvement of precision of so-called sap-flow technology (Bieker, Rust 2010; Guyot et al. 2013), commonly used in tree physiology. However, the electrical resistance value is dependent on many other circumstances (proportion of sapwood and heartwood, natural distribution of moisture in the stem cross-section by different tree species, seasonality, and occurrence of caves, seams and medullary rays). The tomogram has to be interpreted taking these aspects into account.

Naturally, tomography technology has its limits given by the principle of the devices. Combining SoT and ERT provides more reliable results as one eliminates the weak points of the other (Göcke et al. 2008). Li et al. (2014) reached high agreement of their analytical models with real data and stated that sonic tomography can be used for the diagnoses of internal defects of trees; however, velocity patterns and their interpretation are still under research (Arciniegas et al. 2014; Feng et al. 2014). Although sometimes just the SoT technology is able to provide sufficient information about the surveyed tree and the ERT is superfluous, each technology is able to bring some additional information compared the other one. Therefore mostly both SoT and ERT together are favourable to gain comprehensive information about the tree, especially in the doubtful cases.

Measuring with a tomography device is considerably time consuming due to its delicate setting up and many consecutive steps that have to be taken (Li et al. 2014). No matter how many studies focused on tree tomography have emerged in scientific literature, none of the studies known to the authors have evaluated in detail its efficiency and the time demands. The study on work sampling of tree tomography is important for the (potential) users to become aware of time requirements of this technology. Therefore, we assessed the metadata, recorded during the work with a tree tomography for other purposes, to obtain detailed time frames (SoT and ERT). The aim of the article is to create a calculation model to estimate costs of tree tomography scanning procedure, based on the time requirements of measuring in tree tomography, and to propose the optimal step order in the workflow. We presume that the team of two operators is more efficient than if the device is operated by one person.

MATERIAL AND METHODS

General information. The research was carried out mainly in a forest area adjacent to Truba Research Station (GPS: N 50°0.39'; E 14°50.17', altitude 365 m a.s.l., Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Department of Silviculture), and in urban locations in Prague (Suchdol, Dejvice) and Central Bohemia (Vlašim, Buštěhrad). Into our study we included the trees of several species (Scots pine, European beech, pedunculate oak, small-leaved lime) with the trunk diameter (in height of the scanned cross-section) in the narrow range about 40–60 cm. To eliminate a variance in duration time of some work stages, we always used the same count of measuring point (12 and 24 points for SoT and ERT respectively) and we chose only the trees with accessible trunk base without any substantial obstacles and also only the trees with not excessively thick bark. We have neglected the parameters of trunk diameter and tree species, considering their marginal effect on the time consumption of scanning. The cross-section to scan was located mostly in the height of 1–1.5 m. The time samples measurements of working with tomography technology were taken while using it in other scientific studies focused especially on the changes of tomography outcomes during the season. The tomography technology used was designed and produced by Argus Electronic, GmbH, Rostock, Germany. The system consists of the electronic calliper to measure and calculate the shape of cross-section, and of the measuring itself which was performed by two independent technologies:

- The sonic tomograph (SoT); device used: PiCUS Sonic Tomograph, Version 3
- The electrical resistance tomograph (ERT); device used: PiCUS TreeTronic®, Electrical resistance Tomograph for trees

Course of scanning. Before the scanning with tomography devices, the circumference of the trunk needs to be measured in the location (height) of the scanned cross-section and an appropriate number of nails (roofing flat-headed magnetic nails are recommended) driven in to provide measuring points (MP). The identical sensors (nails driven through the bark) are used for both tomography technologies (sonic and electrical).

A recommended number of measuring points is automatically suggested by the operational software according to diameter. In this study, we always used the maximum number of sensors (12 or 24 sensors for SoT and ERT, respectively).

The next step is to discover the stem shape in the location (height) of the contemplated tomograph cross-section. The height of scanning is chosen individually to obtain the tomogram with important information to assess the tree status. The stem anomalies can potentially move the height level.

Mostly the level approx. 1.3 m is preferred. Level near the ground is usually not applicable especially due to frequent occurrence of trunk irregularity. In the case of stems with a regular cross-section shape, the predefined simple circular or elliptical shape can be used. The real shape must be precisely recorded in the case of a free shape of the cross-section (typically, in urban trees). To gain a model of the stem shape, we measure the distances between the pairs of MPs (nails) with a special electronic calliper (component of the PiCUS tomography system). Consequently, the shape is drawn by the software and saved into a file containing geometric data, utilizable for both the sonic and electrical tomograph.

After installing the magnetic sensors on the nail heads, SoT measuring is performed by tapping on the nails (from 1 to 12) with an electronic impact hammer which generates sound waves.

When SoT measuring is complete, the device and sensors are replaced by the other system. For ERT we usually double the number of MPs (24), the additional nails being driven in just into the middle between the nails already installed. The procedure of electrical resistance scanning is launched through an operational program and it runs without any further interventions of an operator.

As a result, we receive two diagrams showing distribution of sound velocities and electrical impedances in the scanned cross-section processed by the device. When both measurements are complete, all the equipment can be packed up and transferred to another tree. Photo documentation or note-taking (if needed) can be easily done during the ERT measuring phase which runs automatically.

Work sampling. The tomography device can be controlled by one or two operators (leader and assistant). To improve the work efficiency, the scanning course may be adjusted to the number of planned scans during one work shift in a given location. It is standard to make one scan on a tree but sometimes several scans are required. For the purpose of this paper, we presume that one scan includes both the sonic and resistance tomography scans. The options of the operational approach were distinguished as follows:

- Option 1: One operator; measuring only one scan during the work shift.
- Option 2: Two operators; measuring only one scan.
- Option 3: One operator; measuring two or more scans.
- Option 4: Two operators; measuring two or more scans.

The process of measuring with a tree tomograph was generalized and segmented into individual operational stages. We notice that real field work with tomography equipment is rather complicated but we had to simplify the workflow to be able to measure, assess and record data in the time-axis chart. Option 3 and 4 presume the proximity of measured trees (not more than several tens of meters). If the distance between following trees is longer, it is necessary to pack up the device, transfer it and unpack again. Then we continue according to Option 1 or 2.

The operational stages were defined analogously to the scheme in study, focused on the time framing of tree planting (Baláš et al. 2011). The duration of partial stages was measured separately with accuracy to min. The course of measuring was segmented into operational stages, as described in Table 1.

All stages include particular software and hardware operations on the laptop (cable or wireless connecting between tomography device and computer, creating and saving the files, setting and entering the parameters). We suppose that the operators are sufficiently practiced to run the equipment.

In the case of Option 1, the particular work stages run subsequently. Therefore, time frames could be recorded separately, as mentioned in Table 1. In the remaining Options (2, 3, 4), some of the stages are performed simultaneously by two persons (or even on two different trees). The recording of separate time frames might be difficult and inaccurate. Therefore, based on the data of Option 1, we arranged the individual stages according the scanning course to create a model to estimate the duration time of one scan of Options 2, 3 and 4. The values gained by the model were compared with the real duration measured as time of the entire scan, not the individual stages.

We used a simple version of the Gantt chart (i.e. Grabowski, Pempera 2000; Rand 2000), modified to suit our requirements, to clearly depict the continuity of individual work stages on the time scale according to the Options 1–4.

Detailed time frames of 95 scans were recorded in the case of Option 1. Number of scans within the individual tree species was as follows: beech, pine, oak – each species of 21 scans; lime – 32 scans. The duration time of 12 scans were recorded in the case of Option 2. The duration time of the remaining Options (3 and 4) were recorded continuously as a block containing at least 3 or more scans performed during one work shift. Duration of the first

Table 1. Overview of the monitored work stages

Stage label	Stage name and description	Computer needed[1]	Dependent on[2]
A	Unpacking – unpacking the equipment (includes also: turning on and booting the laptop)	–	
B	Driving in nails	No	
C	Geometry – cross-section geometry measuring (includes also: circumstance measurement)	Yes	B
D	SoT installing – installing SoT sensors (includes also: installation of carrying belt and the SoT device)	No	C
E	SoT measuring – measuring with SoT (tapping with the electronic hammer as instructed by the software, calculation	Yes	D
F	SoT dismounting – dismounting SoT sensors (includes also: dismounting the SoT device)	No	E
G	ERT installing – installing ERT sensors (includes also: driving in additional nails, installation of the ERT device)	No	F
H	ERT measuring – measuring with ERT (automatic process controlled by the software, followed by the 32 calculation – the duration may depend on the laptop performance)	Yes	G
I	ERT dismounting – dismounting ERT sensors (includes also: dismounting the ERT device	No	H
J	Extracting nails	No	I
K	Packing, ending (or transferring) – packing, ending the operation (or transporting the equipment to another tree)	–	J

[1]indication whether computer is needed for executing of the given stage; [2]given stage cannot start until the stage mentioned in this column is completed.

scan was recorded separately because the measuring course (and duration) of the first scan is different from the second scan and further. An average duration time of one scan (from the second to the last one within the work shift) was calculated as a quotient of total duration and the number of scans. In the case of Option 3, we recorded 4 blocks with the total of 20 scans; in the case of Option 4, we recorded 6 blocks with the total of 24 scans. The recorded data of Option 1 represent the input to the model; recorded data of Option 2, 3, and 4 were used to validate the model.

The actual exchange rate used for the calculation in this paper is CZK 26 per EUR 1.

RESULTS AND DISCUSSION

Options of operational approach

Option 1: 1 operator measuring 1 scan. All stages proceed in steps. The overall time is a sum of duration of the stages. The process can hardly be optimized. The duration time depends mainly on the skills of the operator.

An overview of the measured duration of particular stages of working with a tomography device is depicted in Figure 1. No substantial difference in the duration of measuring was observed among the tree species. One scan average duration in case of beech, pine, oak, and lime, respectively was as follows: 50, 51, 54, and 53 min, respectively. Therefore, the tree species differentiation is not considered for the further calculation.

Option 2: 2 operators measuring 1 scan. Compared to Option 1, the situation slightly changes. An assistant can help the leader with the stages that do not require a computer (see Table 1), and that are independent of the previous stage. This applies for only several stages – driving in the nails/unpacking and extracting the nails/ERT dismounting + packing. An assistant can start to dismount SoT and the leader can follow him with the installing of ERT so that these stages can particularly overlap. In a real situation, the assistant carries out the stages without the computer and the leader carries out only the stages with the computer. Nevertheless, improved coordination between the leader and assistant can speed up the process. Overall model-based time (see Figure 2) for measuring 1 scan is approx. 48 min. The real duration recorded is very similar (47 min on average; see Table 2).

Option 3: 1 operator measuring 2 or more scans. Similarly to Option 1, most of the stages are per-

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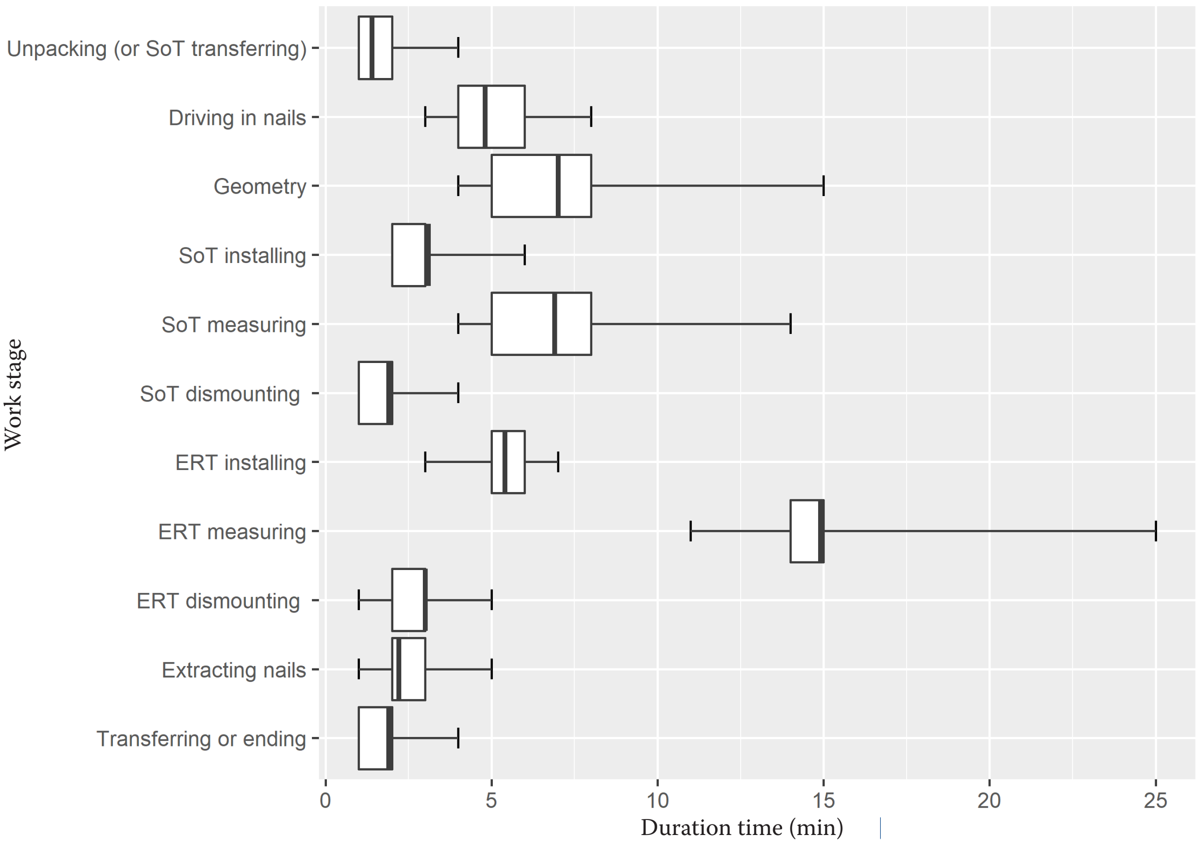

Figure 1. Duration of particular work stages of 95 recorded scans in Option 1 of operational approach (vertical line displays median, box represents lower and upper quartiles, whiskers represent minimal and maximal values)

formed stepwise. Only the *ERT measuring* stage runs automatically, while the operator can start measuring another tree, specifically driving in nails. In Option 3, the duration of the first scan does not differ from Option 1. In comparison to Option 1, time saving begins in the second scan, provided the trees are close to each other (max. 1-minute walk). Overall model-based time (see Figure 2) for measuring 1 scan is approx. 52 and 46 min, respectively (the first scan and the following, respectively). The real duration recorded was 54 and 46 min on average, respectively (see Table 2).

Option 4: 2 operators measuring 2 or more scans. It is based on Option 3 and seems rather complicated but in fact it differs only slightly when working with ERT tomograph. Similarly to Option 3, during the *ERT measuring* stage the assistant prepares measuring on the following tree (driving nails in). When the *ERT measuring* stage is finished, the leader can immediately proceed to scan the following tree and start the *Geometry* stage while the assistant returns back to the *ERT dismounting* and *Extracting nails* stages in the previous scan (tree). The following SoT

Table 2. Observed and model duration of the scans in Options 2, 3, and 4 of operational approach

Option	*n*[1]	Mean (min)	Standard deviation	Lower quartile	Upper quartile	Model duration (min)
2	12	47	5.6	42	50	48
3 – first scans	4	54	3.7	52	56	52
3 – second to last scans	16	46	5.9	42	50	46
4 – first scans	6	52	4.4	50	52	50
4 – second to last scans	18	37	6.1	32	42	38

[1] count of recorded scans

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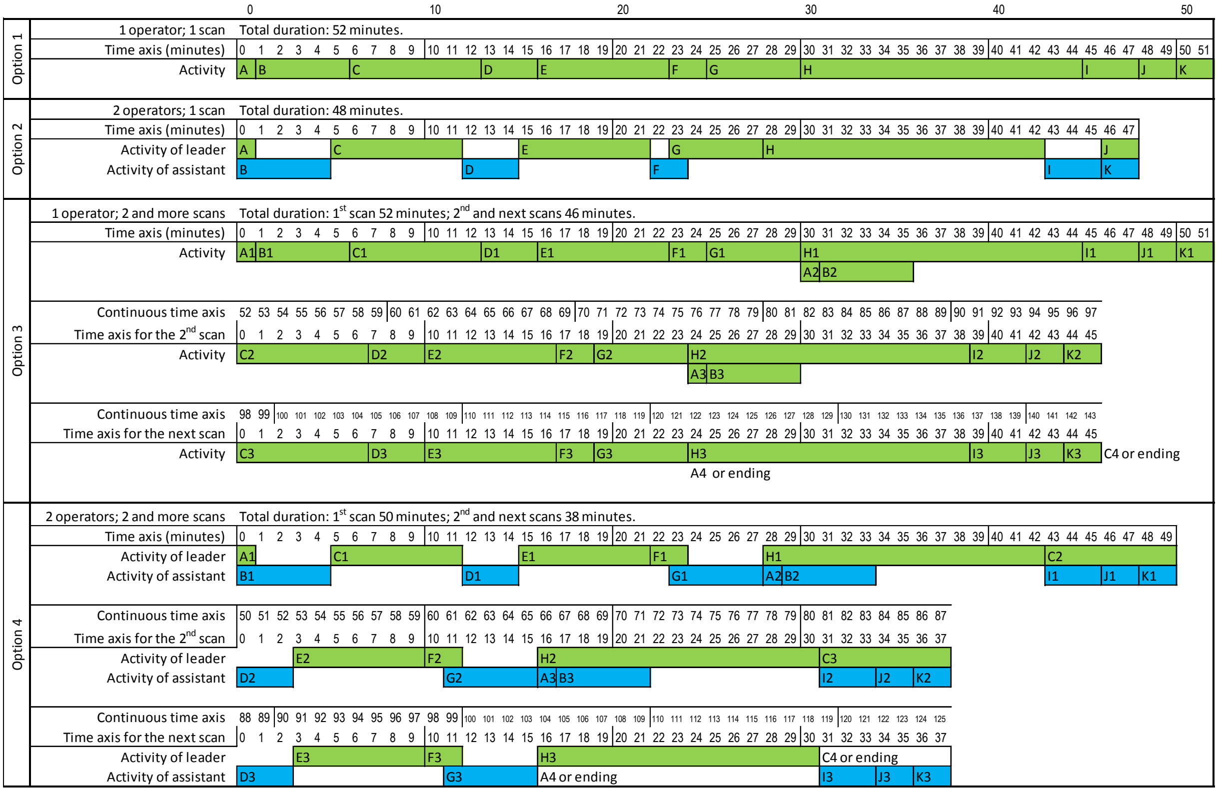

Figure 2. The model of time axis for different operational approaches. Option 1: One operator measuring only one scan during a work shift; Option 2: One operator measuring two and more scans; Option 3: Two operators measuring only one scan; Option 4: Two operators measuring two and more scans during a work shift

tomography is identical to Option 3 till the *ERT measuring* stage when the specific Option 4 approach appears again. The time saving in the first scan (model-based) in comparison with Option 1 is negligible (total duration 50 min). On the other hand, the time saving in the second and next scans is apparent. Under ideal circumstances, the model-based time is 38 min, assuming, an optimal leader-assistant coordination and close proximity of measured trees. The real duration recorded for the first and the second (following) scans, respectively, was 52 and 37 min on average, respectively (see Table 2).

The time saving is obvious especially in the case of two operators performing 2 and more scans in one place. In the remaining options, the second operator's presence does not bring any apparent temporal benefit in the measuring. The time-axis of the chart suggests the assistant is inactive intermittently and seems to be superfluous in some moments, though, he can still efficiently assist the other operator. Well-coordinated cooperation can accelerate the work noticeably.

It is supposed that both leader and assistant are commutable (both should have the similar skills and know all the scanning process). It is also possible to act by the alternative approach when leader and assistant are specialized (mostly assistant cannot perform the leader's stage). Anyway, it is favourable not to change the roles of leader and assistant in the whole work shift to avoid confusion and mistakes.

In some specific cases to perform only SoT or ERT sometimes can be required. The time consumption for SoT-only and ERT-only scanning (geometry and other stages included) reaches about 26 and 39 min, respectively. The longer time of ERT is caused by the automatic run of measurement and calculation.

Costs calculation

The measuring accounts for only a (minor) part of the overall costs. Wage rates, equipment depreciation, transportation costs, office work (report compilation) costs, insurance and material costs have to be included as well. Below, an economic model for estimation of overall costs using particular variables is presented. The following Formula (1) describes the calculation of the general costs for 1 scan in a contract.

$$\text{Costs} = \frac{\text{Dt}\times\text{W}}{60} + \frac{\text{Ep}}{\text{Ui}\times\text{Ls}} + \frac{(\text{Tc}\times\text{Dc}) + (\text{O} \times \text{W})}{N} + \frac{\text{Ic}}{\text{Ui}} \qquad (1)$$

where:

Costs	– general (overall) costs for 1 scan (EUR)
N	– number of scans done in given contract (work shift)
Dt	– duration time for 1 scan (min)
W	– 1-hour wage paid to the operator (or the sum of wages paid to all operators), (EUR)
Ep	– equipment price (EUR 20,400)
Ui	– yearly equipment usage intensity (scans per 1 year)
Ls	– expected equipment service life (years)
O	– office work on the report, device maintenance work can be included (hours)
Tc	– transportation costs per 1 km (EUR)
Dc	– transportation distance per work shift (km)
Ic	– 1-year insurance costs, eventually 1-year repair costs if occur (EUR)

To calculate the overall price of one tomograph scan, it is necessary to estimate real values of the variables to be inserted in the formula of the model.

The **personal costs** depend on 1-hour wage paid to operator. Minimal 1-hour gross wage in the Czech Republic is ca EUR 3.07 (MoLSA, 2019), average 1-hour gross wage in the 3rd quarter of 2018 was about EUR 7.25 (CSO, 2019). The economic model is ranged for 1-hour wage EUR 3–10 (Table 3).

The equipment **depreciation costs** of 1 scan depend on expected service life of the equipment (depreciation time) and on the equipment usage intensity (amount of scans performed per 1 year). The purchase price (in conversion from CZK to EUR) of the PiCUS Tomography equipment (purchased in 2013) was EUR 20,400 (CZK 531,000). The depreciation costs are shown in Table 4. To simplify the model, we do not consider the monetary inflation and money interest rates.

The **transportation costs** of the equipment and operator(s) depend on the distance between the office and the measurement locality, and on the type of vehicle used. An overview of the transportation costs for 1 work shift is presented in Table 5. To calculate the costs of 1 scan the table value should be divided by the number of scans performed during 1 work shift.

Insurance costs: We asked 5 top insurance companies on the Czech market for an estimation of an all-risk insurance price of a tomography equipment (to cover especially: theft, accident, professional negligence, equipment breakdown). The offered 1-year insurance price varied about EUR 481 (CZK 12,500). To see the insurance costs of one scan, we must divide this price by the 1-year equipment usage intensity (Ui). When Ui = 200, then the insurance cost of 1 scan is EUR 2.4.

The direct **material costs** are negligible because they only include purchase of the nails which, moreover, can be used repeatedly.

The **office time** spent to assess the tomograms and to write reports is also included in the formula and it varies substantially depending on the character of the report required. Typically, it takes several hours in the office to assess the tomograms and compile the report from one work shift.

The **repair costs and costs of spare parts** are not considered because probability of malfunction or breakdown is unpredictable. Moreover, the

Table 3. The personal costs (EUR) for 1 scan respecting a 1-hour wage rate and the scan duration time (the value usually achieved in Czech Republic is shaded)

Duration time of 1 scan (min)	1-hour wage (EUR)							
	3	4	5	6	7	8	9	10
40	2.00	2.67	3.33	4.00	4.67	5.33	6.00	6.67
45	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
50	2.50	3.33	4.17	5.00	5.83	6.67	7.50	8.33
52	2.60	3.47	4.33	5.20	6.07	6.93	7.80	8.67
55	2.75	3.67	4.58	5.50	6.42	7.33	8.25	9.17
60	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
65	3.25	4.33	5.42	6.50	7.58	8.67	9.75	10.83
70	3.50	4.67	5.83	7.00	8.17	9.33	10.50	11.67

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Table 4. Depreciation costs (EUR) of 1 scan in dependence on depreciation time and amount of scans done per one year (with the purchase price of EUR 20,400). The value usually achieved in Czech Republic is shaded)

Scans done per 1 year	Expected equipment depreciation time							
	3	4	5	6	8	10	15	20
50	136.0	102.0	81.6	68.0	51.0	40.8	27.2	20.4
100	68.0	51.0	40.8	34.0	25.5	20.4	13.6	10.2
150	45.3	34.0	27.2	22.7	17.0	13.6	9.1	6.8
200	34.0	25.5	20.4	17.0	12.8	10.2	6.8	5.1
500	13.6	10.2	8.2	6.8	5.1	4.1	2.7	2.0
800	8.5	6.4	5.1	4.3	3.2	2.6	1.7	1.3
1,000	6.8	5.1	4.1	3.4	2.6	2.0	1.4	1.0

repair costs should be paid through appropriate insurance.

Other costs (overhead costs, charging, storage, cleaning, small maintenance etc.) in our calculation can be incorporated to office work (O – variable in our calculation formula).

Examples of costs calculation

We set model variables to delineate several typical situations of work with the tomography system (Table 6). Through the model options, we modified only those input variables that commonly and markedly change in different contracts. The remaining input variables, predominantly given by external factors (e.g.: Ep – equipment price, Ls – expected equipment service life, Ic – 1-year insurance costs, eventually 1-year repair costs if occur), were mostly left as constants. We presumed that 1 contract (work shift) is completed in one day (one transportation).

The only available reference about the time requirements of tomography procedure was found in Lin and Yang (2015). They worked with ERT in laboratory conditions to assess the electric properties of palm tree trunk section. Due to the circular shape of stem, they did not measure the geometry. The entire process of ERT measuring was completed within 15 min per tree. Regarding the field condition, this corresponds to our findings.

Errors and difficulties

Work efficiency is affected by the operators' errors and technical difficulties not caused by the operators' poor skills. Below, potential common errors, encountered during the measurements, are listed. They not only slow down the process of measuring, but also deteriorate the precision of the results. Some systematic and random errors occurred particularly often and should be paid attention to:

- unstable bluetooth connection between the equipment and the peripheral devices; the devices must be reconnected (sometimes repeatedly);
- geometry measuring errors (when the operator measures the distance between wrong points or presses a wrong button on the calliper);
- the nails not placed appropriately to represent the real shape of stem cross-section (in this case, the measuring runs without apparent problems, but the tomogram lacks sufficient precision);
- the real number of nails (measuring points) different from what the operator set in the program;
- swapping of the two neighbouring sonic sensors

Table 5. Transportation costs (EUR) of 1 work shift in dependence on transporting distance (round trip) and on the costs of 1 km (the value usually achieved in Czech Republic is shaded)

Transportation costs (EUR.km^{-1})	Transportation distance (km)					
	10	20	50	100	200	400
0.1	1	2	5	10	20	40
0.2	2	4	10	20	40	80
0.3	3	6	15	30	60	120
0.4	4	8	20	40	80	160
0.5	5	10	25	50	100	200
0.6	6	12	30	60	120	240

Table 6. Typical model examples of variables setting

Variables	Example A	Example B	Example C	Example D
O	5	2	4	5
N	10 (i.e. 5 trees à 2 scans or 10 trees à 1 scan)	2 (i.e. 1 trees à 2 scans or 2 trees à 1 scan)	8 (i.e. 4 trees à 2 scans or 8 trees à 1 scan)	10
Dc (km)	100	200	10	100
Tc (EUR·km^{-1})	0.3	0.3	0.3	0.3
Dt (min)	52	52	52	38
W (EUR)	6	6	6	12 (2 persons)
Ui	200	200	200	200
Ep (EUR)	20,400	20,400	20,400	20,400
Ls (years)	8	8	8	8
Ic (EUR)	481	481	481	481
total costs of 1 scan (EUR)	26.4	56.4	23.7	28.8
total costs of 1 scan (CZK)	685	1,465	617	748

O – office work on the report; device maintenance work can be included (hours); N – number of scans done in given contract (work shift); Dc – transportation distance per work shift (km); Tc – transportation costs per 1 km (EUR); Dt – duration time for 1 scan (min); W – 1-hour wage paid to the operator (or the sum of wages paid to all operators) (EUR); Ui – yearly equipment usage intensity (scans per 1 year); Ep – equipment price (EUR 20,400); Ls – expected equipment service life (years); Ic – 1-year insurance costs; eventually 1-year repair costs if occur (EUR)

of SoT or crocodile clips of ERT. This places the connections into wrong positions and makes invalid results;

- nails not driven in properly – the nails must penetrate the bark to the upper layer of wood;
- distorted (or not properly untangled) cables causing poor signal and pulling the sensors down from their correct positions;
- voltage setting in ERT: it is necessary to press the "apply to all" button, otherwise the entered value is set only for the first measuring cycle;
- low battery of tomograph or laptop: according to our experiences, tomography device is able to work the whole day (8-hour work shift) without charging; the battery life of laptop is individual, according to series; battery changing is not considered.

Other findings

Measuring with a tomography device is considerably time consuming (Li et al. 2014). As apparent from the described procedure, tomography scanning is rather a complex set of operations that requires practised operators. The process includes many activities most of which are sequential; only several of them can be performed simultaneously. Although the scanning can be made by one person, operating in pairs is more efficient for the workflow and working comfort. On the other hand, the time savings in comparison to one operator are relatively negligible (only about 10 %) and seem not worth the extended personal costs of two persons. Therefore, in contrary to the assumption, the team of two operators is less efficient than in case the device is operated by one person. Three-person teams seem to be considerably uneconomical.

PiCUS tree tomograph is able to scan the trunk with maximum dimension of about 550 cm in circumference (about 175 cm in diameter). The dimension is limited by the working range of calliper and by the length of cable-loam. The diameter of scanned stems in our study ranged about 40–60 cm and we always used the same number of measuring points (12 or 24 sensors for SoT or ERT, respectively) to avoid any substantial variance in laboriousness and thus the time consumption. If the same number of sensors is still used, the difficulty and time consumption of measuring do not closely depend on the trunk diameter.

The difficulty of scanning can be affected by the accessibility (branches, shrubs, some other obstacles) of trunk base. Very thick bark on the tree base (typical for old larch or pine) potentially can cause slowdown of the driving nails stage. Therefore the trees with excessive thick bark we did not included into our study. The difference in tree species itself does not substantially affect the difficulty and duration of measuring, as we also confirmed by our results.

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The final costs strictly depend on: price of equipment, duration time of 1 scan, 1-hour wage rate, number of operators, equipment usage intensity (number of scans done per the time period), expected service life of the equipment, distance of work place (transport distance), specific price of transportation (price of 1 km), insurance costs (if the insurance policy is arranged). Our results of time-framing are valid for the trees with trunk diameter (in the scanned level) up to about 1 m, which grown in the non-complicated locality without substantial obstacles (branches, shrubs) that should deteriorate access and motion around the trunk base.

Office work (interpretation of tomograms and writing the report etc.) usually also represents substantial costs connected with tree tomography. In this study we consider only the activities closely related with tomography. Other activities connected with assessing tree status vary substantially depending on the extent of the required survey report. Thus we do not comprise them into the time demand of tomography.

The interpretation of tomograms requires experience and knowledge. Briefly summarized, our experience suggests that light brown and green colours in the sonic tomogram usually represent the areas of hard decay; violet and blue colours are soft decay or cave. General health status and failure risk of the tree depends not only on the extension of decay but also on the position of decay, type of branching, crown extensiveness etc.

The values depicted by the colour scale on the tomogram express the ability of wood to transmit sonic waves. With regards to the fact that the acoustic waves spread through the wood by indirect ways depending on different wood characteristics, we are able to measure only "apparent sound velocity" values by the tomography technology, in fact (Göcke et al. 2008; Wang et al. 2009). The tomogram has to be interpreted taking these aspects into account.

The colour scale on the electric tomogram is created in the relative scale. Red colour represents the areas with relatively increased resistance; blue colour represents the areas with relatively decreased resistance. The absolute values may differ substantially among the individual trees. It is almost impossible to relate the moisture content of wood with the specific colour in the tomogram. It is always necessary to take into consideration the relativity of the scale.

Tree tomography finds the commercial application in urban forestry when there is a dispute whether to cut or keep a standing tree. Many arborists use tree tomography as a supporting tool to elaborate more qualified survey of the tree. Regarding the tomography, scanning is rather complicated and expensive, in the practice of urban forestry the method is used only in urgent and disputed cases where an objective and precise outcome is provided, especially when it is necessary to exactly ascertain the decay extent in the stem by as little invasive way as possible in comparison with common methods of increment borer analysis (Nicolotti et al. 2003). Moreover, these invasive methods examine only several spots around the stem, therefore their precision drops rapidly when the pattern of the decayed part is irregular while tree tomography depicts the whole area of tree cross-section. The common invasive methods and the tomography technology are very different, so the direct economical comparison is questionable.

CONCLUSION

Tree tomography scanning for trunk defects and diseases proved to be beneficial in many cases where accurate determination of tree health or safety status of trees was demanded. The advantage of tree tomography is the minimum damage of living trees compared to invasive methods like core borer. The difficulty lies in high equipment purchase price and rather complicated and laborious measuring requiring qualified personnel. Our study covers economic aspects of working with the tomographs. The study records in detail the duration of particular stages of tomography scanning and reveals the structure of the costs of working with tree tomograph. The average time spent on one tomograph scan is 52 min.

Although taking one tomograph scan requires a considerable amount of time, the time costs are only a part of the overall costs inherent in a tomography tree survey. From the strictly economical point of view, the case of only one person is most profitable to operate the tomography device. Assistant can be helpful to improve work comfort especially in case of less accessible trees, but the real expediting is not substantial. The other costs (e.g. transportation costs, expert assessment of the scans) represent the main proportion of the overall costs of the method. Also, thorough planning of field work is necessary to reduce the costs. In a typical case, the overall costs of one scan are approximately EUR 25–30 (~ CZK 650–780) and they may differ under altered circumstances.

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