The advantage of point cloud derived tree modelling on urban greenery maintenance: Shortlisting dangerous trees, assessing ecosystem services

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Abstract

Trees and greenery are the bedrock of a liveable, healthy municipality. Trees need continuous monitoring and maintenance to fit in and nourish in urban environments, to maximize the benefits they provide to their surroundings through provisioning-, cultural-, supporting- and regulating ecosystem services, and to minimize the damages they could potentially cause through falling or branches breaking off. Digital tree inventories are necessary to be able to retain and track the ever-changing condition of the trees. Information for these inventories is collected through regular manual or digital field surveys. This thesis compared the *speed, cost, accuracy and usability* of these methods through an empirical example of the measurement and digitization process of 134 selected trees in a canyon in Budapest, Hungary. The gathered differing information was used as an input in the i-Tree Eco software to attain and highlight the differences in the monetary valuation of certain regulating ecosystem services provided by the trees. The thesis found that a terrestrial LiDAR created point cloud could bear the necessary information with otherwise unmatched accuracy, in centimetres, yet to acquire the tree semantics manually from these robust files is rather time consuming. GreeHill extracts tree-semantics automatically from point clouds through their machine learning algorithm, drastically reducing the needed time and resources for tree measurements. Point cloud derived data can offer digital Voxel models of the trees, which are necessary elements of semantic 3D models of cities. These representations could allow the simulation of surface-plant-air interactions to enable to create sustainable living conditions in a constantly changing environment and curtail the dangers through data driven, pre-emptive decision making.

Keywords: tree management, tree measurement, tree inventory, tree benefit assessment, LiDAR point clouds, urban planning, machine learning

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1 Introduction

1.1 Trees and problem statement

Trees are complex, living organisms. They need continuous monitoring and maintenance to fit in and nourish in the urban ecosystem, where available space is ever more limited, both on the surface and underground. It is a puzzling task for municipalities to keep track of the condition of trees in urban environments. A city's tree population can consist of street trees, park trees, trees in urban forests and private trees as well, making it hard to estimate the total tree count, which can range from 300 thousand to well-above 10 million, depending on the city and surroundings.

Creating tree inventories manually by greenery agencies could be *time consuming and resource intensive*, depending on the size of the city's greenery and the goal of the data collection. This goal defines the trees' measured parameters and the regularity of the measurements. [1]–[3]

Another problem with manual inventories could be the *accuracy*. Crudely recorded data might result in conflicts with infrastructure. For example, if a tree next to a high-voltage power transmission cable is not pruned properly and the tree touches the cable, the whole area could experience a severe electricity blackout, burdening the town with otherwise avoidable expenses. Many municipal authorities responsible for greening efforts failing to construct credible, practical implementation and maintenance strategies.

For the above-mentioned reasons, the goal of this thesis is to provide an empirical comparative study in order to help municipalities to select the fastest, industrially available method with the best accuracy to create useful tree cadastres with the least resources needed.

1.2 Tree benefit assessment

Trees provide different benefits to its surroundings. The UK National Ecosystem Assessment [4] divides these benefits into four groups:

- *Provisioning services* include food production (fruits, nuts, berries), leaves for decoration purposes, and timber production.

- *Regulating services* provided by urban trees include the cooling of the air, the interception of rainwater – regulating the stormwater runoff, filtering gaseous pollutants and particulate matter and sequestrating carbon.
- *Cultural ecosystem services* include the opportunity for the urban population for exercise and relaxation, urban parks create areas for socializing, they enhance the cities landscape with art inspiring scenery, places for education, learning and development.
- *Supporting services* are the overarching services to enable the other categories, enhancing biodiversity in cities by providing natural habitat for different animal species [5] and the cycling of nutrients.

Trees can have *disservices* as well, for example some trees' pollen would cause allergic reaction to part of the human population. Trees are living organisms, they grow and change, hence could cause damage to the local infrastructure (pavements, underground piping, high voltage electricity cables) if they are not pruned and maintained properly.

The quantification of the above-mentioned services is often time-consuming and expensive [6]. This thesis focuses on the *regulating ecosystem services* provided by urban trees [7], since they mitigate the impacts of climate change, maintaining the air and soil quality, lessen the risks of floods through avoiding stormwater runoff.

In particular urban trees provide several regulating ecosystem services:

- Cooling the air through shadow casting and evaporative transpiration [8], [9]
- Filtering the air from gaseous pollutants (NO_2, SO_2, O_3, CO) and particulate matters (PM_{10}, $PM_{2.5}$) [10]–[13]
- Intercepting rainwater with the canopy, decreasing stormwater runoff [14]
- Sequestrating CO_2 through photosynthesis and producing O_2 [15]–[17]

The assessment of regulating ecosystem services provided by urban trees is always based on a comprehensive inventory of those trees. In this thesis, as a modelling software, the i-Tree Eco (v6) [18], [19] is used which was developed by the USDA Forest Service. The software allows the user to define tree instances through different parameters and combines it with other field data and local hourly weather and air pollution information to calculate estimates and monetary valuation of certain regulating ecosystem services provided by urban trees, which is described in detail in Chapter 4.4.1.

It is complicated to quantify some of the above-mentioned benefits, due to the number of influencing factors. For example, trees cool their surroundings mitigating the Urban Heat Island effect (improving the energy efficiency of nearby buildings), and the amount of cooling provided depends mainly on the tree's geometry (age, size, crown characteristics) [20] and species [21] , but other factors also play important roles, such as the vitality of the tree, its immediate environment; surrounding buildings, climate, weather, location, access to water, space to grow, etc. Today much effort is put towards digital modelling of vegetation, e.g. SOLWEIG [22], and of cities e.g. CityGML [23] which will enable to plan and maintain sustainable living conditions in the urban environments. Today's most advanced microclimate simulation software, such as ENVI-met [24], use computational fluid dynamics to model surface-air-plant interactions and has inputs such as position and height of buildings, surface materials and soil types, vegetation models (trees, bushes, green façade) and emission sources, which all add to the formulation of temperature, wind, humidity, pollution and the human thermal sensation in specific areas of the urban environment. Since these calculations are robust, ENVI-met currently handles the data with a minimum of 0.5 metres resolution, which can only offer relatively coarse LOD regarding the trees [25]. In the future, more and more detailed, comprehensive digital models of trees will be needed to simulate the urban microclimate accurately and optimize it by using different composition and layout of future vegetation [26], enabling ecosystem service based decision - making [27].

1.3 Tree inventories

Tree collection methodologies vary all around the world, modern cities tend to collect more detailed and regularly updated data about their trees. A smart city needs to know its trees' location, size, shape, species in order to be able to design and maintain the city's infrastructure, air-quality, climate and the general well-being of its citizens. [28]

To collect this data, different cities use different methodologies and different parameter lists, and these got more sophisticated, and accurate with time: [2], [3], [29]

Manual measurements can be slow and resource intensive, therefore certain cities organize community surveys, for example New York (USA) did it in 1995, 2005 and 2015, counting and measuring the total of 666134 street trees, creating a digital map afterwards [30]. They also used the collected data with i-Tree Eco to estimate the regulating ecosystem services provided by them. The regularity of data collection was every 10 years to follow up the changes in the status of the trees. New York also used digital, airborne data; based on ALS scanning, they provided canopy cover estimations using Treepedia [31].

Technology allows municipalities to create digital tree inventories, either by digitizing manually recorded data or extracting the relevant data from digitally created images, which can be terrestrial sourced or airborne data [32], [33], with a possibility to use deep-learning and street level imagery [34]. In a digital database more, and more comprehensive data can be stored, queried and updated with significantly less resources and man-hours.

A regularly updated database of trees can help municipalities with data driven decision making. For example, Singapore is facing regular typhoons and has around 3 million street trees, which can serve as a windbreaker, but when the storms are getting stronger, they could destroy the older or irregularly shaped tree instances, potentially causing considerable physical damage to their surroundings. This is why NParksSG [35], Singapore’s greenery agency decided to create digital tree inventories. NParksSG contracted greeHill [36], a company which extracts tree-semantics automatically from LiDAR created point clouds through machine learning. Formulating different queries on the trees’ geometry and health could help to reveal the dangerous trees, which needs pre-emptive maintenance for the safety of the citizens and infrastructure.

1.4 Remainder of the thesis

The following of the thesis firstly explains the empirical objectives, then describes the employed methods and tools in Chapter 3. In the Design subchapter, it explains the reasons behind the site selection and the collected tree parameters with the specification of the scope and limitations of the thesis. As a part of the same Chapter, the thesis describes how the data was collected and extracted using the different methods. Chapter 4 talks about the results obtained and compares the methods in terms of speed, cost, accuracy and talks about their usability: The thesis explains how the (differently) obtained tree data can be used for the monetary valuation of the regulating ecosystem services using i-Tree Eco, then explores the possibilities to use the data to shortlist dangerous trees. The Discussion Chapter talks about the conclusions derived from the comparison of the methods and explores the scalability of manual and digital tree inventories. The Conclusion and Future work Chapter highlights the takeaways from the thesis, and the desired future work regarding the assessment, monitoring, maintenance and valuation of urban tree stock.

2 Objectives

2.1 Performance of manual vs. digital tree inventories

The objective of this thesis is to compare the performance of manual vs. digital tree inventories. In EU countries tree ownership implies liability for damages, therefore many countries would need to keep tree cadastres to monitor the vitality of the trees. These cadastres could also be used to assess ecosystem service provided by the trees. [6]

Municipalities have different options to collect and update information about their trees, yet there is no globally accepted methodology which would offer fast results with the best accuracy. Hence, the aim of this thesis is to compare different methods, to provide a guide for municipalities on selecting the best way to create usable tree inventories. Usable in the meaning; the inventory should contain comprehensive tree semantics to offer different benefits, such as the monetary valuation of certain regulating ecosystem services (using i-Tree Eco), or to assist pre-emptive decision making regarding the vitality of the trees.

3 different methods were compared in terms of speed, cost, accuracy and usability of the tree-measurement and digitization process, through an empirical example of selected trees in a canyon in Budapest:

- “Manual”: Manual tree measurements, and digitation of the recorded data
- “Digital - manual”: Digital tree measurements by a terrestrial laser scanner (TLS) to create point clouds of the inspected area, and then extracting the tree semantics by measuring manually in the created point clouds using the software: PointCloudScene [37]
- “Digital – automated”: Tree measurements provided by greeHill’s automated machine learning process, which extracts the values from point clouds.

The gathered differing results of the various methods were analysed in terms of practicability by using them as inputs in the i-Tree Eco software to perform a monetary valuation assessment of the trees’ regulating ecosystem services. The results of these estimations were compared to understand; how the various methods differences would influence the assessments. The method’s data was analysed whether they could help to shortlist dangerous trees.

3 Methods and Tools

3.1 Design

There are different ways to collect data about trees, but the methods highly depend on the reason of the collection: which parameters and how often to collect them. In this thesis these parameters were selected for usability: to be able to represent an extensive model of the trees. The reason behind it is twofold: firstly, to achieve the best possible regulating ecosystem service assessment which can be performed using the i-Tree Eco and secondly for the cadastre to be able to shortlist dangerous trees. Due to the list of parameters, aerial scanning of trees was excluded from the design, because it would not be able to provide the minimum necessary parameters for the analysis.

3 methods were selected for comparison through an empirical example of selected trees in a canyon in Budapest, they are indicated as: *"manual"*, *"digital-manual"* and *"digital-automated"*.

According to the objectives of this thesis, the methods' speed, cost, accuracy and usability are compared through the empirical example. For each of the trees measured with the different methods, the required time and labour force, as well as the associated costs were documented; as it is described in detail in the Data Collection and Data Extraction sections of this Chapter. The accuracy depends on the source of truth for each of the parameters, please see the detailed description in the Chapter: Results. The usability describes the methods ability to collect the required parameters. The whole workflow and the results of the thesis is depicted on Figure 1.

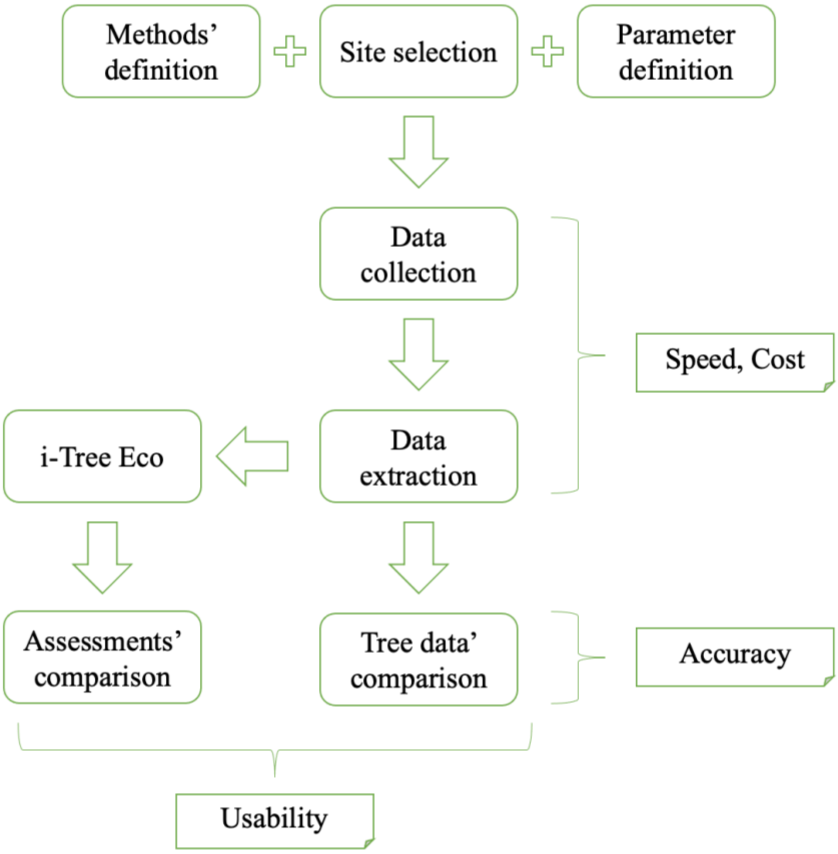


Figure 1. Workflow and results of the thesis

3.1.1 Site selection

The site selection was done through analysing canyons of Budapest, which would meet the selection criteria:

1. At least 100 trees: old & big trees preferable
2. Can be measured with TLS: enough facades / flat surfaces in order to fit the point clouds.
3. It is authorized to measure at the location
4. TLS won't disturb the traffic
5. Proximity to buildings should be low - canyon effect - narrow streets
6. Mostly street trees
7. Needs to be georeferenced: Global Navigation Satellite System (GNSS) needs certain points where satellite access is available
8. Friendly/helpful neighbourhood
9. Diverse species

After analysing 9 different options in Budapest; the Bartók Béla street between Móricz Zsigmond körtér and Gellért-tér have been selected for the measurements as it met all the predefined criteria, please see the options on Table 1, which uses the numbers from the list of criteria defined above. The KML file containing all the options for the possible sites can be found in the Appendix.

Table 1. Site selection

Site	Missing criteria	Matching criteria
Kecskeméti street	1, 4, 9	2, 3, 5, 6, 7, 8
Andrássy street	4, 5, 6, 8, 9	1, 2, 3, 7
BME park	2, 5, 6	1, 3, 4, 7, 8, 9
Bogdánfy street	4, 5	1, 2, 3, 6, 7, 8, 9
Benczúr street	4, 6, 7, 9	1, 2, 3, 5, 8
Mester street	5, 9	1, 2, 3, 4, 6, 7, 8
Városligeti tree-line	1, 2, 5, 6, 9	3, 4, 7, 8
Tóth – Árpád walkway	3, 4, 9	1, 2, 5, 7, 8
Bartók Béla street	-	1, 2, 3, 4, 5, 6, 7, 8, 9

The inspected canyon is 720m long, and has street trees on both sides of the road, amounting to a total of inspected 136 trees, of which 2 got excluded due to unavailability of data: 09_04_1_1 and 09_07_5_5, resulting in 134 comparable trees. The total area is 2.53ha, which can be seen on Figure 2. Figure 3 shows the location of the trees as exported from Google Maps. The map containing the pictures of the trees can be accessed through the references [38].

Figure 2. The inspected area seen from above (south) and from the tram (north)

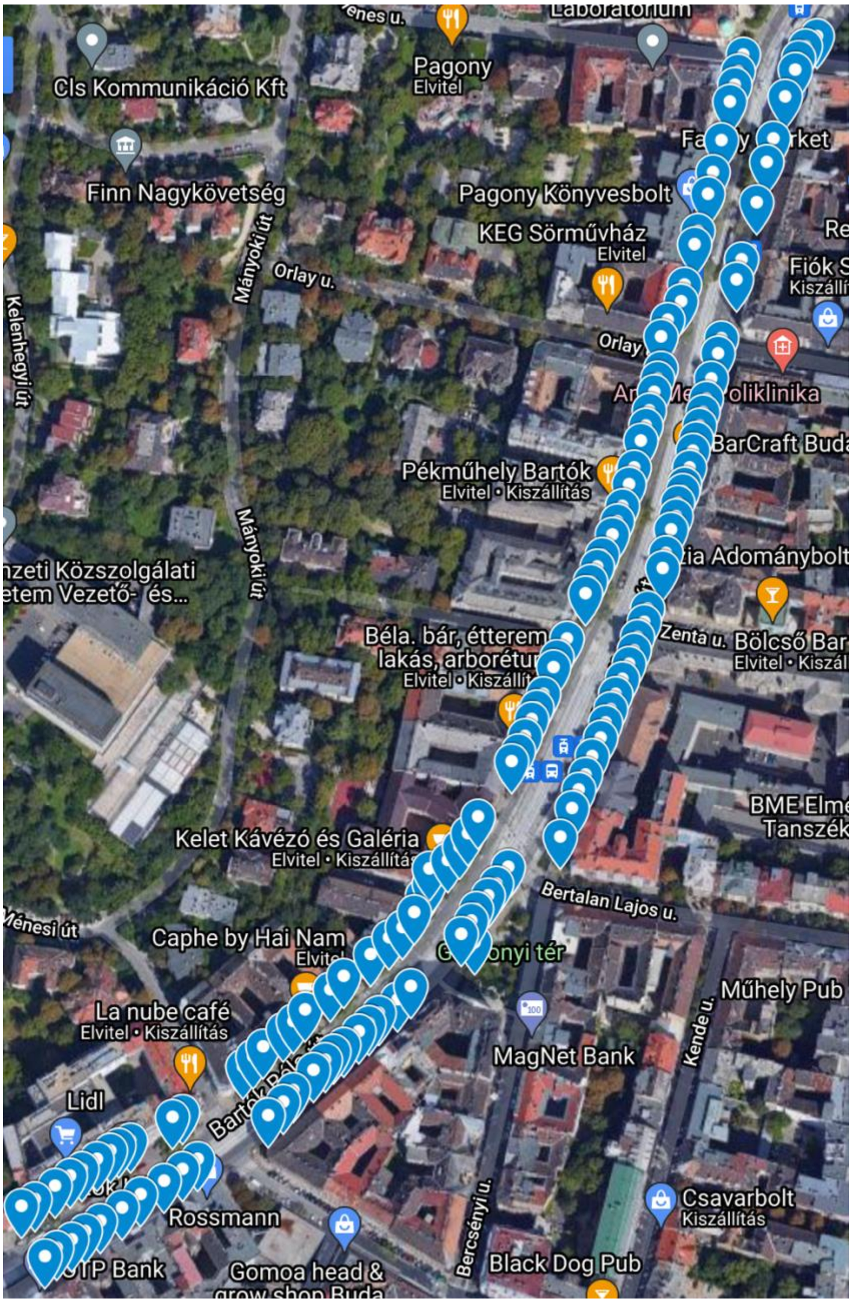


Figure 3. The inspected trees

Out of the 134 trees, there is 70 instances of the Narrow-leafed ash (Fraxinus angustifolia subsp. pannonica), 61 instances of the Oriental planetree (Platanus orientalis) and only one instance of each of the following: Green ash (Fraxinus pennsylvanica), Ailanthus (Ailanthus) and Chestnut (Castanea).

Each tree received a unique ID, according to the dates and sequences of the manual measurements: [month]_[day]_[sequence]_[number]. For example; 09_08_1_3 points to the third tree measured in the first sequence of the measurements on the 8th of September. The ID-s of the trees can be seen on the left part of Figure 4 - Figure 7 (2D view). These

Figures are screenshots from the software PointCloudScene in a North-to-South order. The colouring of the point cloud was set according to the elevation, in order to distinguish the trees better. The right side of these Figures shows the selected area in 3D view. The selection is highlighted with a yellow rectangle on the 2D view.

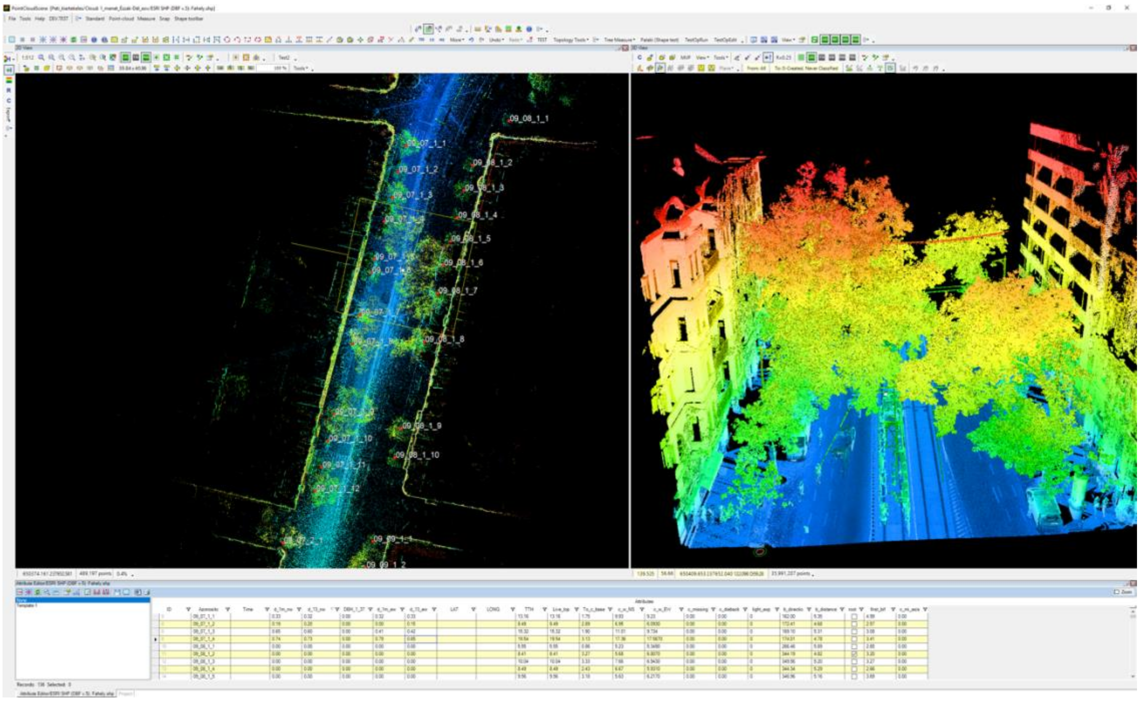


Figure 4. ID-s of trees, northernmost section

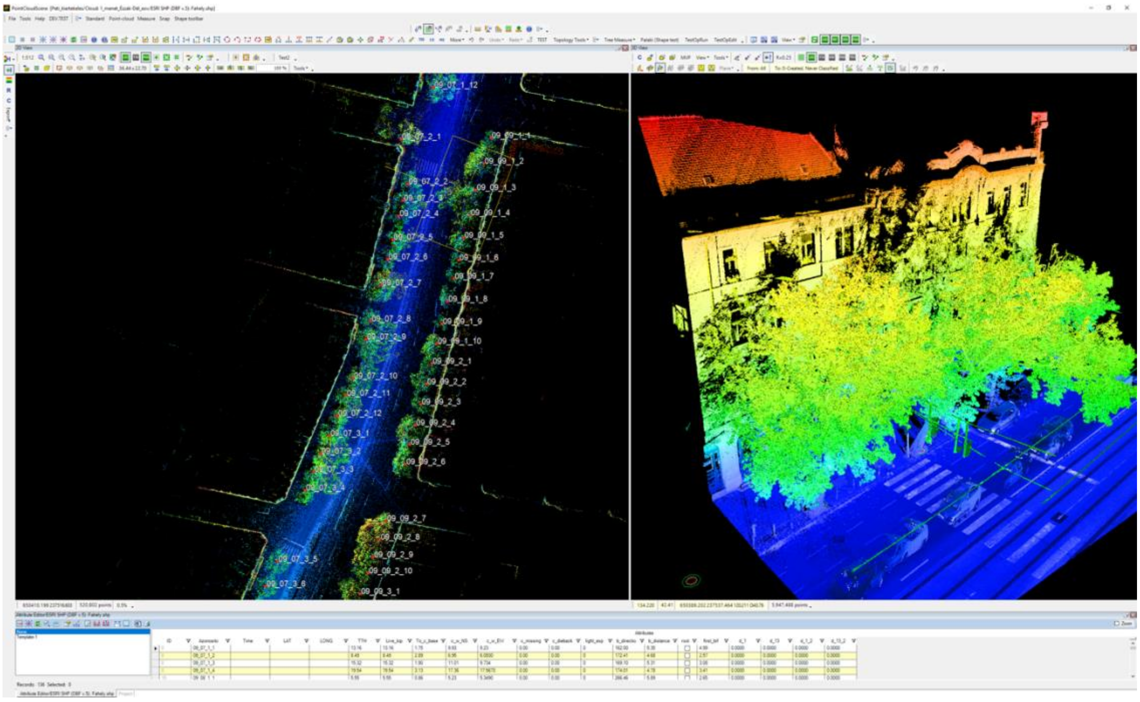


Figure 5. ID-s of trees, mid-north section

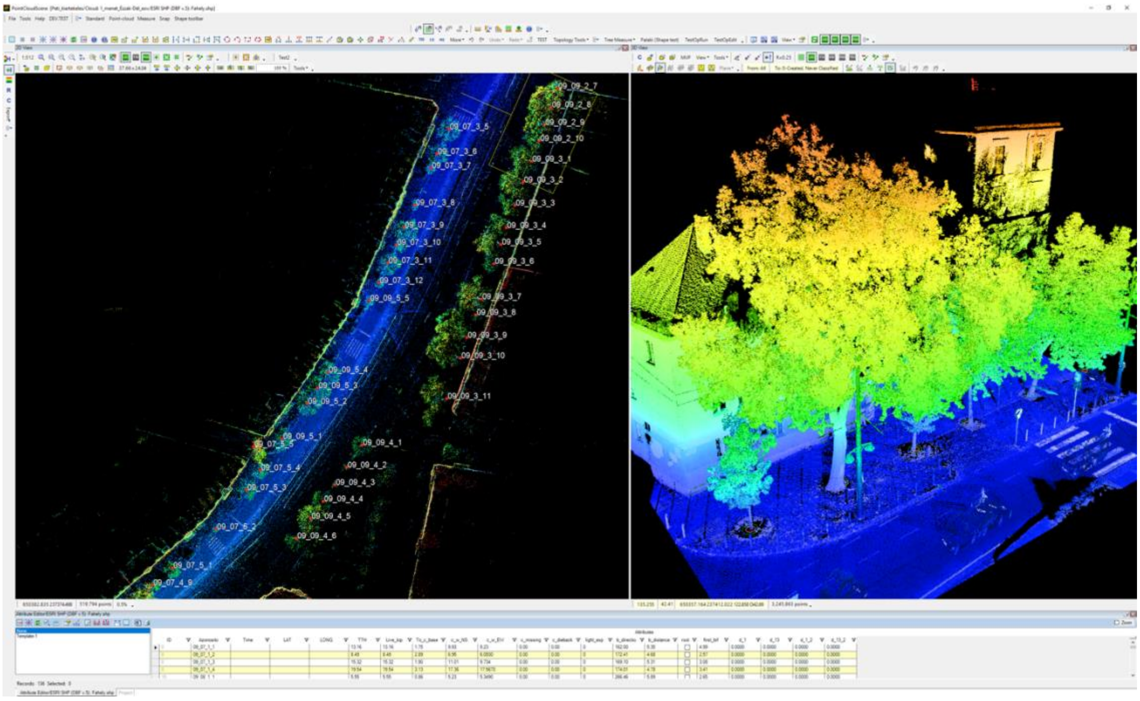


Figure 6. ID-s of trees, mid-south section

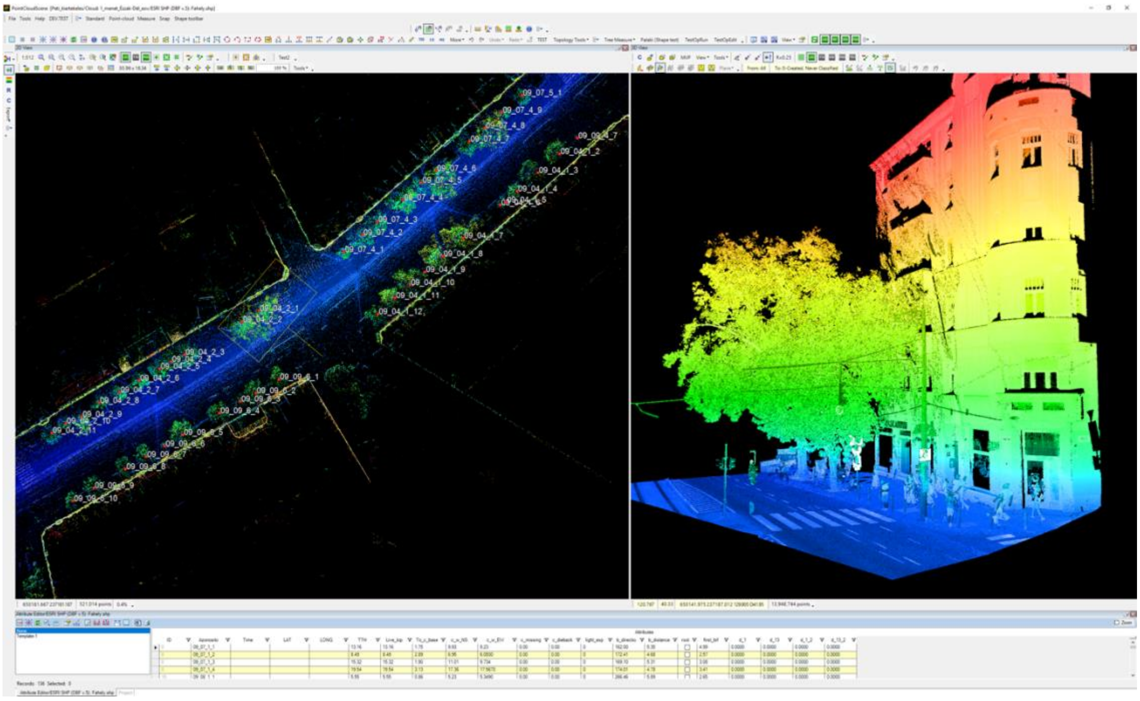


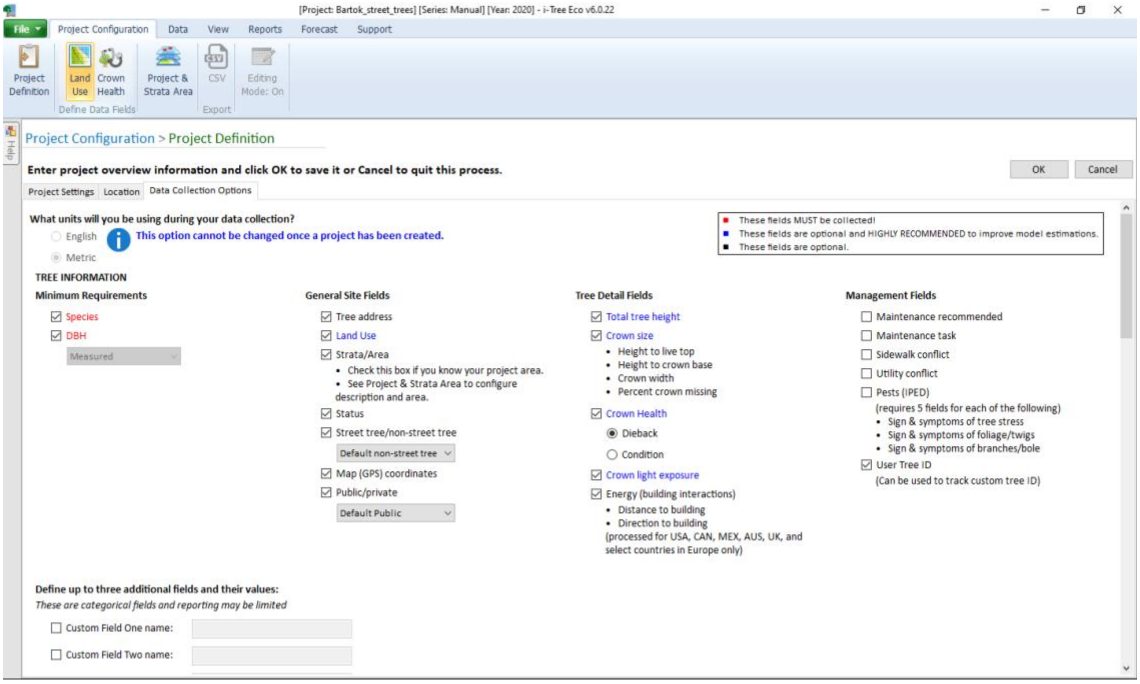
Figure 7. ID-s of trees, southernmost section

3.1.2 Parameters to collect

The trees’ parameters to be collected were selected based on 2 groups, for the collected information to be able to be used for monetary assessment of ecosystem services and to shortlist dangerous trees. Besides tree related parameters, for each record, the time needed to measure was recorded as well, in order to assess the speed of the methodology. Some parameters overlap in the 2 groups, hence those only needed to be collected once.

Based on ecosystem service estimation

i-Tree [18] is a software programme suite developed by the USDA Forest Service. This thesis used the i-Tree Eco v6 package, which is a model that uses tree measurements and other data to estimate ecosystem services and structural characteristics of the urban forest. Tree data and field information are used as an input and the software merges this information with local pre-processed hourly weather and air pollution concentration data. This makes it possible for the model to calculate structural and functional information using a series of scientific equations or algorithms, which can be accessed through their website [39]. I-Tree Eco v6 requires only two information about the trees to complete an Eco project: the species and the diameter at breast height. It is designed this way, so that with minimal information on the trees, one can estimate its benefits, but with substantial limitations. Therefore, to improve the quality and accuracy of results in addition to the required parameters they strongly recommend that users collect the following parameters as well: Species, DBH, Land use, Total tree height, Crown size (height to live top, height to crown base, crown width, percent crown missing), Crown health (% dieback), crown light exposure, energy (building distance, building direction), strata, status, street-tree/non-street tree, coordinates, public/private. All these parameters were used in this thesis as presented on Figure 8; the used parameters are checked with checkmarks.



Project Configuration > Project Definition

Enter project overview information and click OK to save it or Cancel to quit this process.

Project Settings | Location | Data Collection Options

What units will you be using during your data collection?

○ English

● Metric

This option cannot be changed once a project has been created.

- 🟥 These fields MUST be collected!
- 🟦 These fields are optional and HIGHLY RECOMMENDED to improve model estimations.
- ⬛ These fields are optional.

TREE INFORMATION

Minimum Requirements

☑ Species

☑ DBH

Measured

General Site Fields

☑ Tree address

☑ Land Use

☑ Strata/Area
- Check this box if you know your project area.
- See Project & Strata Area to configure description and area.

☑ Status

☑ Street tree/non-street tree

Default non-street tree

☑ Map (GPS) coordinates

☑ Public/private

Default Public

Tree Detail Fields

☑ Total tree height

☑ Crown size
- Height to live top
- Height to crown base
- Crown width
- Percent crown missing

☑ Crown Health

● Dieback

○ Condition

☑ Crown light exposure

☑ Energy (building interactions)
- Distance to building
- Direction to building

(processed for USA, CAN, MEX, AUS, UK, and select countries in Europe only)

Management Fields

☐ Maintenance recommended

☐ Maintenance task

☐ Sidewalk conflict

☐ Utility conflict

☐ Pests (IPED)

(requires 5 fields for each of the following)
- Sign & symptoms of tree stress
- Sign & symptoms of foliage/twigs
- Sign & symptoms of branches/bole

☑ User Tree ID

(Can be used to track custom tree ID)

Define up to three additional fields and their values:

These are categorical fields and reporting may be limited

☐ Custom Field One name:

☐ Custom Field Two name:

Figure 8. Used parameters from i-Tree Eco

Based on shortlisting dangerous trees

The second group of parameters were based on the contractual agreements between greeHill and Singapore’s gardening agency NParksSG. NParksSG required the following parameters in order to be able to use the models for different purposes, not limited to shortlisting dangerous trees:

- GUID (laser scan GUID) or primary key for each tree
- NPID (NParksSG ID)
- Base coordinates
- Date of scan
- Translation vector
- Tree Height
- Trunk girth at 1 m
- Trunk girth at 1.3 m
- Trunk girth at difference of 0.1 till first bifurcation (i.e.; girth at 0.1 m, 0.2 m to first bifurcation for trunk)
- Root above existence (Y/N)
- Trunk Height until first bifurcation
- Crown Width
- Crown Depth B

- Crown Height
- Crown Ellipse Angle or crown orientation
- Crown Eccentricity
- Crown X Offset from Base Coordinates
- Crown Y Offset from Base Coordinates
- Branch Voxel model
- Crown Voxels
- Branch Diameters and Coordinates of Diameters along with branching pattern
- Trunk bending angle (yaw, pitch, from ground)

Some parameters can be found in both of the lists; therefore, the values could be derived from one group to the other, namely the GPS coordinates, the total tree height, and the crown's height were derived from the i-Tree required parameters to fill in to the NParksSG required parameters.

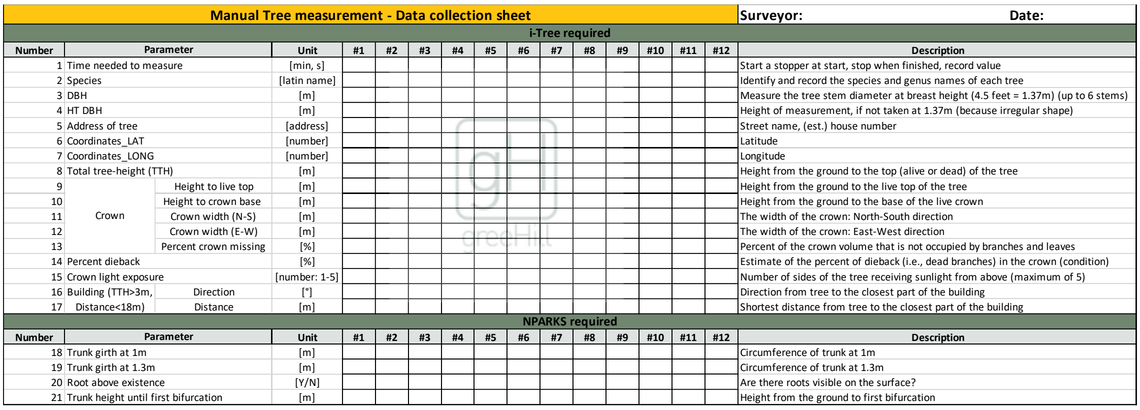
3.1.3 Scope and limitations

The given location, date, methodologies and the selected parameters formed the scope and limitations of the thesis. The selected location offered 134 tree instances to work with, and the date of the different measurements regulated their status, in this case, they were measured in foliated condition in the same time period for the different methods. An important limitation of the thesis is the source of truth for each of the parameters, which depended on the methods they were measured with. greeHill's algorithm's results was excluded from the considerations of being the source of truth, because it depends on its own correctness, hence the source of truth was either the manual or digital-manual measurements for each of the parameters. This limitation meant, that the comparison was performed firstly between the manual and digital-manual measurements and then between the source of truth and the digital-automated, highlighting the average difference between the methods, their standard deviation and the margin of error with 96% confidence.

3.2 Data collection

3.2.1 Manual

The manual data collection was performed within 3 working days between the 4th and 9th of September 2020, using the workload of 2 person. The theoretical knowledge was first explained by Péter Békési, a gardening specialist working at Garden kft [40], when the needed equipment for the measurements were listed, and were leased to the writer of this thesis free of charge, yet, the list with estimated original prices can be seen in Chapter 4.2’s Table 3 along with their respective costs for the 3 days period. Besides the needed tools, the specialist explained which parameters are collectible manually, and for those, unique manual survey sheets were designed and printed to assist the collection procedure, please see the sheet on Figure 9. According to the limitations, the i-Tree required fields were designed to be able to be collected manually, but most of the fields for the NParksSG required fields were not possible to collect manually, as it is described in Chapter 4.4’s Table 5.



Manual Tree measurement - Data collection sheet																**Surveyor:** **Date:**
i-Tree required																
Number	**Parameter**		**Unit**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**Description**
1	Time needed to measure		[min, s]													Start a stopper at start, stop when finished, record value
2	Species		[latin name]													Identify and record the species and genus names of each tree
3	DBH		[m]													Measure the tree stem diameter at breast height (4.5 feet = 1.37m) (up to 6 stems)
4	HT DBH		[m]													Height of measurement, if not taken at 1.37m (because irregular shape)
5	Address of tree		[address]													Street name, (est.) house number
6	Coordinates_LAT		[number]													Latitude
7	Coordinates_LONG		[number]													Longitude
8	Total tree-height (TTH)		[m]													Height from the ground to the top (alive or dead) of the tree
9	Crown	Height to live top	[m]													Height from the ground to the live top of the tree
10		Height to crown base	[m]													Height from the ground to the base of the live crown
11		Crown width (N-S)	[m]													The width of the crown: North-South direction
12		Crown width (E-W)	[m]													The width of the crown: East-West direction
13		Percent crown missing	[%]													Percent of the crown volume that is not occupied by branches and leaves
14	Percent dieback		[%]													Estimate of the percent of dieback (i.e., dead branches) in the crown (condition)
15	Crown light exposure		[number: 1-5]													Number of sides of the tree receiving sunlight from above (maximum of 5)
16	Building (TTH>3m, Distance<18m)	Direction	[°]													Direction from tree to the closest part of the building
17		Distance	[m]													Shortest distance from tree to the closest part of the building
NPARKS required																
Number	**Parameter**		**Unit**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**Description**
18	Trunk girth at 1m		[m]													Circumference of trunk at 1m
19	Trunk girth at 1.3m		[m]													Circumference of trunk at 1.3m
20	Root above existence		[Y/N]													Are there roots visible on the surface?
21	Trunk height until first bifurcation		[m]													Height from the ground to first bifurcation

Figure 9. Manual data collection sheet

After obtaining the needed equipment as well as the printed-out measurement sheets, the practical knowledge was explained through measurements performed together with the gardening specialist, illustrated on Figure 10.

Figure 10. Specialist explaining the manual tree measurement methodology

The practical knowledge for the manual measurements was supported by the i-Tree Eco Field Guide [41]. In the following, the methodology of the manual measurements for each of the parameters on the Manual Data collection sheet will be described. The measurements needed the assistance of 2 person harmonizing the work of measurements and recording the obtained results on the paper sheets. Arriving to the inspected tree's location, a stopper has been started to measure the needed time. After taking a picture of the tree for identification purposes, the species have been determined from the experience of the gardening specialist. The inspected area contained a total of 5 species, dominated by Oriental planetree and Narrow leafed ash.

The previously prepared measuring stick had marks at 1m, 1.3m and 1.37m respectively, and it was placed next to the trunk, so that the tree bark could be marked with a pencil at these heights, helping the girth and diameter measurements. The diameter at breast height (1.37m) was measured with a forestry calliper from 2 directions of 90° difference, and the obtained values were averaged to assess the correct value. It is done like that, because not all the trees' trunks' cross section is shaped like a circle, there might be considerably big differences between the measured diameters from each of the sides. Among the inspected trees, there were no irregularity of the trunk which would result in measuring the DBH at different height than 1.37m. The girth at 1m and 1.30m were determined by wrapping a plastic measuring tape around the tree's trunk to read the values.

The address of the tree was read from the nearby buildings, and the GPS location was measured with a smartphone, providing *coarse results*, due to the nearby buildings' shading effect. The height of the tree and the nearby buildings influenced the crown light exposure, according to the i-Tree Eco Field Guide. The building's direction was determined using a compass on a smartphone, and the distance to it was measured with a laser distance meter.

The total tree height was measured using a SUUNTO clinometer [42], with which, the user needs to walk 15m or 20m away from the tree (using the practiced metre – long steps), and see through the clinometer to read the correct values of the height. The same methodology was used to assess the height until the crown base and the height until the first bifurcation if they were not reachable by hand, nor by the measuring stick.

The crown width for both of the directions were measured by the practiced metre – long steps, meaning that the surveyor needed to walk under the crown, in both directions. In some cases, this resulted in walking out to the street, disturbing the traffic. The crown's dieback, and the percent crown missing were estimations based on the i-Tree Eco Field Guide. Whether the root was visible above ground was based on visual observation.

After all the needed values have been filled out for the inspected tree, the stopper was then stopped, and the total time needed to measure was recorded on the measurement sheet. The data collection for the manual measurements could be completed in 3 working days with the workload of 2 person.

3.2.2 Digital

The digital-manual and the digital-automated methodologies both require a point cloud of the inspected area as the input data, therefore in this thesis the data collection was performed once for both of the digital measurements. It was done through contracting a company called Geodézia zrt. [43], who used a customized Riegl VMX-1HA terrestrial mobile laser scanner to create the point clouds. On Figure 11, the mobile solution can be seen, paired with a "Ladybug" camera system, which was triggered to take pictures at every 5m in 6 directions, these are later referred as "geophotos". The colouring of the point cloud is based on these images at the post-processing stage. All together there were

7 ways of the inspected area recorded, 3 times both ways and one more time in south-north direction.

Figure 11. Mobile laser scanner

The system needs a driver and an operator to record the area. A recording session starts with a 5-minute standby GPS calibration, at a nearby location where the system can communicate with more than 7 satellites. After this, the custom inertia navigation system is initialized by moving the vehicle around without recording. The inertia navigation system is used to calculate the correct position of the vehicle from the starting point and is used alongside with the position received from the satellites, and alone if there is no satellite signal available.

After the initialization, the recording can start. Every time after the car has stopped because of a red light, the recording is stopped by the operator so that it won’t record data unnecessarily. Before starting to go again, the recording is started by the operator. The current recordings, position, available satellites and inertia calculation along with other supporting information is shown on the front monitor in the car, illustrated on Figure 12.

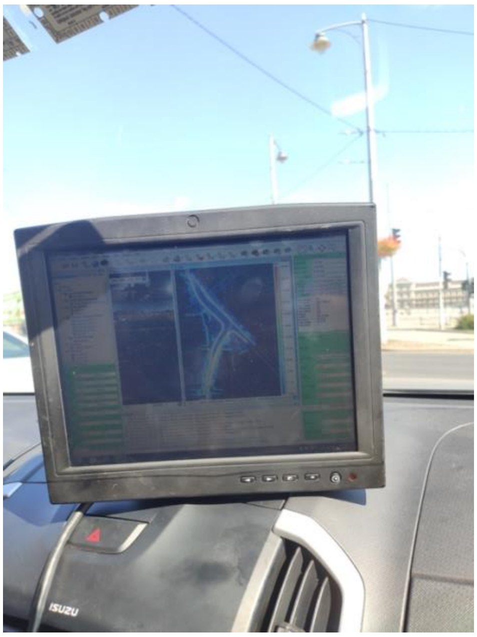


Figure 12. Information shown on the monitor while recording

Every second 2 million points are recorded by the 2 spinning laser scanners, whose mirrors make 250 turns every second, that is 15000 turns per minute. The system can operate in dry condition between -10 and +50 °C. The whole system costs around €700-800 thousand, excluding the vehicle but including the inertia navigation system which costs around €60 thousand. The yearly software updates issued by Riegl cost between €20 and €40 thousand. The scanner bearings would need to be changed once every 8 years, due to the extreme mechanical exposition. In this custom system a wheel rotation sensor is also built in to assist the inertia navigation system. 5 SSD stores the recorded information with 2x500GB available storage for the scanners' recordings, and 3x1TB for the camera imagery. The supporting system can be seen on Figure 13, where the chief engineer, Péter Csörgits explains the different parts of the hardware.

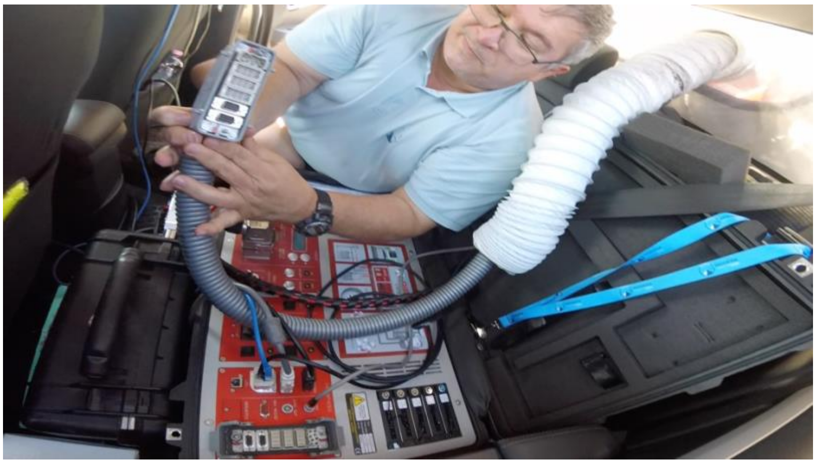


Figure 13. Lead engineer explains the supporting system

Since the GPS along with the inertia navigation system is less accurate (2-3 cm) than the LiDAR scanners (1-2 mm), the 7 ways would have mismatching images, therefore a software component called “reprecision” pulls these images together based on voxel arithmetic calculations. All together the relative precision of the system is less than 1 cm. After the 7 ways of recordings, the recording stopped. There is a need for 5 minutes of movement of vehicle after, and 5 minutes of standby for the finishing GPS calibration. A day’s recording usually takes 1 day long post-processing, to create and colour the point clouds, and to fit the supporting geophotos. The 7 ways of the inspected area of 720m (2.53ha), after post processing takes up 70GB of storage, of which the point cloud files amount up to 60GB, resulting in a dense point cloud.

The whole recording session and post-processing was done by the company for €286, paid and contracted by greeHill, and at the end they have supplied the geophotos taken, and the coloured point clouds as LAS files. LAS is an open, binary file format used for interchange and archiving of point cloud data and is regarded as an industry standard for LiDAR data.

3.3 Data extraction

3.3.1 Manual

The data extraction for the manual measurements included the digitization of the manually recorded data, meaning that the filled out manual measurement sheets’ information was manually entered to an MS Excel table, for it being able to be stored and processed digitally – to be able to compare the obtained values of the different methods.

This extraction procedure took 1 minute per tree in average, the individual results are presented in the Appendix.

3.3.2 Digital – manual

The digital – manual measurement got its name because the measurements were taken digitally, providing a dense point cloud of the inspected area with centimetre accuracy, yet the required tree parameters need to be extracted manually from that point cloud. For this, a software called PointCloudScene by Digicart ltd. [37] was used. PointCloudScene is a software solution for the 2D/3D visualization and analysis of laser acquired point cloud data. The software is capable of handling point clouds, vector files, orientated images and georeferenced raster together. The loaded information is shown in a two-dimensional top view navigation window and in a three-dimensional window, the software offers a versatile collection of more than 300 tools for navigation, analysis, classification and digitization tasks, and can easily handle enormous sets of data.

The software is a great tool to measure the trees' parameters with millimetre accuracy, the only limit is the correctness of the created point cloud. The user can create shape files which can contain user defined values, and exact GPS locations, by matching to the Hungarian EOV map projection system. The software also allows to show the position where the geophotos were taken by the Ladybug camera, and the user can select the associated images to see, as presented on the bottom-right section of Figure 15.

In the following, the measurement procedure will be introduced by an example of tree 09_04_1_3 (narrow leafed ash), please see the tree itself on Figure 14. After selecting the measurable tree instance, the data extraction is the following: the user highlights the area of the tree on the 2D view which can be loaded to the 3D view to double check if all parts of the tree are inside the selected area. After that, the tree's insertion point (where the tree's trunk touches the ground) needs to be marked, from which the measurements will take place. Selecting the profile mode before rendering the 3D image of the selection will force the points to a 2D plane from the selected point of view, which will enable the correct measurements, because there is no depth to the image, the user can select the desired points of the clouds. For example, to measure the total tree height, the distance measurement tool was used between the tree's insertion point, and its highest point of the crown, as depicted with the case of the tree 09_04_1_3, on Figure 15.

Figure 14. The tree 09_04_1_3

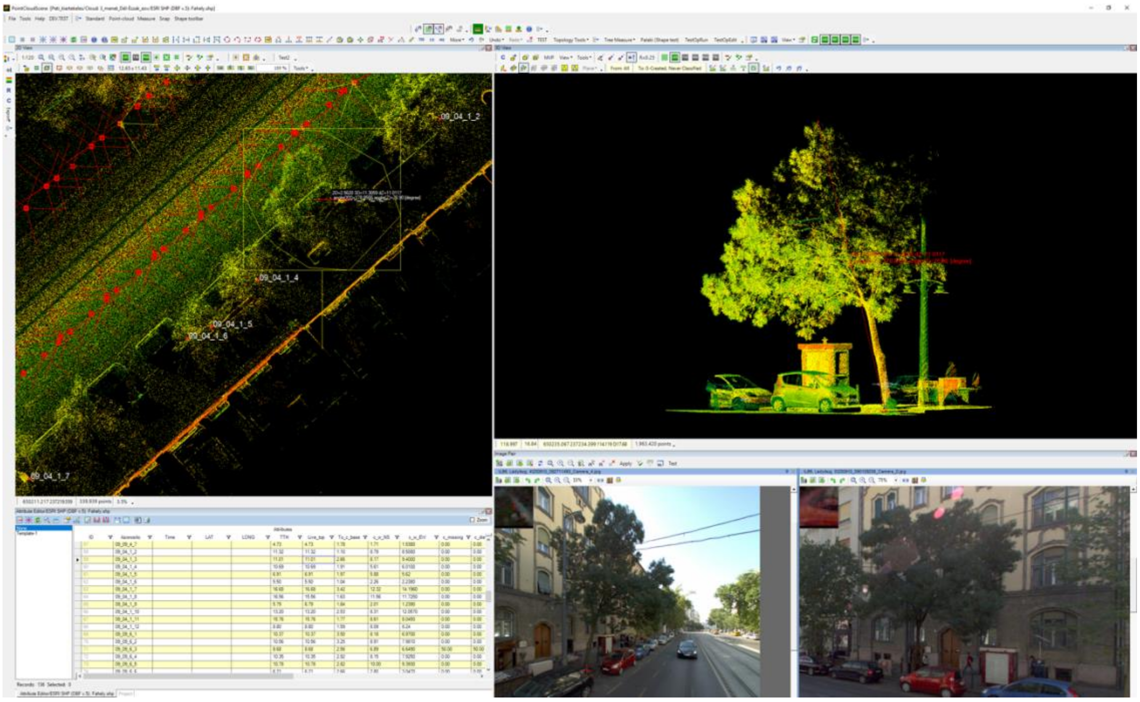


Figure 15. Total tree height of tree 09_04_1_3

The 2D view can be seen on the top-left side of Figure 15, with the inspected area highlighted by the yellow selection polygon. The 3D view (top-right side) shows the profile mode of the selected area from southern point of view on which the measurement is taken by reading the values of the red text, in this case dZ shows the distance on the third axis (Z – height) between the insertion point and the selected highest point of the tree: 11.0117 [m]. After the measurement the obtained value was recorded in the shape file’s attribute table, which can be seen on the bottom-left part of Figure 15.

The crown width was measured in two directions according to the i-Tree Eco specification, for this the selection’s point of view was set to see the area from either south/north and east/west direction, as shown on Figure 16 and Figure 17. The values read are the 2D distance of the measurements: 9.1470 m for N-S direction and 9.3800 m for E-W direction.

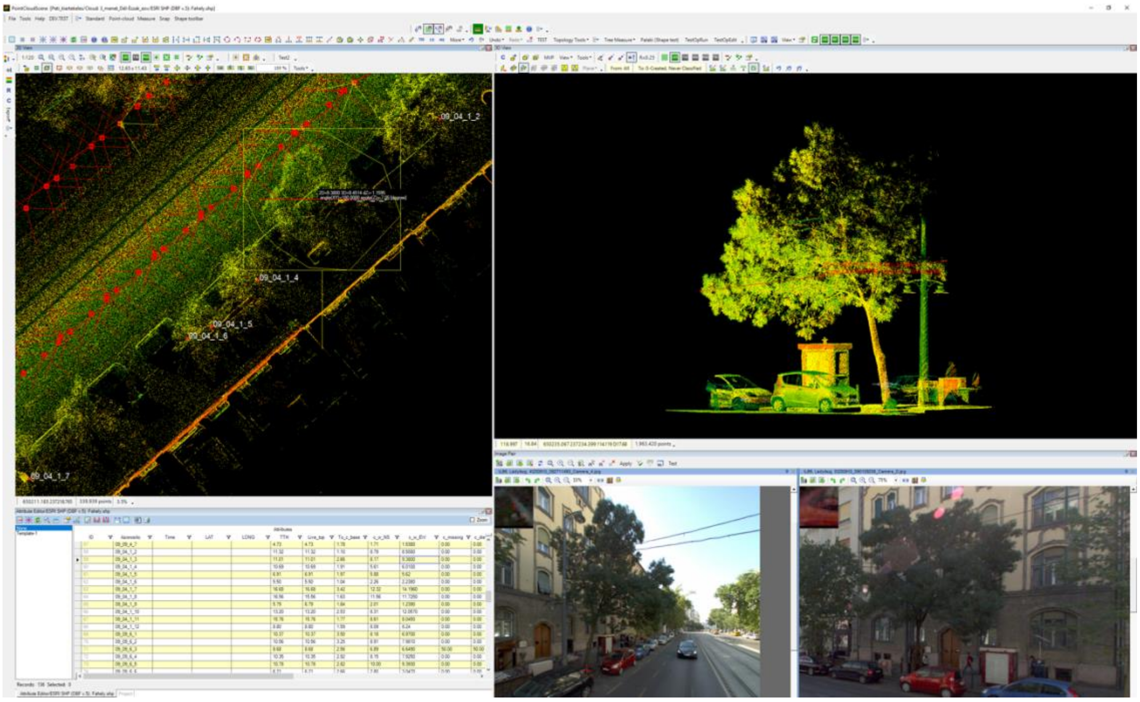


Figure 16. Crown width (E-W) of tree 09_04_1_3

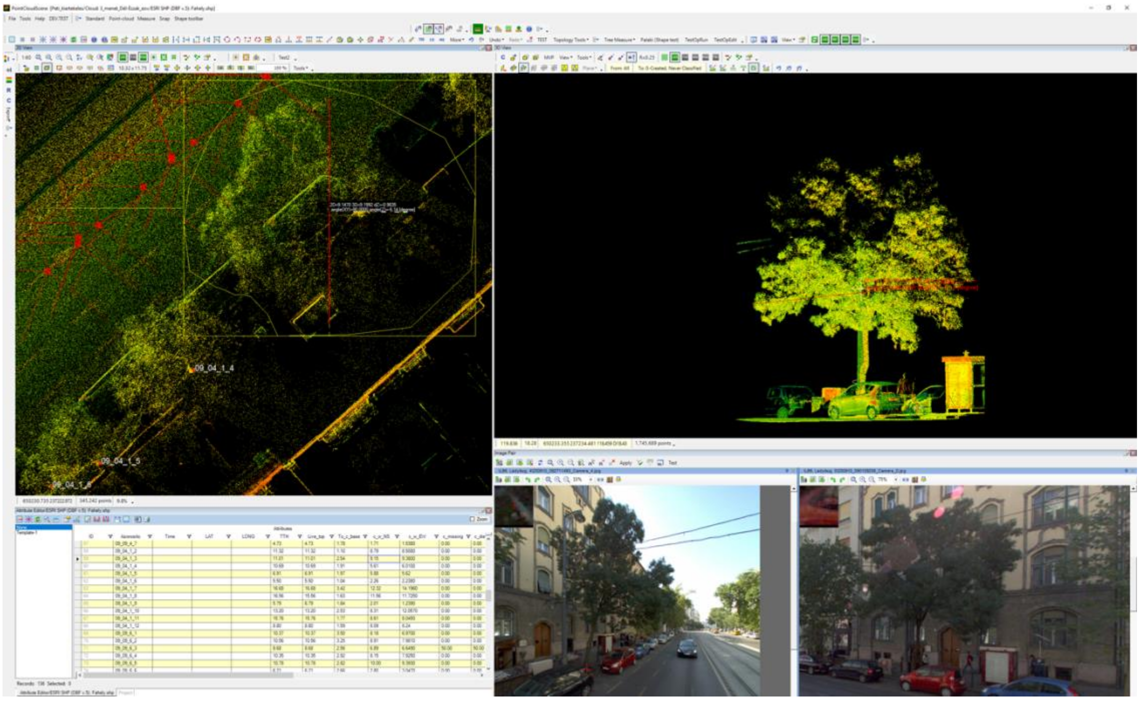


Figure 17. Crown width (N-S) of tree 09_04_1_3

The height until the first bifurcation is measured using the measurement tool inspecting the profile mode of the selected area, please see the measurement on Figure 18, with the result of dZ = 3.7610m.

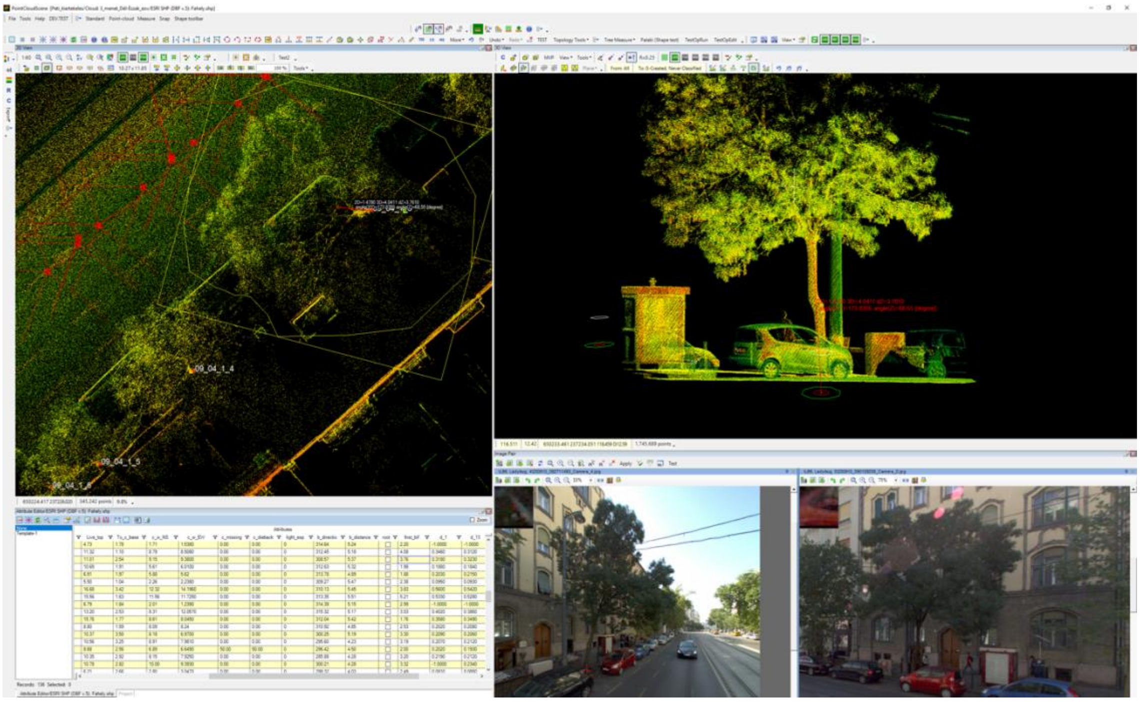


Figure 18. Height until first bifurcation of tree 09_04_1_3

Similarly, to the “total tree height” and the “height until first bifurcation”, the “height until the crown base” was measured also from the insertion point of the tree, which can be seen on Figure 19.

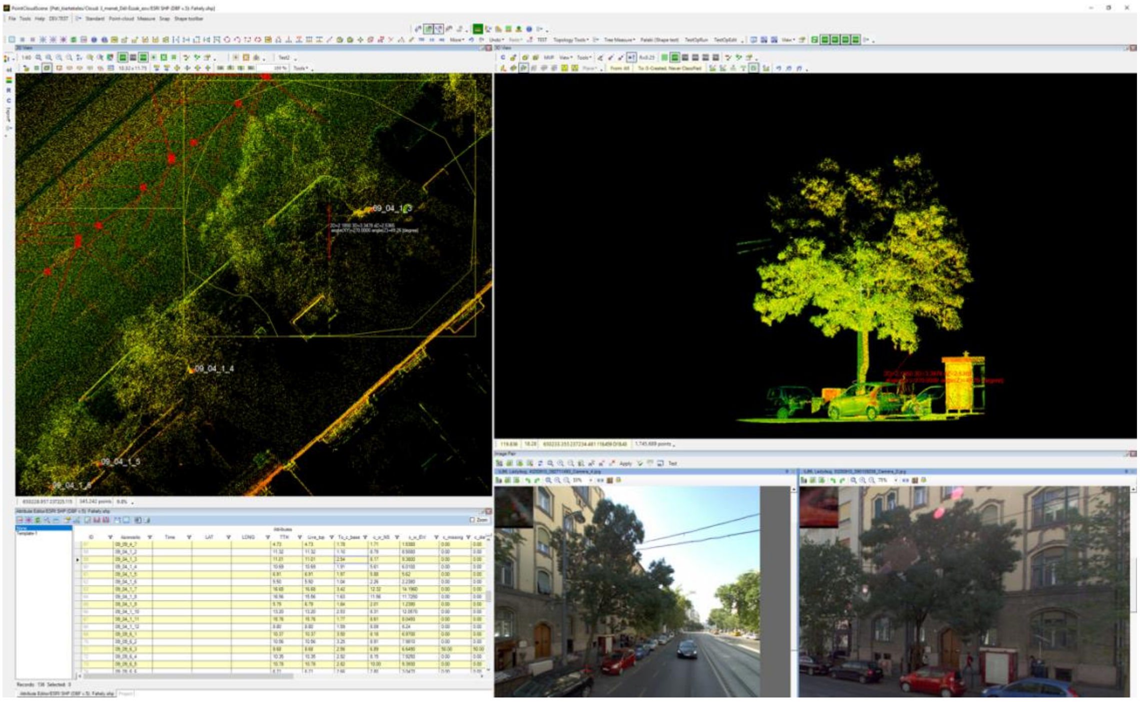


Figure 19. Height to crown base of tree 09_04_1_3

The building direction and distance were measured according to the specification of i-Tree Eco Field Guide, selecting the closest point of the building from the tree’s insertion point, as it is shown on Figure 20. The direction and distance can be read from the measurement as the 2D distance (5.3740 m) and the angle (XY): 308.5686. This degree is then subtracted from 450, to match the values of the manual measurements.

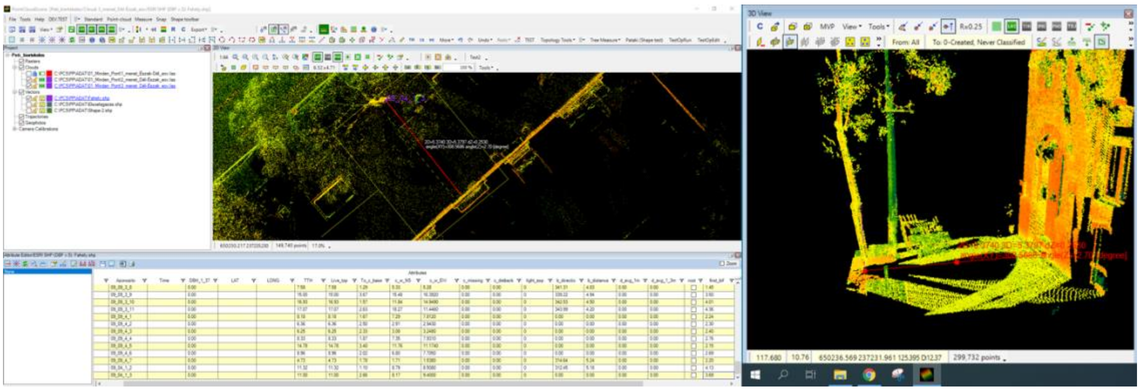


Figure 20. Building direction and distance of tree 09_04_1_3

To measure the diameter at breast height and the girth at 1m and 1.3m, the colouring of the point cloud was set to elevation increment to help the measurement. The insertion point’s Z value can be manually incremented using the command “setXYZ”. First with 1m, then 1.3m and 1.37m respectively to know the height were the assessments needs to be taken. The 2D distance value was used to get the diameters at the different heights, and the girth was calculated using the equation of the circle. Figure 21and Figure 21 shows the screenshots of the measurements at 1m and 1.3m, respectively.

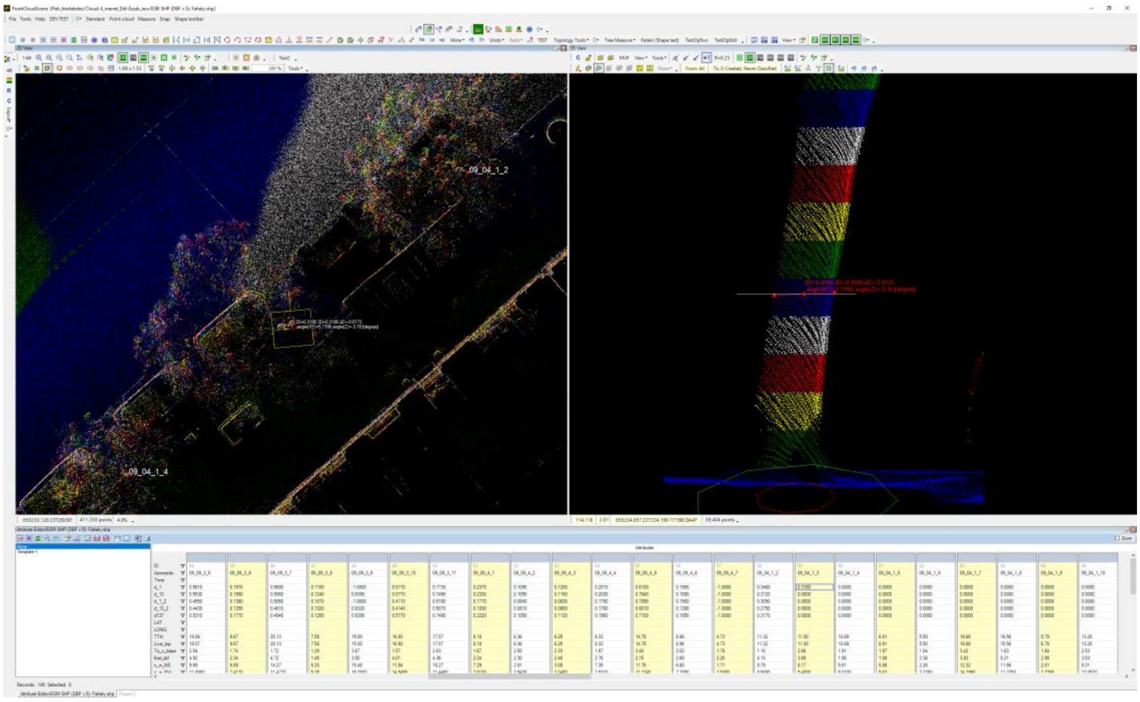


Figure 21. Diameter at 1m of tree 09_04_1_3

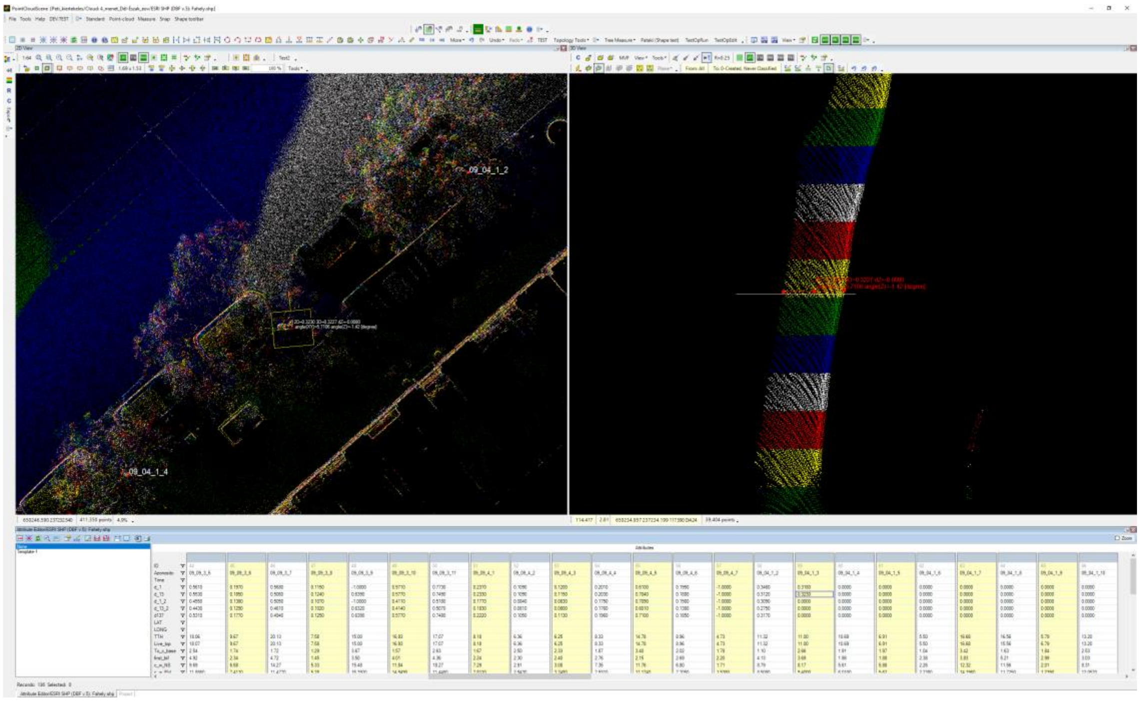


Figure 22. Diameter at 1.3m of tree 09_04_1_3

Obstacles with the digital – manual measurements

It is important to mention the problematic scenarios, in which, (even though the point cloud offers centimetre accuracy), the measurements were harder, or impossible to take using exclusively the point clouds. Firstly, when the trees have overgrown, and overlay each other, it is really hard to distinguish which point belongs to which tree. It is impossible to select an area from the 2D view, which only contains one tree instance's points, because the trees overlap each other. An incremental colouring of the point cloud could help to distinguish alongside with the examination of the geophotos taken by the Ladybug cameras, please see the measurements of tree 09_07_3_3 (Figure 23), shown on Figure 24 and Figure 25.

Figure 23. Tree 09_07_3_3

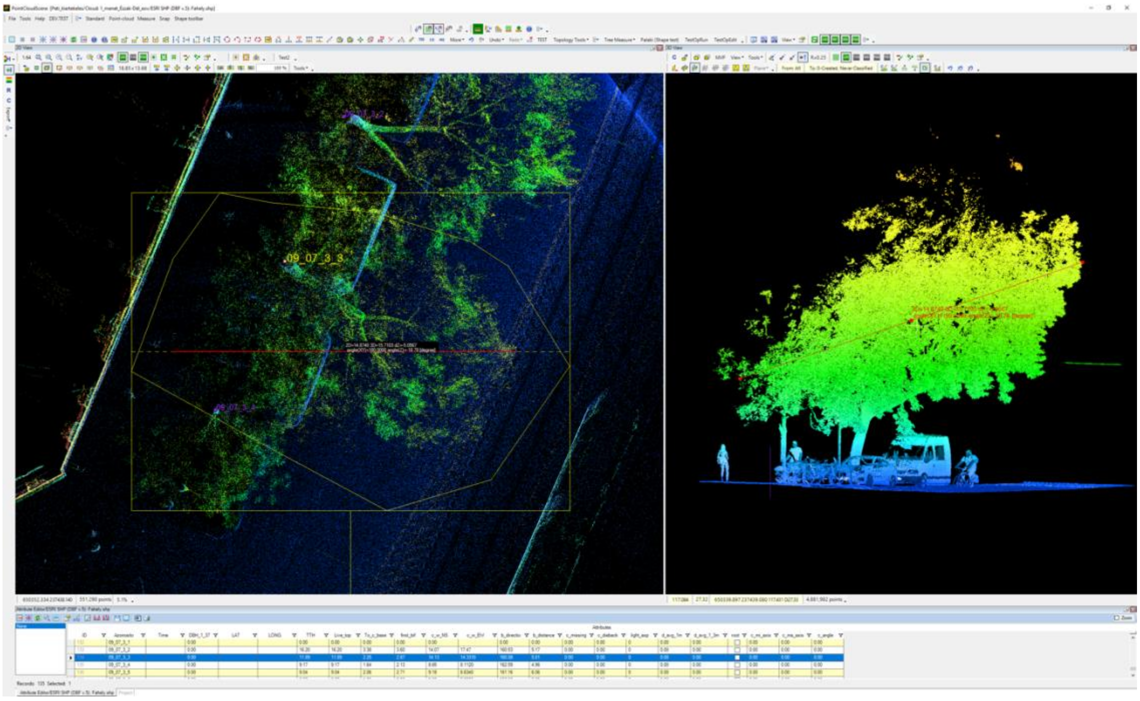


Figure 24. Crown width (E-W) of tree 09_07_3_3

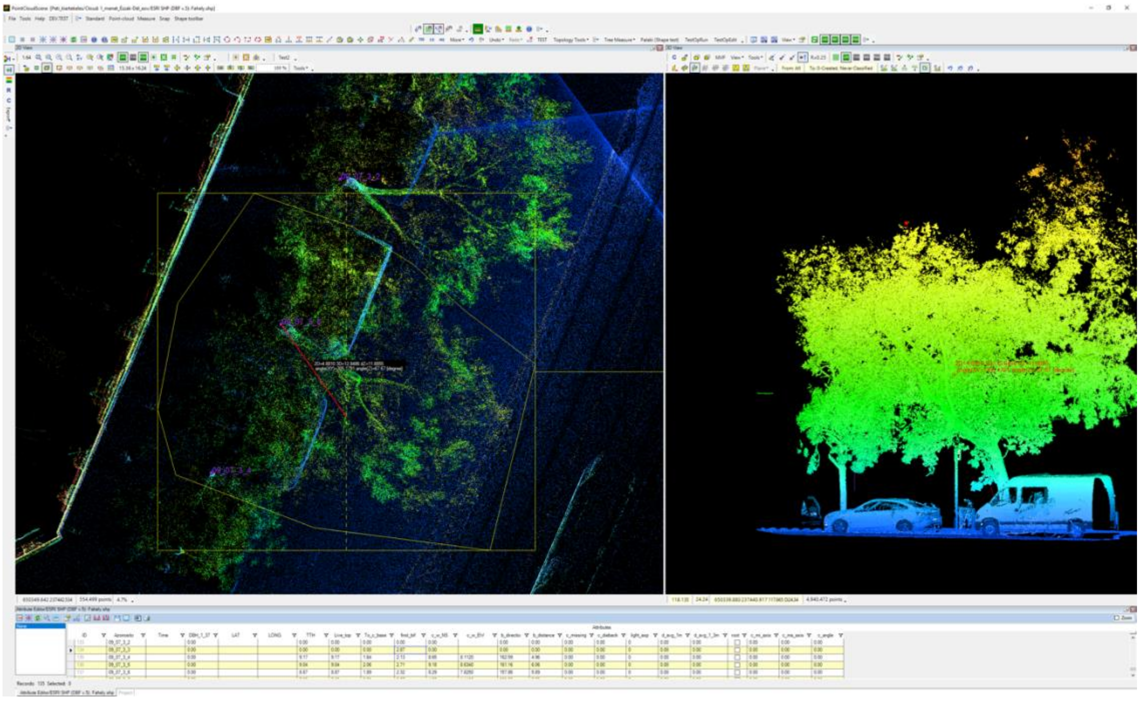


Figure 25. Total tree hight of tree 09_07_3_3

Manually, the diameter at breast height is measured with a forestry calliper, from 2 directions with 90° difference, and the obtained values are averaged to assess the diameter. The issue with digital-manual measurements is the fact, that the lasers cannot penetrate through big trunks of trees, therefore at the farther end of the trunk, the point cloud is less dense. For this reason, the diameter was measured only from one side, the side which the mobile laser scanner was passing by. Please see the difference in the point density between the two sides on Figure 26, in that case, the tree was on the west side of the road, and the scanner was passing from the east (right side of image). In certain instances, certain areas of the trunk were not visible by lasers, due to conflicts in surroundings: for example, this was the case of tree 09_09_3_9, where the nearby cars covered the tree's trunk, it is show on Figure 27 and Figure 28.

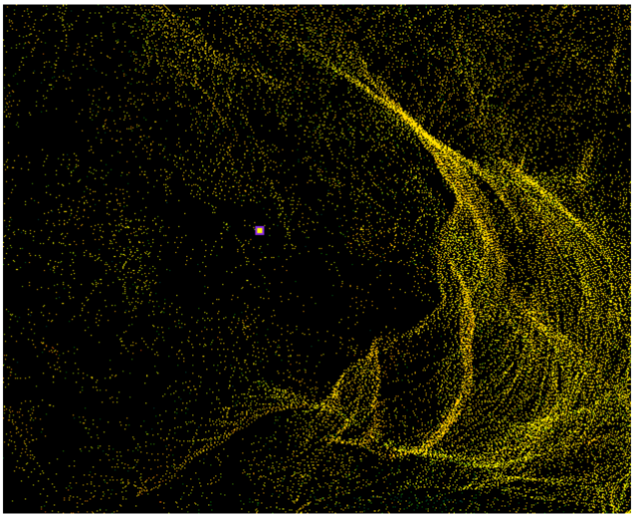


Figure 26. Point density difference of the two sides of the trunk – 2D view

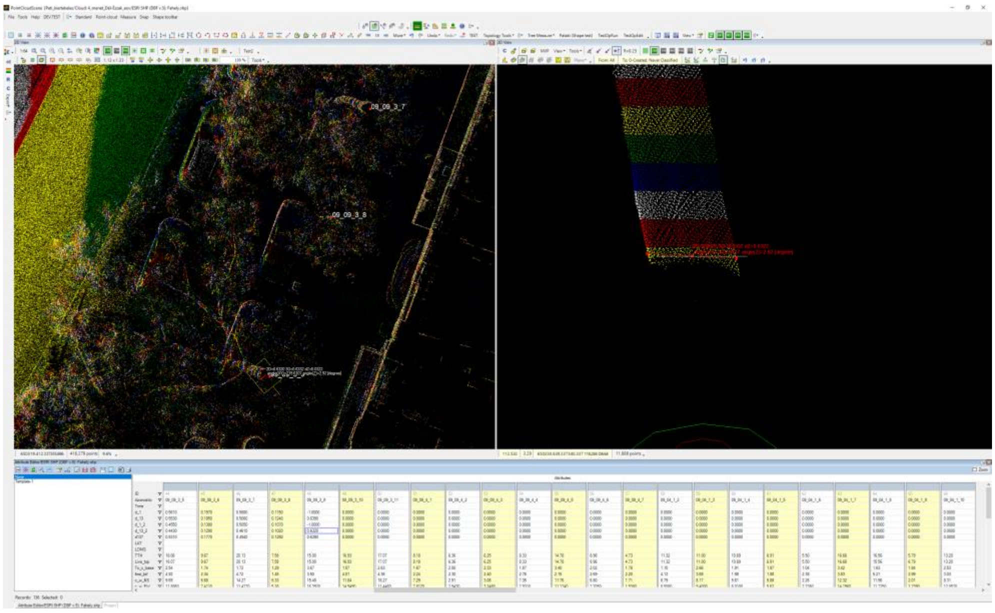


Figure 27. Trunk covered by nearby cars, tree 09_09_3_9

Figure 28. Tree 09_09_3_9 surrounded by cars

3.3.3 Digital – automated

The algorithm of greeHill uses the MLS created point cloud files and pictures to identify the tree instances and determines their main attributes. It is a machine learning algorithm, processing through more and more trees would make faster and better results in the future. The solution can also extract Voxel models of the trees, as it is presented on Figure 29 and Figure 30.

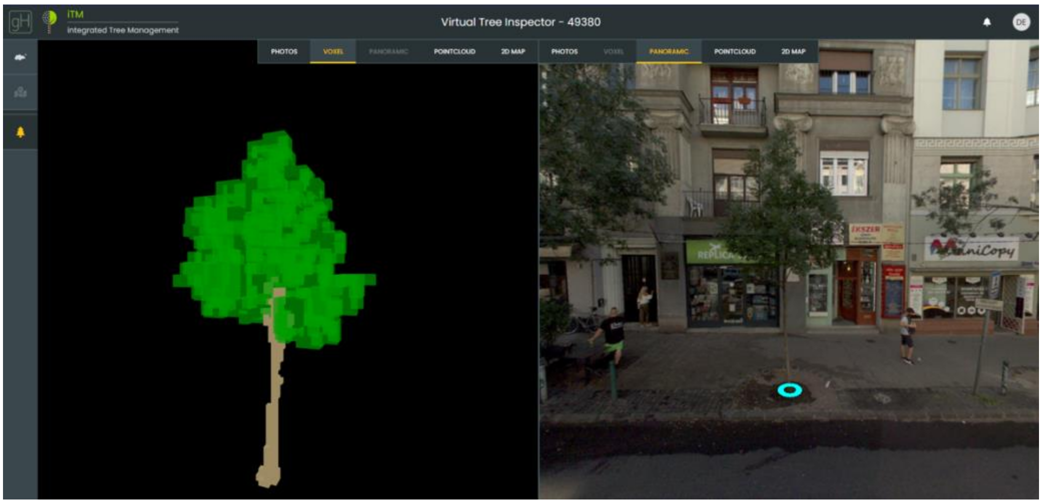


Figure 29. Voxel representation of a tree

Figure 30. Detailed Voxel representation of a tree

The further explanation of the process is considered as a business secret; hence it is not detailed in this thesis.

4 Results

4.1 Speed

The speed for each of the methodologies was formed by the time needed for the data collection, plus the time needed for the data extraction, until the exact values of the tree parameters (which were feasible to obtain) were put in the Master Excel table.

4.1.1 Manual

Data collection

In average, using the focused work of two person, a tree was measured in 4 minutes and 2 seconds while recording the results on paper, please see the Appendix for the individual results. This time needed depends on the conditions around the specific location, for example, it could happen that there is a need to wait for the traffic to pass, or it is hard to access the tree itself, it might be surrounded by bushes.

Data extraction

The digitization from the manual measurement sheets was done by 1 person, and in average it took 1 minute for each of the trees.

4.1.2 Digital – manual

Data collection

The data collection for the digital – manual measurements took one hour in total for the company specialized in mobile LiDAR measurements, including the initialization times and the standby GPS calibration after the recordings. The activities needed the work of an operator and a driver, and practically it meant to drive through the area with the custom mobile laser scanner (MLS) multiple time, in this specific case 3 times both ways and an extra south-north direction.

According to the information provided by Geodézia zrt; one day of recording usually takes one day of post-processing to prepare the LAS files, therefore doubling the recording time resulted in the total time needed for the data collection: two hours.

Data extraction

The data extraction can be done by one person, who is an experienced user of PointCloudScene. For the writer of the thesis the total time was measured without the time needed to get accustomed to the software, and in the end for each of the trees it took 30 minutes to collect the values for each of the required parameters while recording the measurements with screenshots.

4.1.3 Digital – automated

Data collection

The data collection methodology is the same as in the case of digital-manual measurements it consists of the acquirement of the point cloud (LAS files and geophotos) for the inspected area, incorporating the recording, and post-processing time.

Data extraction

After the data collection, there is a need to setup the machine learning environment, after which the extraction runs as an automated process providing fast results; currently it took 10-20 seconds / tree to extract the predefined parameters. In the calculations 15 seconds / tree was used for the data extraction part. Since it is a machine learning algorithm, the more tree instances it will work with through time the better and faster the algorithm will become, optimally the speed could be reduced to 2 seconds / tree.

4.1.4 Comparison

To compare the speed of the methods, for each of the parts the person needed was multiplied by the time needed to normalize the time for the whole process. Please see the time needed for the different methods on Table 2 and Figure 31. The resource intensity of each of the method was maximum 2 person’s workload.

Table 2. Time needed for the different methods

		Manual	**Digital - manual**	**Digital - automated**
Data collection	Time	9h 3m 23s	2h	2h
	Person	2	2	2
Data extraction	Time	2h 16m 18s	67h	33m
	Person	1	1	1
Total time / person		*20h 23m 04s*	*71h 1m 12s*	*4h 34m 12s*

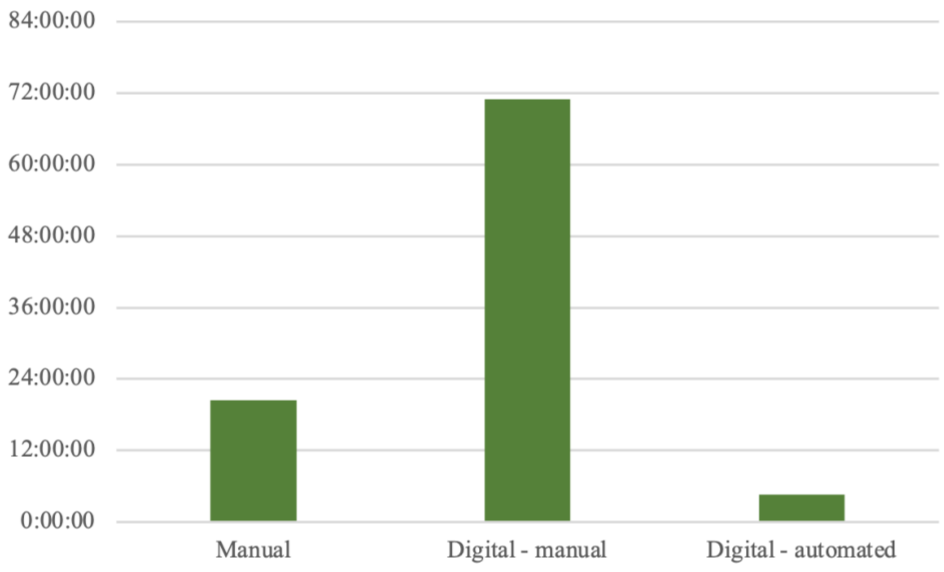


Figure 31. Total time needed per person for 134 trees

4.2 Cost

The aggregated costs of the methodologies include all the monetary requirements from the start of the data collection, through the data extraction until the obtained tree semantics were put in to the Master Excel table. All the cost calculations can be found in the Master Excel table in the Appendix. To accumulate the needed costs for each of the methods, it is important to mention the necessary equipment and software costs. Even for the manual measurements, to create a digital tree inventory, one would need a computer. All the methods could be performed using the laptop of the writer of the thesis hence this cost is ignored from the accumulated cost calculation. It is important to mention that for the sake of simplicity the cost calculations do not include taxes or benefits to be paid after the workers, nor a break from the work.

4.2.1 Manual

For the manual measurements, the total aggregated cost consisted of the working hours of the Arborists multiplied by their wage, plus the used tools' depreciation costs. These cost calculations only use the effective working time, without breaks in the working hours.

The equipment and their respective costs for the 3 days of measurements using depreciation can be seen in Table 3.

Table 3. Equipment and depreciation for the manual measurements

Item name	**Price [€]**	**Depreciation**	**Cost / 1 day [€]**	**Cost / 3 days [€]**
Clinometer	180	10 years	0.05	0.15
Forestry calliper	80	10 years	0.02	0.07
Laser distance meter	30	3 years	0.03	0.08
Measuring tape	8	5 years	0.00	0.01
Measuring stick	3	1 year	0.01	0.02
Pencils	1	0.5 year	0.01	0.02
Paper	1	3 days	0.33	1.00
Printing	2	3 days	0.67	2.00
SUM				**3.35**

According to chapter 4.1 the needed total time for the data collection was 20 hours 23 minutes and 4 seconds and this work can be done by an Arborist. According to Salaryexpert [44] data, an average hourly rate of an Arborist in Spain is €9.20, therefore the total data collection and extraction costed €187, plus the depreciation costs, making the total cost to *€190.89*.

4.2.2 Digital-manual

For the digital-manual measurements, the total cost consisted of the contracted price of Geodézia zrt; €289 (to record the area and to create the LAS files and geophotos), plus the time needed for the manual extraction from the point cloud multiplied by the salary of a GIS analyst, plus the software license costs for PointCloudScene calculated for that time period. According to Salaryexpert data [45] the average hourly rate of a GIS specialist in Spain is €23.61. The cost of PointCloudScene depends on the contractual agreements and consists of a flat purchase price of the software (€1000 - €2000) plus there is a licence fee of €7-9 / day. The purchase price of the software was excluded from the calculation, only the daily fees were added to the total cost with a fee of €8 / day. The calculation of the total costs can be found in the Master Excel in the Appendix. The total costs amount to *€1937.87*.

4.2.3 Digital-automated

For the digital-automated measurement, this thesis calculates with greeHill’s pricing. GreeHill extracts the tree semantics for an average price of €1/tree in case there is an available point cloud, and €1.5/tree if there is a need to create the point cloud, hence the total cost for this specific empirical example was *€201*.

4.2.4 Comparison

Please see the accumulated total cost on Figure 32, for each of the methods to perform the measurements and to record the results for this specific empirical case of 134 trees.

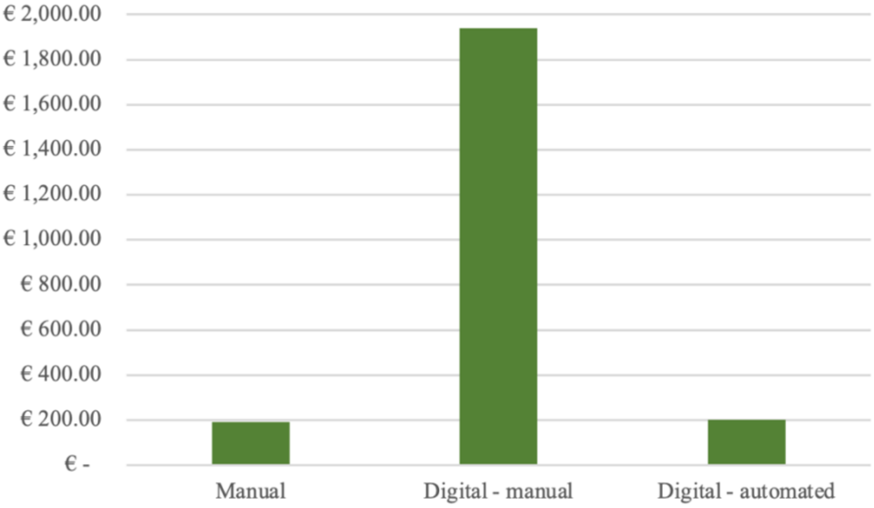


Figure 32. Total cost of methods for the 134 inspected trees

4.3 Accuracy

The accuracy of the methodologies depends on the way on which each of the parameters were measured, because it defines the source of truth. Since greeHill’s machine learning algorithm’s accuracy is based on the correctness of itself, it is not considered as the source of truth for any of the comparable parameters. In the following, for each of the corresponding parameters the source of truth will be defined, and a comparison analysis will be presented as it was performed between the manual and digital-manual methods, and between the source of truth and the results of the digital-automated. All the regarding calculations can be found in the Master Excel file in the Appendix. It is important to mention, that in this empirical example in Budapest, the algorithm of greeHill has successfully identified 112 trees, and in some cases certain parameters had errors, since the algorithm was optimized for the environment in Singapore, and was trained on specific tree instances according to that local climate.

4.3.1 Diameter at breast height [cm]

To collect the diameter at breast height (DBH), arborists use a forestry calliper to measure the diameter of the trunk at 1m 37cm from two sides with 90° difference, and they average the obtained values. Manually this was performed using the same process, but to determine the value in the same way from the digital point clouds was impossible, due to the point cloud's drawback of having less points on the far side of the tree trunk than the closer side (Figure 26) offering invalid results. Therefore, the source of truth for the DBH was the manual methodology, even though it had obvious errors in the cases of trees 09_04_1_2, 09_04_1_5 and 09_07_4_5 due to humanly mistakes. The DBH was hidden from the lasers or was too small to distinguish from the supporting wooden frame the tree, hence it could not be obtained digitally in 5 cases: 09_04_1_9, 09_07_1_5, 09_07_1_6, 09_08_1_7 and 09_09_4_7. Comparing the remaining 129 instances, the thesis found that the margin of error was 0.57 centimetres with 96% confidence with a range of 29.50 cm due to the human, possibly recording error of certain instances. The average difference from the source of truth (manual) was 1.75 centimetres with a standard deviation of 3.3 centimetres.

4.3.2 Latitude, Longitude

To determine the GPS position of the trees manually, a smartphone was used, while digitally the point cloud was fitted to the Hungarian EOV projection system, allowing to extract exact coordinates from PointCloudScene at the tree's marked insertion points, which then were transformed to WGS 84 system and got transformed to decimal values for the purpose of the comparison. This method makes the digital-manual method the source of truth. The obtained GPS coordinates were used as an input to Google Maps to show the differences graphically, it is illustrated on Figure 33.

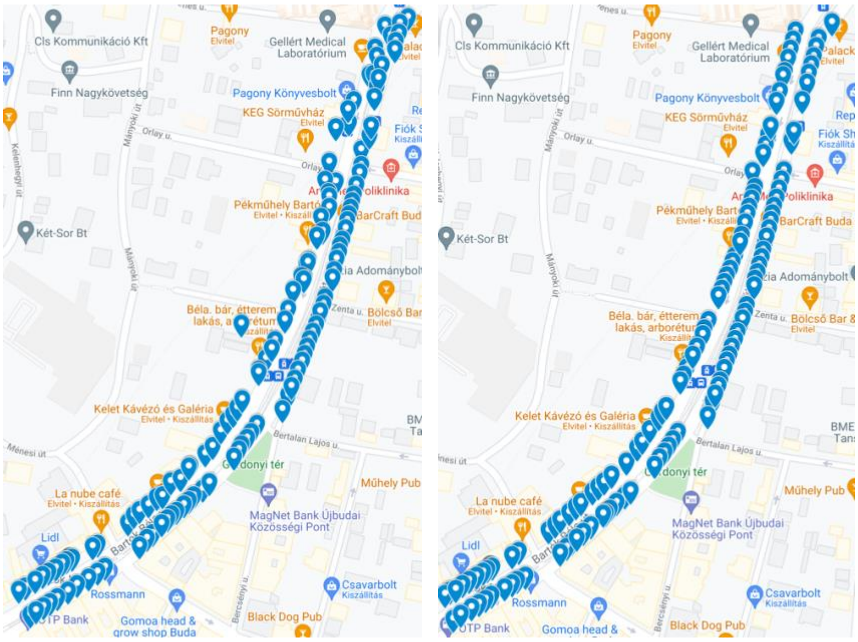


Figure 33. Manually and digitally obtained GPS locations

For the latitude, the average difference from the digital measurement was 5.59*10^{-6} with a standard deviation of 3.39*10^{-5}. Having 96% confidence, the margin of error was 5.73*10^{-6}. For the longitude, the manual assessments had an average difference of 1.29*10-5, with a standard deviation of 7.5*10^{-5}. The margin of error was 1.27*10^{-5} with 96% confidence.

Analysing the differences between the digital manual (source of truth) and digital automated results; the standard deviation was 8.6*10^{-5} with a margin of error of 1.71 *10^{-5} and a deviation of 2.3*10^{-5} with a margin of error of 4.3*10^{-6} for the latitude and longitude respectively.

4.3.3 Tree height [m]

The height of the tree manually was assessed using the SUUNTO clinometer, 15 or 20 metres away from the tree, assessing it by looking through the clinometer. Digitally, the height of the tree was determined by the distance between the highest point of the tree and the tree’s insertion point. For the inspected trees, the height to live top was always the same as the total tree height, the possible decay was represented with the percent dieback parameter. A clinometer will never offer as accurate results as a laser scanner, in many cases the highest point of the tree cannot be seen from the ground due to the covering crown of the tree, therefore the source of truth was determined from the digital-manual evaluation. Out of the 134 trees in average the manual assessments were 56 centimetre lower than their actual values. There were cases with considerably high differences, when the inspected tree was too big to assess the height correctly with a clinometer; in the case of tree 09_08_1_7 the manual method resulted in 4 metres and 12 centimetres higher than the actual value and in the case of tree 09_09_3_11 the estimation with a clinometer resulted 4 metres and 7 centimetres lower than the actual value making the range 8 metres and 19 centimetres. The mentioned trees can be seen on Figure 34.

Figure 34. Tree 09_08_1_7 and 09_09_3_11

The margin of error for the tree height measurements of the tree height was 22 centimetres with 96% confidence making the upper limit 36 centimetres lower and the lower limit 80 centimetre lower than the actual values. The standard deviation was a considerable 1.31m.

4.3.4 Height to crown base [m]

The height to crown base was determined as the distance between the lowest point of the crown (specified by the i-Tree Eco Field Guide) and the tree’s insertion point. Manually it was assessed using the measurement stick while digitally using the measurement between 2 points in profile mode. The source of truth was determined by the values of the digital-manual method. The average difference was 26 centimetres higher for the manual measurements, with a standard deviation of 0.53 centimetres. For all the 134 comparable trees, the margin of error was 9 centimetres with 96% confidence.

4.3.5 Crown width N-S and E-W [m]

The crown widths were determined manually by walking under the trees in the designated directions using the practiced metre-long steps. Since this is not an accurate method, the source of truth was the digital-manual method, at which, the tree was placed to profile mode from the desired direction and the distance was obtained using the measurement tool of PointCloudScene. In average, the manual results were 66 and 71 centimetre lower than the actual values with a considerably high standard deviation of 1.84 metres and 1.60 metres respectively. The margin of error at 96% confidence was 31 centimetres for the north-south direction and 27 centimetres for the east-west direction. The maximum difference was a significant 8 metre 28 centimetre in the case of tree 09_07_1_8 in the north-south direction due to the width of 17.3m of the 17m tall tree, which was severely underestimated by the manual method. In the east-west direction the maximum difference was 7.57 metres in the case of tree 09_07_1_4, also underestimated by the manual method. A drastic overestimation happened in the case of tree 09_09_2_8 when the actual 13.84 metres was estimated to be 21 metres, most probably because of the bad orientation of the manual measurement. Please see the case on Figure 35.

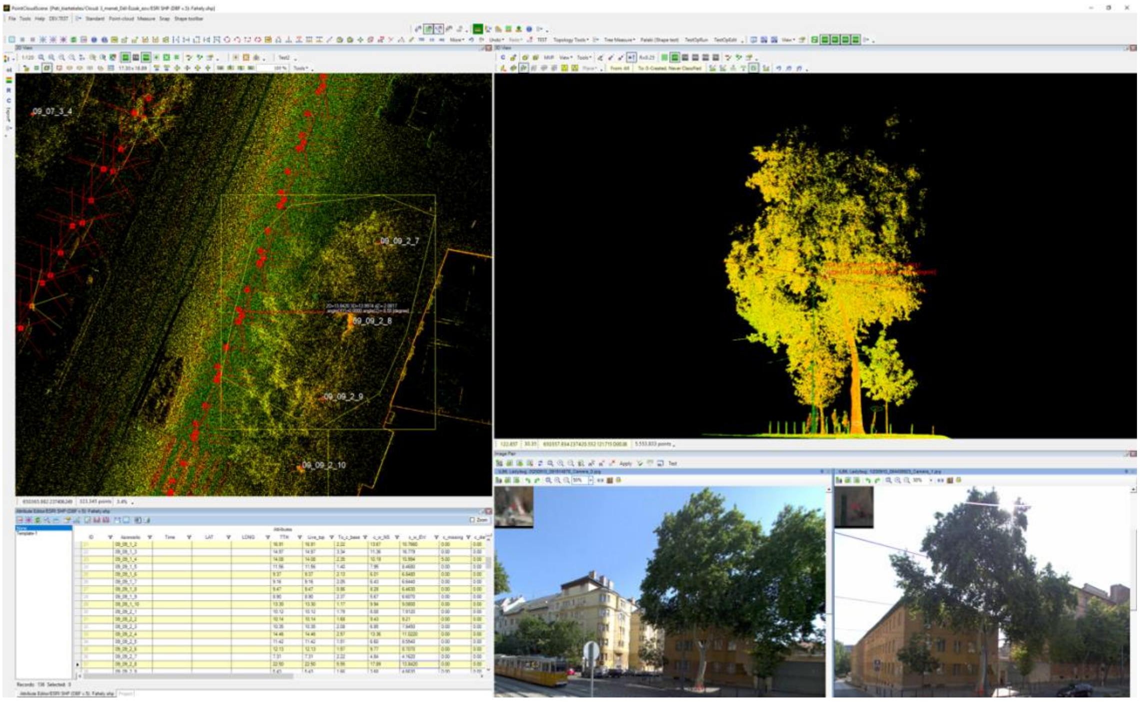


Figure 35. Crown width of tree 09_09_2_8

4.3.6 Building direction [°] and distance [m]

Not all the trees had information on the building direction and distance, since 6 trees were located at the Gárdonyi square, next to the street, but far from the buildings, please see them on Figure 6 of Chapter 3.1.1 with the IDs being 09_09_4_1 – 09_09_4_6. Manually, the building direction was determined using a smartphone's compass, which offered crude results due to the shading effects of the buildings. PointCloudScene offered the actual results by connecting the tree trunk to the nearest point of the surrounding building, hence it is considered to be the source of truth. Manually, the distance was obtained with a laser distance meter, yet in many cases it did not provide accurate results, or could not provide results at all, and was measured with meter-long steps instead, therefore, the digital-manual method was the source of truth. The building distance parameter had a standard deviation of 0.28 metres, in average the manual measurements were 13 centimetres shorter than the actual values. The margin of error was 5 centimetres with 96% confidence. The building direction comparison shows the inadequate manner of collecting that information with a smartphone's compass, the standard deviation was 10.68° with an average of difference of 2.43°. The margin of error was 1.85° with 96% confidence, and the maximum difference between the actual and manual values was 33.64°.

4.3.7 Girth at 1m and 1.3m [cm]

At the digital-manual method, the girth at the different heights were calculated using the circumference of the circle equation and the obtained diameter assessed from the direction of which the point cloud is the densest (as it is illustrated on Figure 26). For example, in the case of tree 09_04_1_3 on Figure 22, the diameter was measured as 32.30 cm, hence the girth is $2*r*\pi = 32.30*\pi = 101.5$ cm. This way of calculation leads to inaccurate results, because not all the trees' trunks' cross-section is shaped as a circle. The manual measurements for the girths were the source of truth, when a measurement tape was wrapped around the trunk at the specified heights, and the value was read from it. For instance, in the case of mentioned 09_04_1_3, the circumference was manually assessed as 86 centimetres. In two cases, the difference was a substantial 57.67 centimetres and 58.56 centimetres in the case of 09_09_3_1 and 09_09_1_5, at 1m and 1.3m respectively - the digital-manual method was overestimating the actual manually collected results. For the comparison of the circumference at 1m only 127 trees had available data, and 128 trees had available data at 1.3m. The standard deviation was 11.32 centimetres at 1m with an average of 3.84 centimetres difference from the actual results. At 1.3m the standard deviation was 9.91 centimetres with an average of 3.93 centimetres difference from the manual measurements. The margin of error at 96% confidence was 1.97 centimetres and 1.71 centimetres respectively.

4.3.8 Trunk height until first bifurcation [cm]

The trunk height until the first bifurcation was defined and determined manually as described in the i-Tree Eco Field Guide, by the measurement stick, or with the clinometer in the cases when the bifurcation point was too high to reach by hand. Digitally, the same distance was taken with the 2D measurement tool, making the digital-manual method the source of truth. From all the parameters, the biggest differences were experienced at this parameter, which is due to the crudely recorded manual data (e.g., trees 09_07_1_8, 09_07_3_2), and the methods' different decisions regarding the point of bifurcation itself. The standard deviation was 38.43 centimetres with an average of 6.6 centimetres overestimation by the manual method. One tree was excluded from the comparison due to the condition of the tree 09_04_1_9. The margin of error was 6.53 centimetres with 96% confidence.

4.4 Usability

Certain parameters cannot be measured with certain methods, and it is important to define, which parameters could be collected and which not, as it is an important factor regarding the performance of the manual vs. digital tree inventories. This information is summarized in Table 4 and Table 5 for the parameter lists respectively.

Table 4: i-Tree required parameters and their measurability for the given location

i-Tree required parameters			**Unit**	**Manual**	**Digital - Manual**	**Digital - automated**
1	Time needed to measure		[min, s]	Yes	Yes	Yes
2	Species		[latin name]	Yes	Yes	No
3	DBH		[m]	Yes	Yes	Not yet
4	HT DBH		[m]	Yes	Yes	Not yet
5	Address of tree		[address]	Yes	No	No
6	Coordinates (LAT)		[number]	Yes	Yes	Yes
7	Coordinates (LONG)		[number]	Yes	Yes	Yes
8	Total tree-height (TTH)		[m]	Yes	Yes	Yes
9	Crown	Height to live top	[m]	Yes	Yes	No

10		Height to crown base	[m]	Yes	Yes	Not yet
11		Crown width (N-S)	[m]	Yes	Yes	Yes
12		Crown width (E-W)	[m]	Yes	Yes	Yes
13		Percent crown missing	[%]	Estimation	Estimation	No
14	Percent dieback		[%]	Estimation	Estimation	No
15	Crown light exposure		[number: 1-5]	Yes	Yes	Not yet
16	Building (TTH>3m, Distance<18m)	Direction	[°]	Yes	Yes	Not yet
17		Distance	[m]	Yes	Yes	Not yet
18	Land use		"M / P”	Yes	Yes	Not yet
19	Status		"P"	Fixed	Fixed	Fixed
20	Street-tree?		"Y"	Fixed	Fixed	Fixed
21	Public vs Private?		"Public"	Fixed	Fixed	Fixed

i-Tree Eco designed its parameter list, so that all the fields can be collected manually by a field survey. The percent crown missing and percent dieback were visual estimations based on the i-Tree Eco Field Guide [41]. The thesis’ given location fixed the following 3 required parameters according to the Field Guide: “Status”, “Street-tree?”, “Public vs Private?”, because all the trees were planted intentionally, street trees, publicly managed by the municipality. The “Land use” field could take the value of “M” (Multi-family residential) or “P” (Park), because there were trees measured on Gárdonyi square as part of the Bartók Béla street, which had no buildings nearby, but all the rest had structures containing more than four residential units in less than 18 metres away. Please see Figure 6 in Chapter 3.1.1, and Figure 38 in Chapter 4.4.1.

The digital representation of the area bears all the information needed for the i-Tree required parameters, except the address of the tree, which in the case of manual surveys was read from the nearby buildings, but were not possible to retrieve from the point clouds. Acquiring species, a very important attribute still requires human eye, research to extract species information from point clouds are still needed [25]. In the digital-manual measurements, all the rest of the parameters were determined by performing manual measurements on the point cloud in the PointCloudScene software. The digital-automated measurements were designed and developed to extract the geometric parameters required by NParksSG, hence some parameters from the first group were not yet possible to extract automatically.

Table 5 shows the required parameters by NParksSG and their measurability with the different methods. Since those parameters focus on the digital representation of the tree, most of the values cannot be, or are not worth to measure manually. For example, it is impossible to provide a Voxel model of a tree using regular manual measurements, and while the trunk girths every 10 cm until the first bifurcation would be theoretically possible to measure with a measuring tape, in practice it is not worth the difficulty due to the required time. The point cloud representation of the area bears the necessary geometric, and digital information required by NParksSG, yet only half of the parameters are possible and worth to measure manually from the point clouds. The competence of greeHill's digital-automated machine learning algorithm is demonstrated by the possibility to provide all these parameters automatically from point clouds, offering diversified digital representation of the tree instances.

Table 5: NParksSG required parameters and their measurability for the given location

NParksSG required parameters		Unit	Manual	Digital - Manual	Digital - automated
22	GPS location (LAT)	[number]	Yes	Yes	Yes
23	GPS location (LONG)	[number]	Yes	Yes	Yes
24	Tree height	[m]	Yes	Yes	Yes
25	Trunk girth at 1m	[m]	Yes	Yes	Yes
26	Trunk girth at 1.3m	[m]	Yes	Yes	Yes
27	Trunk girth every 10cm until first bifurcation	[m]	Not worth	Not worth	Yes
28	Root above existence	[Y/N]	Yes	Yes	Yes
29	Trunk height until first bifurcation	[m]	Yes	Yes	Yes
30	Crown height	[m]	Yes	Yes	Yes
31	Crown ellipse major axis length	[m]	Not worth	Yes	Yes
32	Crown ellipse minor axis length	[m]	Not worth	Yes	Yes
33	Crown ellipse angle from North	[°]	Not worth	Yes	Yes
34	Crown eccentricity	[vector]	No	No	Yes
35	Crown X offset from trunk base	[m]	No	No	Yes
36	Crown Y offset from trunk base	[m]	No	No	Yes

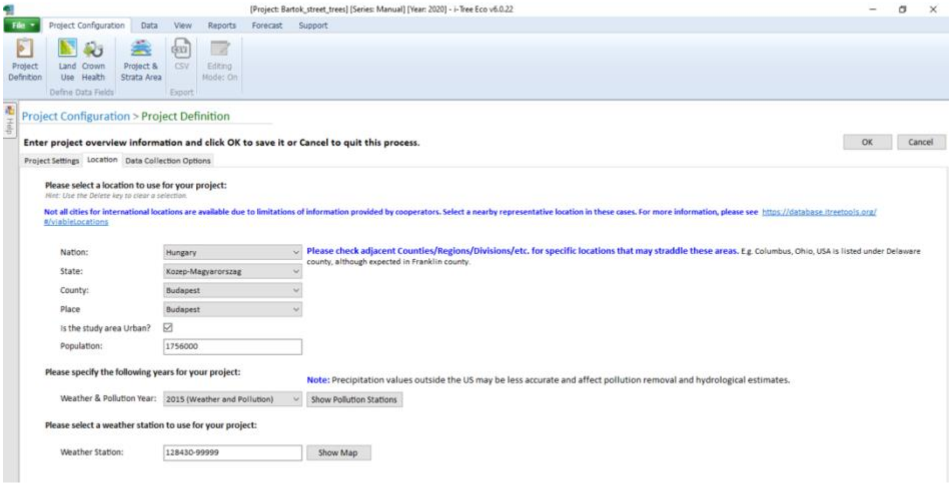
37	Branch voxels	[Voxel model]	No	No	Yes
38	Crown voxels	[Voxel model]	No	No	Yes
39	Branching pattern	[XML description]	No	No	Yes
40	Trunk bending angle (from ground)	[vector]	No	No	Yes
41	Trunk bending angle (yaw)	[°]	No	No	Yes
42	Trunk bending angle (pitch)	[°]	No	No	Yes
43	Crown's gravity center (LAT)	[number]	No	No	Yes
44	Crown's gravity center (LONG)	[number]	No	No	Yes

All together from the 44 selected parameters, 29 was measurable or possible to estimate with the manual method, 31 digital-manually, and 32 digitally – automated including the 3 fixed parameters. These numbers exclude those parameters which weren't worth to measure.

4.4.1 Tree-benefit assessments

i-Tree project description

When creating an i-Tree Eco project, the software asks the user to set up the project settings, including the name and series year of the project. There were 3 sample projects created for the 3 methods, to explore the differences between the model outputs according to the differences in the methods' obtained values. The software requires to specify the location information from the user, as it is shown on Figure 36. As a limitation, in the software the latest available pollution and weather data for this region was from 2015, which was used for the assessments. Since greeHill's algorithm could not identify all the inspected trees, it was excluded from the i-Tree assessments.



[Project: Bartok_street_trees] [Series: Manual] [Year: 2020] - i-Tree Eco v6.0.22

Project Configuration > Project Definition

Enter project overview information and click OK to save it or Cancel to quit this process.

Please select a location to use for your project:
Hint: Use the Delete key to clear a selection.

Not all cities for international locations are available due to limitations of information provided by cooperators. Select a nearby representative location in these cases. For more information, please see https://database.itreetools.org/#/viableLocations

Nation: Hungary
State: Kozep-Magyarorszag
County: Budapest
Place: Budapest
Is the study area Urban? ☑
Population: 1756000

Please check adjacent Counties/Regions/Divisions/etc. for specific locations that may straddle these areas. E.g. Columbus, Ohio, USA is listed under Delaware county, although expected in Franklin county.

Please specify the following years for your project:

Note: Precipitation values outside the US may be less accurate and affect pollution removal and hydrological estimates.

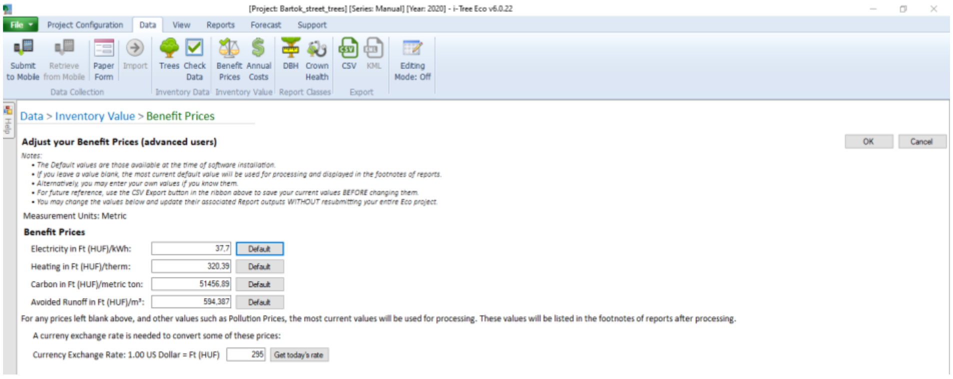
Weather & Pollution Year: 2015 (Weather and Pollution)

Please select a weather station to use for your project:

Weather Station: 128430-99999

Figure 36. i-Tree Eco location settings

The software also allows the user to specify the benefit prices which are presented on Figure 37. The electricity price was obtained from one of the Hungarian electricity provider's (E-On [46]) website and specified as HUF 37.7/kWh. The exchange rate of USD 1 = HUF 295 was used, which is an average of the last 6 month's exchange rate. The default values were used for heating (HUF 320.39/therm), carbon (HUF 51456.89/metric ton) and the price of avoided runoff (HUF 594.387/m^3).



[Project: Bartok_street_trees] [Series: Manual] [Year: 2020] - i-Tree Eco v6.0.22

Data > Inventory Value > Benefit Prices

Adjust your Benefit Prices (advanced users)

Notes:
- The Default values are those available at the time of software installation.
- If you leave a value blank, the most current default value will be used for processing and displayed in the footnotes of reports.
- Alternatively, you may enter your own values if you know them.
- For future reference, use the CSV Export button in the ribbon above to save your current values BEFORE changing them.
- You may change the values below and update their associated Report outputs WITHOUT resubmitting your entire Eco project.

Measurement Units: Metric

Benefit Prices

Electricity in Ft (HUF)/kWh: 37.7
Heating in Ft (HUF)/therm: 320.39
Carbon in Ft (HUF)/metric ton: 51456.89
Avoided Runoff in Ft (HUF)/m^3: 594.387

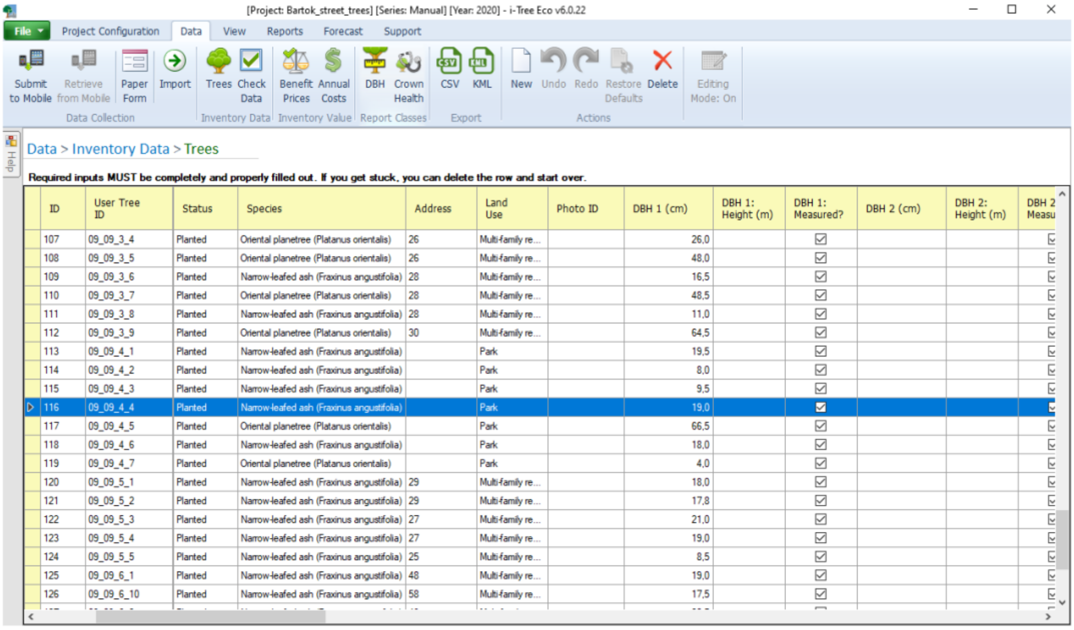
For any prices left blank above, and other values such as Pollution Prices, the most current values will be used for processing. These values will be listed in the footnotes of reports after processing.

A curreny exchange rate is needed to convert some of these prices:

Currency Exchange Rate: 1.00 US Dollar = Ft (HUF) 295

Figure 37. i-Tree Eco Benefit prices

The Project & Strata area was set to Urban, with an area of 2.53ha, and the number of trees inspected were set to 134, detailed information on the projects' metadata can be found in the Appendix. The software allows the user to import existing data about the trees, therefore the already digitized data could be imported easily from the existing MS Excel sheet. Because the quality of the model outputs will be enhanced by the extent of the data collection, in this thesis, all the possible parameters were provided to the software, as it was illustrated on Figure 8 of Chapter 3.1.2. The software than shows the information about the trees in a table view, and allows the user to easily modify and export the data, which can be seen on Figure 38.



[Project: Bartok_street_trees] [Series: Manual] [Year: 2020] - i-Tree Eco v6.0.22

Data > Inventory Data > Trees

Required inputs MUST be completely and properly filled out. If you get stuck, you can delete the row and start over.

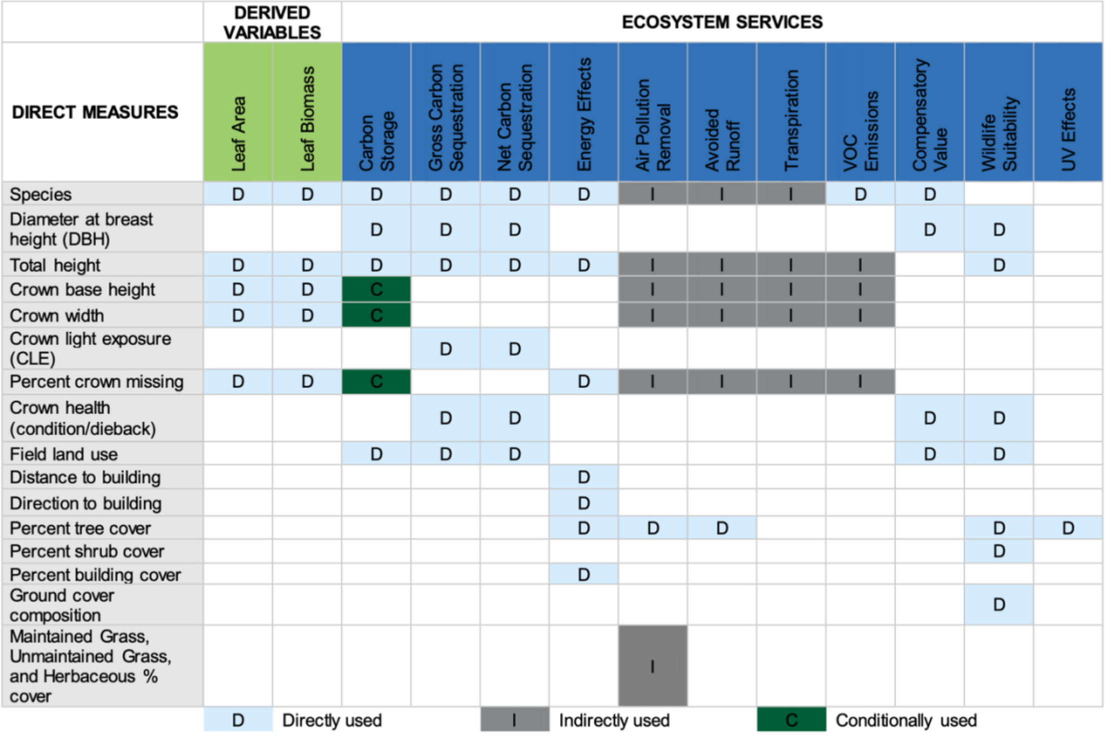
ID	User Tree ID	Status	Species	Address	Land Use	Photo ID	DBH 1 (cm)	DBH 1: Height (m)	DBH 1: Measured?	DBH 2 (cm)	DBH 2: Height (m)	DBH 2 Measu
107	09_09_3_4	Planted	Oriental planetree (Platanus orientalis)	26	Multi-family re...		26,0		☑			☑
108	09_09_3_5	Planted	Oriental planetree (Platanus orientalis)	26	Multi-family re...		48,0		☑			☑
109	09_09_3_6	Planted	Narrow-leafed ash (Fraxinus angustifolia)	28	Multi-family re...		16,5		☑			☑
110	09_09_3_7	Planted	Oriental planetree (Platanus orientalis)	28	Multi-family re...		48,5		☑			☑
111	09_09_3_8	Planted	Narrow-leafed ash (Fraxinus angustifolia)	28	Multi-family re...		11,0		☑			☑
112	09_09_3_9	Planted	Oriental planetree (Platanus orientalis)	30	Multi-family re...		64,5		☑			☑
113	09_09_4_1	Planted	Narrow-leafed ash (Fraxinus angustifolia)		Park		19,5		☑			☑
114	09_09_4_2	Planted	Narrow-leafed ash (Fraxinus angustifolia)		Park		8,0		☑			☑
115	09_09_4_3	Planted	Narrow-leafed ash (Fraxinus angustifolia)		Park		9,5		☑			☑
116	09_09_4_4	Planted	Narrow-leafed ash (Fraxinus angustifolia)		Park		19,0		☑			☑
117	09_09_4_5	Planted	Oriental planetree (Platanus orientalis)		Park		66,5		☑			☑
118	09_09_4_6	Planted	Narrow-leafed ash (Fraxinus angustifolia)		Park		18,0		☑			☑
119	09_09_4_7	Planted	Oriental planetree (Platanus orientalis)		Park		4,0		☑			☑
120	09_09_5_1	Planted	Narrow-leafed ash (Fraxinus angustifolia)	29	Multi-family re...		18,0		☑			☑
121	09_09_5_2	Planted	Narrow-leafed ash (Fraxinus angustifolia)	29	Multi-family re...		17,8		☑			☑
122	09_09_5_3	Planted	Narrow-leafed ash (Fraxinus angustifolia)	27	Multi-family re...		21,0		☑			☑
123	09_09_5_4	Planted	Narrow-leafed ash (Fraxinus angustifolia)	27	Multi-family re...		19,0		☑			☑
124	09_09_5_5	Planted	Narrow-leafed ash (Fraxinus angustifolia)	25	Multi-family re...		8,5		☑			☑
125	09_09_6_1	Planted	Narrow-leafed ash (Fraxinus angustifolia)	48	Multi-family re...		19,0		☑			☑
126	09_09_6_10	Planted	Narrow-leafed ash (Fraxinus angustifolia)	58	Multi-family re...		17,5		☑			☑

Figure 38. Tree data presented in i-Tree Eco

After the validity check of the data, it could be submitted to processing, and the program will be able to provide the estimates of:

- the structure of the urban forest,
- the hourly pollution removal,
- the public health impacts
- the amount of carbon stored and sequestered
- the effects on nearby buildings' energy use
- the yearly avoided surface runoff
- the forecasts about growth, storm effects and mortality
- the hourly urban forest volatile organic compound emissions
- the economic values of the urban forest

i-Tree Eco provides the relationship between the data variables and the ecosystem services, highlighting which value influences which service directly, indirectly and conditionally, as it is illustrated on Figure 39.



DIRECT MEASURES	DERIVED VARIABLES		ECOSYSTEM SERVICES										
	Leaf Area	Leaf Biomass	Carbon Storage	Gross Carbon Sequestration	Net Carbon Sequestration	Energy Effects	Air Pollution Removal	Avoided Runoff	Transpiration	VOC Emissions	Compensatory Value	Wildlife Suitability	UV Effects
Species	D	D	D	D	D	D	I	I	I	D	D		
Diameter at breast height (DBH)			D	D	D						D	D	
Total height	D	D	D	D	D	D	I	I	I	I		D	
Crown base height	D	D	C				I	I	I	I			
Crown width	D	D	C				I	I	I	I			
Crown light exposure (CLE)				D	D								
Percent crown missing	D	D	C			D	I	I	I	I			
Crown health (condition/dieback)				D	D						D	D	
Field land use			D	D	D						D	D	
Distance to building						D							
Direction to building						D							
Percent tree cover						D	D	D				D	D
Percent shrub cover												D	
Percent building cover						D							
Ground cover composition												D	
Maintained Grass, Unmaintained Grass, and Herbaceous % cover							I						

D Directly used I Indirectly used C Conditionally used

Figure 39. Relationship between data variables and ecosystem services

For example, crown light exposure was directly used to calculate the gross and net carbon sequestered, as these services of the trees would need sunlight [16].

i-Tree assessments

The different inputs resulted in significant differences in the model’s estimations as it captured the structure and function of the urban forest in the study area differently [47]. The main results are illustrated in Table 6 for the different methods, while the detailed reports created by the i-Tree Eco can be found in the Appendix.

Table 6. Main findings of the i-Tree ecoservice assessments

	Manual	**Digital - manual**
Number of trees	134	134
Tree Cover	31,4 %	37,1 %
Percentage of trees less than 6" (15.2 cm) diameter	23,9%	16,4%
Pollution Removal	106 pounds/year (Ft275 thousand/year)	124,3 pounds/year (Ft320 thousand/year)
Carbon Storage	33,86 tons (Ft1,58 million)	36,81 tons (Ft1,72 million)
Carbon Sequestration	2,072 tons (Ft96,7 thousand/year)	2,209 tons (Ft103 thousand/year)
Oxygen Production	5,525 tons/year	5,89 tons/year

Avoided Runoff	1,974 thousand cubic feet/year (Ft33,2 thousand/year)	2,304 thousand cubic feet/year (Ft38,8 thousand/year)
Building energy savings	Ft227 000/year	Ft274 000/year
Carbon Avoided	366,4 pounds/year (Ft8550/year)	648,9 pounds/year (Ft15100/year)
Structural values	Ft75,4 million	Ft81,6 million

4.4.2 Shortlisting dangerous trees

Well maintained, healthy vegetation plays an important role to attain safe living conditions in urban environments. Decay regarding trees is detected through using a combination of visual inspection, acoustic testing and resistance micro drilling: [48], [49]. These methods need inspection on a tree-by-tree basis; therefore, they are time consuming to apply on all the trees in the urban area. If the tree population could be shortlisted to deal with questionable instances on a focusable manner, it could help to relieve the unnecessary workload from arborists.

The current imaging technologies restrains the digital tree modelling to their geometry, and tree representation beyond visualization purposes were hindered by limited “Level of Detail” (LOD) definitions, even though they should support the rising demand for qualitative and quantitative assessments, spatial analysis and operations to manage vegetation in the urban environment. The work of Lessie M. Ortega-Córdova at the University of Delft deals with this issue, revealing that while much research has been done acquiring vegetation parameters from LiDAR data, the methods, algorithms are scattered [25].

There are different algorithms to segment and model a tree using airborne or terrestrial laser acquired data, such as treeSeg [33] which handles individual trees, Ptrees [50] to assess forests’ structure, TreeArchitecture, PlantScan3D and SimpleTree for representation purposes offering different strengths and drawbacks [32].

Industrially used information regarding digital tree modelling can be found in the contractual agreements between NParksSG and greeHill, and the complete parameter list can be seen on Table 5 in Chapter 3.1.2, with the concerning descriptions in the Appendix. This list offers parameters such as branching patterns (XML description), crown eccentricity, the trunk’s bending angle, and the crown’s gravity centre based on geometric calculations. These parameters are too time consuming, or not possible to extract manually, nor manually from the digital point clouds. The supporting Voxel models of trees enable the user to enrich their digital city models with exact tree data, allowing to simulate surface-plant-air interactions. These city models could be stressed with extreme weather data, pre-emptively highlighting the instances which would need maintenance before the danger happens. This thesis emphasizes the importance of sophisticated digital tree modelling to reduce the time needed for manual tree inspection.

5 Discussion

The empirical measurements of 134 trees with 3 different methods showed that the fastest among them was greeHill's automated machine learning process. This difference in the needed time is radically getting greater with the increased number of inspected trees. Manually, it would take the same time to measure a tree (around 4 minutes field work + 1 minute digitization), but digitally to measure areas having more trees using mobile LiDAR scanners would decrease the time needed for the data collection per tree, since the creation of the point cloud does not depend on the number of trees enclosed in the area. It is important to mention, that in the case of digital-automated method, the data collection (LiDAR measurements) is more time intensive than the data extraction (automated process), and many of today's cities already possess point clouds of their cities (which were created for different planning and maintenance purposes), and these point clouds could be ready to be processed by the machine learning algorithm to extract the tree features. The machine learning algorithm would get faster and faster as it works through more and more data, optimally reducing the data extraction speed down to 2 seconds per tree. The digital – manual method was the slowest from all, since the data extraction was time consuming, taking 30 minutes per tree for the writer of the thesis; a more experienced PointCloudScene user could have done it faster (20 min), but it would still justify the need for automatic extraction of accurate tree semantics from point clouds. This great difference in the needed time was the main reason why the digital-manual method had the least favourable results in terms of speed and cost, as it can be seen on Figure 31 and Figure 32 respectively.

The comparison of the cost showed, that the digital – manual method was the most expensive due to the slowness of the method – the salary of the GIS expert, and the licensing fees of the needed software to process the point clouds. For the 134 trees, there was only €10 difference in the cost between greeHill's algorithm and the manual measurements, due to the fact, that manual measurements require salaries to be paid, but the cost of greeHill's algorithm only depends on the number of trees. As the number of inspected trees would increase, they would require more time from the manual and digital-manual methods, increasing the cost of salaries, therefore increasing the monetary gap between the machine learning algorithm and the other methods.

The outcomes of the different methods presented in Chapter 4 indicate, that manual measurements of the geometric parameters of trees using clinometer, forestry calliper and measuring sticks offer rather coarse results, while incorporating human errors in the creation of tree inventories. A point cloud’s accuracy on distance assessments is indisputable. Cutting edge terrestrial LiDAR imaging technology could carry the necessary geometric information of trees accurately, while also having certain limitations. If the trees are measured *from only one side*, the parameters regarding the girth of the trunk cannot be extracted manually from the point cloud as precisely as one could manually with a measurement tape, yet machine learning algorithms could model and assess those values even better than a manual measurement. The currently accepted and used manual method to assess the DBH of a tree (averaging the diameter obtained with a forestry calliper from 2 sides) is questionable if we account the global tree population and its magnificent variety as well as the possible digital solutions of the 21st century; which could be the reason why NParksSG asked for girth measurements at different heights instead of diameter measurements. It is important to mention, that while point clouds offer unmatched accuracy on geometric parameters, it is not capable to offer information regarding the decay of the trees which, in many cases happens inside the trunk, and can be assessed only using a combination of visual inspection, acoustic testing and resistance micro drilling [48], [49].

Regarding the usability of the created datasets, the thesis found that all the i-Tree required parameters are possible to collect manually and digital – manually, while some of the parameters are not yet implemented in greeHill’s digital-automated algorithm. While the point cloud carried the necessary information (except the address of the tree) the species determination still needs a human eye [25], in this thesis this information digitally was extracted using the geophotos taken by the custom mobile laser scanner. In the future, further developments in greeHill’s machine learning algorithm will enable the access to the parameters which were the not yet available automatically; providing an edge over the other methods, which could not be improved drastically in the future. For example, manual methods won’t be able to offer parameters, such as digital Voxel models of the trees, deterring the opportunity to use the data in microclimate simulations, to shortlist dangerous trees.

6 Conclusion and future work

In this thesis 134 trees on Bartók Béla street in Budapest have been measured and digitized in foliated condition through 3 different methods (manual, digital-manual, digital-automated) to assist municipalities on digital tree cadastre production, based on accuracy, speed, cost and usability. The trees' parameters to collect were sourced from 2 groups; firstly, for i-Tree Eco software to be able to estimate ecosystem services provided and structural characteristics of the urban forest with the best possible quality. The second group of parameters were formed by the different geometric information about the trees, which was requested by NParksSG from greeHill. The speed, cost and accuracy of these methods were compared, and the thesis found, that the fastest and least resource intensive method was greeHill's machine learning algorithm, radically increasing its edge over the other methods when increasing the number of inspected trees. LiDAR created point clouds offer unmatched accuracy regarding the geometric parameters of the trees, and they could be quickly extracted with the examined industrially proven machine learning algorithm, which will get faster and faster as it has worked through more and more trees around the world. The significant differences in the i-Tree Eco results highlighted, the accuracy regarding urban tree stock information is an important factor if one would like to understand the urban forest's structure, function and value to promote management decisions that will improve human health and environmental quality. Knowing the exact location and geometry of the trees is important to design and maintain the cities' ever-changing infrastructure. Since trees are living organisms, and change their shape through time, it is advised to repeat the measurements and refresh the database every half year, no matter the methodology. While manual measurements would take longer, it is important to mention the need for manual maintenance, intervention in specific cases regarding the decay of trees. Point clouds can offer digital models of the trees (such as Voxel models), which could be quickly extracted using the right algorithm to be used in cutting-edge replications of urban areas, allowing municipalities to perform city-wide microclimate simulations. Stressing this digital-twin environment with extreme weather enables municipalities to pre-emptively select the dangerous trees which could endanger the safety of its citizens. By pre-emptively shortlisting threatening trees from a regularly updated extensive tree cadastre, municipalities could save efforts, employing time intensive human intervention in a directed manner.

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Appendix

The appendix is a compressed file attached, containing the following files:

- “Bartok_str_trees.kml”: File containing the location and links to the pictures taken for all the inspected trees
- “Master_Excel.xlsx”: The Excel file containing the tree data obtained with all the methods, the comparisons, the costs, speed and parameters.
- “Tree_Measurement_options.kml”: The inspected optional locations for the measurements.
- “Manual_sheets.zip”: The scanned manual measurement sheets in a compressed format.
- “Trees_digman.zip”: The compressed file of each of the trees, their pictures, and screenshots for each of the digital-manual measurements for their comparable parameters.
- “I-tree_digman_ecosystem_analysis.pdf”: The i-Tree ecosystem analysis for the digital-manual method
- “I-tree_digman_project_metadata.pdf”: The i-Tree project metadata for the digital-manual method
- “I-tree_digman_tree_location.kml”: The file containing the tree locations for the digital-manual method.
- “I-tree_export_digman.csv”: The tree data exported from i-Tree for the digital-manual method
- “I-tree_export_manual.csv”: The tree data exported from i-Tree for the manual method
- “I-tree_manual_ecosystem_analysis.pdf”: The i-Tree ecosystem analysis for the manual method
- “I-tree_manual_project_metadata.pdf”: The i-Tree project metadata for the manual method
- “I-tree_manual_tree_location.kml”: The file containing the tree locations for the manual method