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Pruning Management Protocol

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Author	Matteo Santilli, Valerio Cristofori, Ciro Potena, Renzo Fabrizio Carpio, Cristian Silvestri, Marco Paolocci
Approved by	Andrea Gasparri, Laura Giustarini, PMC

Executive Summary

This document proposes automated models to determine the canopy architecture of the plant and to identify its portions or branches to be removed. The developed models, to be applied in large-scale hazelnut orchards, will be used both in young plants during the growing phase and in adult ones during the period of full fruiting. An analysis of current best practices in hazelnut tree training and pruning is here reported, followed by the proposed new automated or semi-automated solutions. The following aspects have been analysed:

1. State of the art analysis on current hazelnut pruning acquisition and application
2. Real tree canopy reconstruction models through field acquisitions with properly equipped UGV
3. Virtual tree canopy reconstruction model and pruning guidelines
4. Trials for field validation

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Abbreviations and Acronyms

PA	Precision Agriculture
2D / 3D	Two-dimensional / Three-dimensional
UGV	Unmanned Ground Vehicle
UAV	Unmanned Aerial Vehicle
Ad	Adult Tree
Yo	Young Tree
ID	Identification Code
HD	High Density
NBI	Nitrogen Balance Index
cv	Cultivar
DGNSS-RTK	Differential Global Navigation Satellite System
UTM	Universal Transverse Mercator
LiDAR	Light Detection and Ranging
$\mathbb{Z}$	Set of integer numbers

1 State of the art on hazelnut training and pruning

1.1 Main objectives and types of pruning

Thinning cut is the removal, at the base, of an entire shoot or branch in order to eliminate it. On the contrary, heading back cut is a partial removal of the distal part of a branch to shorten it [1]: it may vary in intensity. The cut of two-year old or older branches has the following goals: to bring the branch back to its natural position or to limit the development of the branch. Heading back cut is also intended to allow the shortened branches to resume their "apical function" efficiently, with new shoots growing below the branch diversion (Figure 1). The wounds caused by the cuts heal and cambial tissues repair the wound through a process called "compartmentalization". For trees with soft wood (e.g. peach), it is advisable to prune in late spring or after fruit harvest, when temperatures are relatively high (at least 10-15 °C), or alternatively in late summer, to prevent health problems. Other woody species, such as pome fruits and hazelnut trees, can tolerate winter cuts much better than *Prunus* species, and pruning can be performed in late winter or early spring.

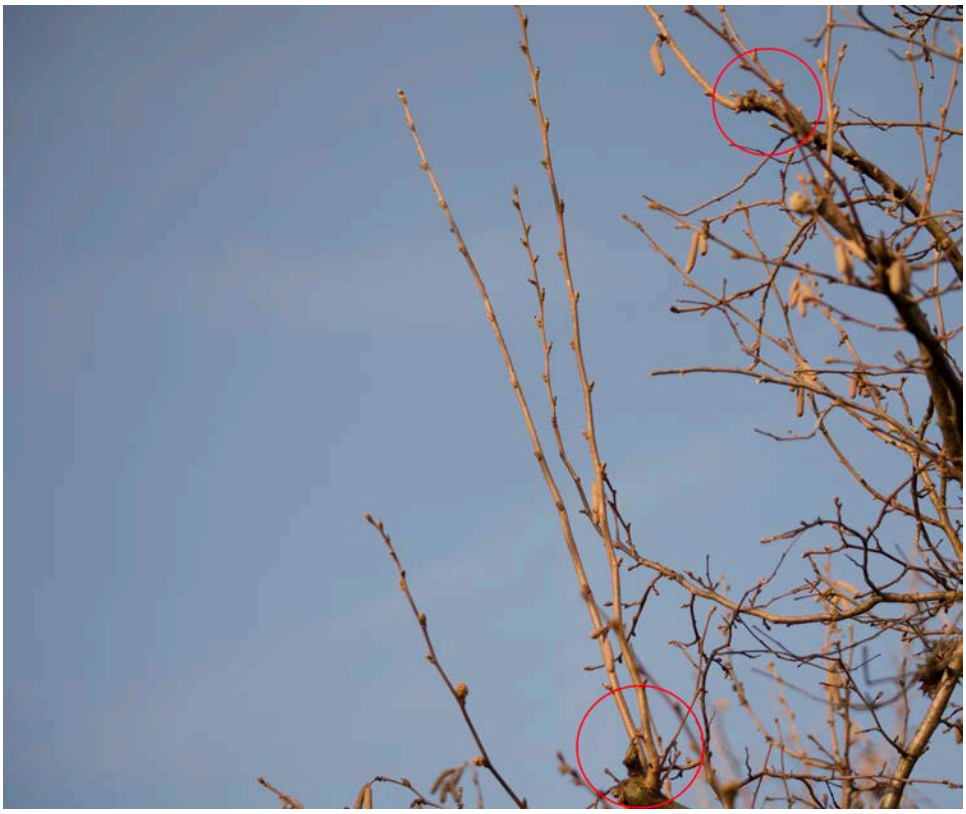

Figure 1 - An example of shortened branches in hazelnut to let them resume their "apical function", through the growth of new shoots below the branch diversion. The red circles highlight the insertion of new vigorous shoots developed as consequence to the heading back cut.

The intensity of the cuts distinguishes long pruning from short pruning. The long pruning of fruiting branches tends to leave the apical part of the branch intact. The short pruning consists in systematically shortening shoot with flowering-vegetative buds, obtaining a strong reduction of the number of buds per tree.

Pruning is also classified according to the number of the shoots or buds which are left on the tree after pruning. It is classified as "rich" when the tree retains many buds which can then generate several flowers and shoots. Conversely, pruning is "poor" when many buds are removed and consequently the few remaining will form less flowers and fertile buds. A poor pruning can also be short, while the long pruning is almost always rich.

The common practice in temperate fruit species, including hazelnut trees, is to apply winter thinning cuts, with the aim to suppress excessively vigorous and poorly positioned shoots and removing unnecessary branches. These cuts should be carried out every year, removing the shoots near their attachment point. For one-year-old shoots some operation such as "trimming", "shortening" and "spur pruning" are possible alternative to thinning cuts and according to the physiological concept that more intense the cut is, the more vigorous the shoot growth will be.

The removal of branches can be done both during the plant training period, to remove surplus branches, or when tree is mature, and it is especially used in high-density orchards. It eliminates shaded or weak parts of the canopy, thins out the branches growing too close to one another or mutually interfering with one another, and increases light penetration in the inner portion of the canopy [2].

The desired effect of spring pruning is to limit vigour when excessive. Furthermore, during vegetative growth the vascular cambium activity is at its maximum and it is possible to reduce the vigour of a shoot by "twisting". This technique is less traumatic than shortening, because it only disrupts the internal portion of the stem. Furthermore, during the growing season it is possible to thin out the fruit, if necessary [3].

The intensity and timing of pruning is also related to the adopted training system of the trees. The type of training system depends on the design of the planting system, on the choice of planting distances and therefore the density of the trees. However, it is also a function of genetics and environmental factors and on agronomic management.

For European hazelnut trees, the guidelines for training young plants mostly suggest "free shape" and "volume shape", given the nature of wild hazelnut as shrubs. The "free shape" stimulates the natural development of the tree and does not impose limiting structural hierarchies, therefore inducing an autonomous development of new shoots in determined positions of the framework (Figure 2). The cuts are done to re-establish a free harmonious growth of the shoots, compatible with the natural growth habit of the species. The "volume shape", also named "vase shape", requires framework structures that are well-defined and balanced in space, in which the branches project uniformly towards the outside, producing a three-dimensional canopy (Figure 3). The branches are robust and well ramified and consequently well-balanced, equidistant and ensuring a solid insertion on the trunk. The primary branches require several years (3 to 5) to form completely.

Figure 2 - Mature hazelnut tree trained as "free shape", also known as multi-stemmed bush.

Figure 3 - Mature hazelnut tree trained as "vase shape".

In the following introductory paragraphs, a list of the most applied hazelnut pruning strategies are briefly discussed, considering both the training of young plants and the pruning of mature ones.

1.2 Plantation density and young plant training

The hazelnut is a suckering plant tending to develop into multi-stemmed bush, and its vegetative habits is exploited by the growers for shaping the commercial orchards, mainly in traditional Turkish and Italian hazelnut districts. Anyway, many growers prefer to shape plants in single trunk with an open V-shape, and this is routine in some hazelnut districts such as in Oregon (USA) and Cancon (France). This shaping facilitates mechanical harvesting and permits more sunlight penetration into the orchard [4]. Furthermore, some operations such as sucker removal, irrigation and weed control are facilitated. Anyway, this shape has also some disadvantages. For instance, young single trunk plants are more vulnerable to storm damages, due to their shallow rooted. Moreover, the multi-stemmed bushes permit to the grower to gradually renew the plants eliminating the old stems to be replaced selecting new lignified suckers.

In suited hazelnut districts such as in the Mediterranean area, in Oregon (USA) and in the new hazelnut growing areas, the orchards are trained to a multi-stem bush type or to vase shape at a density of 400-500 plants ha^{-1} [5]. Nevertheless, there are higher density plantations also for this nut species and the most common hazelnut plantation densities are reported in Table 1. Higher or lower planting densities are often determined according to the vigour of the cultivars.

Distance in the row (m)	**Distance between rows (m)**			
	4.5	**5.0**	**5.5**	**6.0**
2.5	-	800	727	667
3.0	740	667	606	555
4.0	555	**500**	454	**417**
4.5	494	400	364	333
5.0	-	**400**	364	333

Table 1 - Plantation density of hazelnut orchard according to the main planting distances. The values underlined in bold represent the most common plantation densities at present.

The new orchards are frequently made by hand planting three-four rooted suckers per hole. More recently, Differential Global Navigation Satellite System – Real Time Kinematic (DGNSS-RTK) technology has been introduced to design and mechanically plant single-trunk high-density new orchards spaced at 4.5–5.0 × 3.0–2.5 m, which can be managed with a high level of mechanization of future pruning operations [6].

Dynamic spacing of the orchard has recently been suggested for fruit tree species with a long unproductive period after planting, such as hazelnut [7]. This plantation technique consists of planting double the number of plants (i.e. 800 plants/ha, spaced 5 × 2.5 m) with the aim of enhancing the yield during the first 10–12 years of the plantation and then eliminating 50% of the plants to achieve the final orchard design (i.e. 400 plants/ha, spaced 5 × 5 m). Nevertheless, this system has not been applied on a large scale because the higher plant costs, the tendency of the farmer to delay the timing of tree spacing and the risks of competition among the plants [5]. Also, the HD systems have received little attention. Moreover, in Turkey, namely the first hazelnut producer country, growers prefer to adopt the row system with spacing of 5–6 m between the rows and 1–2 m between contiguous plants to replace the traditional 'ocak system' that consists of planting at least four rooted suckers around a circle 1 m in diameter (Figure 4).

Figure 4 - Hazelnut trees trained to a multi-stem bush, namely 'ocak system', in Turkey.

Training young hazelnut plants as multi-stemmed bush requires the choice of 4-5 vigour stems to be grown for the bush formation starting at the second leaf in field (second year in the field). For promoting a fast grown of the selected stems, that will be the main branches of the shrub, the basal shoots and suckers that will develop during the following growing season needs to be removed.

In plants to be grown as vase-shape and sapling-shape (Figure 5) one main stem is selected planting only one rooted sucker or one rooted scion and it will be cut in the second year at 50-60 cm or at 80-90 cm from the ground for plants trained with the first or second shape, respectively. During the winter rest of the plants, 4-6 healthy, vigour and well oriented shoots developed near the cutting point of the future trunk will be selected and the other poorly oriented shoots will be eliminated. Table 2 reports the guidelines to be followed for training the young hazelnut plants in the most spread shapes adopted by the growers.

Training system	Number of branches	Second year	Following years	Notes
Multi-stemmed bush	From 3 to 5 branches per bush	Select 4-5 vigorous shoots to growth for the bush formation	Keep the tree canopy free from excess branches and shoots by operating with a light annual pruning. Annual sucker removal	Training system widespread in traditional hazelnut districts
Vase-shape	Single trunk shape: trunk standing 50-60 cm above the ground	Cutting the main stem at 50-60 cm from the ground leaving 4-5 vigorous shoots suitably oriented to form the scaffolding of the future vase-shape	Keep the 4-5 shoots vigorous to obtain a uniformly developed tree canopy. Annual sucker removal	Intermediate training system between multi-stemmed bush and sapling-shape. Facilitates suckering operations and working near the trunk
Sapling-shape	Single trunk shape: trunk standing 80-90 cm above the ground	Summer selection of the most vigorous shoot to growth and cut at 80-90 cm above ground at the beginning of the third year	Maintain the single trunk and sapling-shape by removing excess branches in the tree canopy. Annual sucker removal	Training system suitable for vigorous varieties. Facilitates the mechanization of field operations

Table 2 - Guidelines for setting the shape of the young hazelnut plants.

Figure 5 - Young hazelnut tree trained as "sampling shape".

1.3 Pruning of mature plant

In traditional hazelnut orchards, the pruning operations are limited to a few annual pruning interventions. During the first years after plant training, pruning operations are limited to elimination of suckers and to maintain the shape, while in the following years, when the canopies become denser with a consequent decrease of productivity and difficulties for mechanization (i.e. obstacles in the correct atomised distribution of agrochemicals and foliar nutrition), pruning of mature plants is usually done by hand during wintertime when the plants are in winter rest and mainly consists in removing lignified suckers, dead wood and diseased or bad oriented branches [6]. An uneven pruning, such as often occurs in the various producing areas, is the reason of the increase in canopy density and over the years the overlap of the branches stimulates the reduction of shoots vigour and reduce the light penetration inside the plant. The resulting physiological plant disorders stimulate the low yield, the kernel quality decline [8] and the biennial bearing [9]. Accordingly, annual pruning is highly recommended especially since some authors observed that hazelnut productivity is positively related to the develop of mixed one-year-old shoots, and a shoot length of 15-20 cm has been identified ideal for a high incidence of fertile buds [10].

Thus, pruning applied during the dormant season is carried out with the main aims to shorten the branches along the row, reducing the plant size and stimulating the production of new shoots. Usually, the annual pruning of an adult plant removes 20-25% of the wood and it also depends on the characteristics of the orchard (tree spacing, training system, soil fertility, cv choice).

Nevertheless, pruning is often neglected for its high labour requirement and time consuming since literature reports at least 15-18 labour hours per hectare for its execution in mature orchards [11]. The intensity of pruning operations in hazelnut also affects the amount of harvestable woody biomass, which needs to be removed from the orchard. Usually, the highest quantities of pruned wood are obtained from medium-high vigour plants over 20 years old.

Recently has been observed as the pruning intensity significantly affected the yield in mature orchard grown at multi-stemmed bush [6]. Plants subjected to high intensity pruning, through the removal of about 40% of wood to renew the crown, mainly shortening vigorous and poorly orientated branches on the top of the tree, showed ah higher cumulative yield and higher nut traits over three years investigation in comparison to low intensity pruning plants where only about 20% of wood was removed. These enhancements were also confirmed by the measured light infiltration at the base of the trees in the different thesis of the trial among the vegetative seasons, that positively influenced the reproductive phase and the floral induction of new buds in the inner portion of the plants.

To reinforce the role of light in the fertile bud induction on hazelnut, some authors [12] highlighted their finding in trials subjected to summer pruning protocols carried out in May, where the mature plants showed an increased yield starting with second year after pruning and showing a decrease in biennial bearing. Anyway, differently to other major temperate fruit crops where summer pruning is routine, more trials need to be carried out on hazelnut for better understanding the role of this seasonal operation on yield and nut quality.

1.4 Rejuvenating pruning

The renewal pruning interventions are usually applied in traditional hazelnut orchards with plants over 40-50 years-old, especially when ordinary annual pruning has not carefully been carried out to periodically restore the architecture of the plants.

The rejuvenating pruning mainly consists in thinning and heading back cut of the main branches, with the aim to promote the development of numerous new sprouts (Figure 6), that in the following years will be selected to regenerate the new plant's crown. This kind of pruning is normally applied only once, in senescent orchards only.

Figure 6 - Rejuvenation pruning applied in adult hazelnut orchard. Pruned plants at the vegetative bud break stage.

1.5 Mechanical pruning approaches

Mechanical pruning was recently applied to hazelnut in both trials and commercial orchards and was performed using a rotating blade bar carried by a tractor (Figure 7). The effectiveness of this operation, advisable for large orchards and in medium- to high-density plantations, is confirmed by the positive effects on production obtainable in the medium period. Mechanical pruning is performed with side-cutting interventions along the row (hedging) and cutting the top of the plants (topping). The first intervention can occur when the branches of the two contiguous rows come to meet on the half of the row, on average from years 10 to 12 of the plantation depending on cultivar vigour. To avoid the pruning of all trees, which can drastically reduce productivity in the first year of application, hedging interventions can be foreseen over some years (from 3 to 5). Figure 8 shows a hedging scheme that is adoptable every 3 years in the same row side. Topping may be less frequent than hedging and is performed on the whole orchard every 5–8 years [6]. The more promising technique involves cutting one side of two rows facing each other; this type of cut is carried out during the first year on an inter-row every three, leaving the two following inter-row spaces unaltered. The following year the first pruned inter-row is not cut, but the second one is, leaving the two following ones unchanged and resuming the sequence. The third year ends by pruning all the inter-row threads not yet pruned in previous years. The rotation every 3 years of pruned rows allows diluting the loss of nuts production due to pruning and maintaining a constant rhythm of renewal of the plantation.

Another approach in mechanical pruning to alleviate the initial nut losses may be applied. For instance, in medium-large farms the grower could generate a pruned plots rotation, cutting only on a portion of orchards each year to dilute the application and thus to alleviate the initial production losses.

To complete mechanical pruning, it is advisable to proceed with the manual cutting of those branches that exhibit any mechanical damage or that are badly positioned. The clippings are transported out of the orchard and are eliminated or can be collected and treated for biomass energy production.

Some growers also use mechanical hedging to renovate overgrown orchards, such as this is a fast and economical way to remove large amounts of wood, and the re-growth often is so rapid that the space between plants created by hedging is filled in after two or three vegetative seasons. Furthermore, mechanical pruning applications may promote hazelnut as a great source of biomass for energetic uses [13].

Figure 7 - Mechanical hedger during "topping" application in a mature hazelnut orchard.

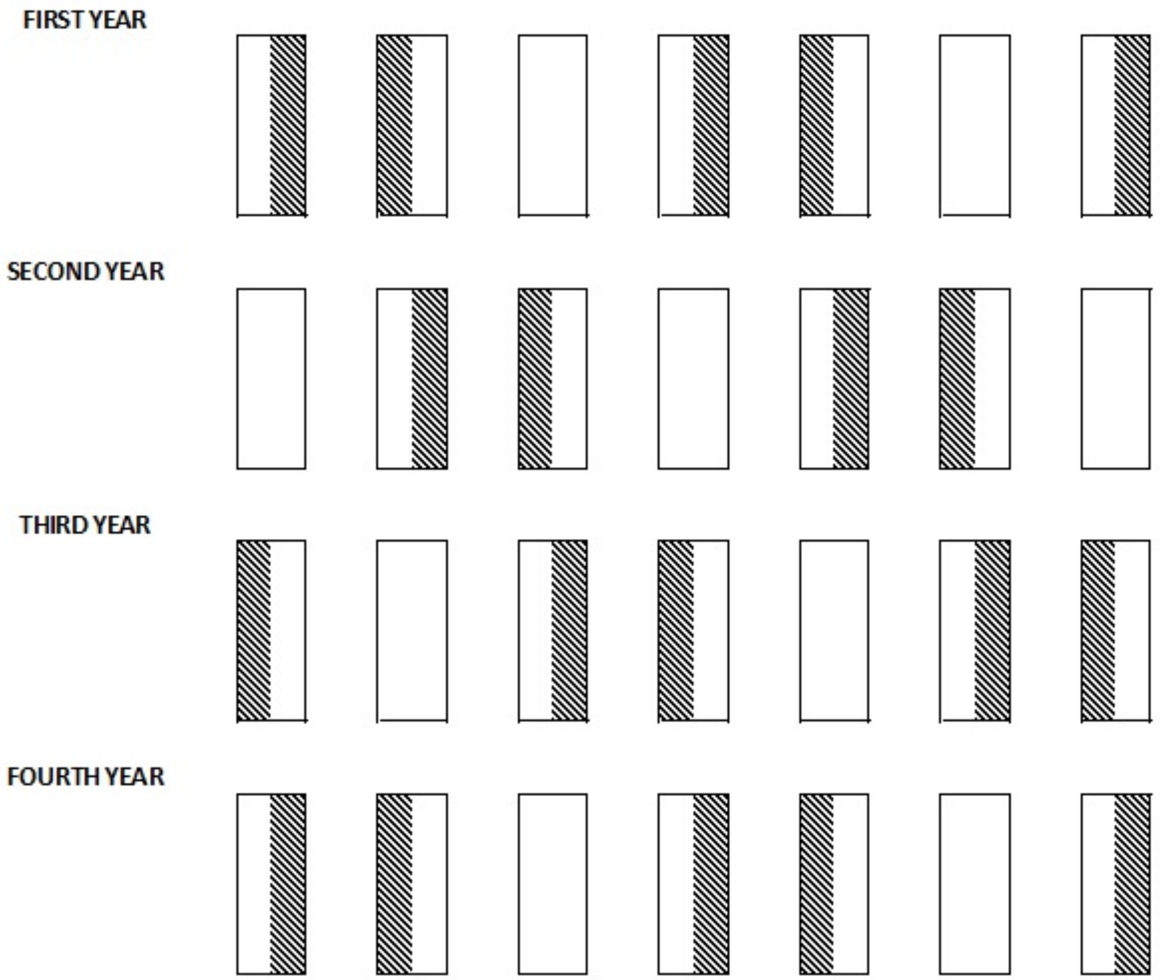

Figure 8 - Hedging scheme for mechanical pruning adopted in large commercial orchards. The same row side is cut every 3 years. Alternatively, the intervention can be extended to 4 or 5 years.

2 Field trial to develop mathematical models for canopy detection and pruning recommendations

The chapter discusses the field trial established to develop protocols and mathematical models able to capture the plant architecture and canopy detection. The objective is to schedule pruning recommendations both to train young plantations and to seasonally prune mature plants. Three different plant training systems have been established in the 16 and will discussed in the next paragraph.

The field trial, after three years of growth management, will also be used for the validation of the protocols to detect and guide the automated pruning approaches through the use of properly equipped UGVs.

2.1 Experimental setup and plant training

In order to establish the trial in a portion of the orchard suitable both for uniformity of plant growth and to facilitate the transmission of raw data acquired by UGVs and UAVs to the cloud, at the beginning of the project a deep evaluation of the plantation has been carried out.

After the preliminary observation, a total of 30 plants selected in two contiguous rows (15 plants per row) were labelled for establishing the field trial. At the time of the trial implementation, the plants, planted by the grower with a planting design of 4.5m x 3m, were growth to be subsequently trained as shrubs, and at the third leaf on field (three years old plants) they had never been pruned, with the only exception of the manual sucker removal, which began in the second year.

The selected plants were geo-referenced and for each plant an ID code were assigned depending by the future training system being applied, as reported in Table 3.

Three different training systems have been implemented and ten plants were trained at regular bush at four stems (Yo A_n), ten plants at sapling-shape with single trunk (Yo B_n) and ten plants at multi-stemmed bush (Yo C_n).

Plant ID	Latitude N	Longitude E	Plant ID	Latitude N	Longitude E
Yo A1	42°16'47.27''	12°17'55.17''	**Yo B6**	42°16'47.26''	12°17'56.98''
Yo A2	42°16'47.29''	12°17'55.29''	**Yo B7**	42°16'47.25''	12°17'56.85''
Yo A3	42°16'47.29''	12°17'55.43''	**Yo B8**	42°16'47.24''	12°17'56.72''
Yo A4	42°16'47.30''	12°17'55.55''	**Yo B9**	42°16'47.24''	12°17'56.60''
Yo A5	42°16'47.31''	12°17'55.68''	**Yo B10**	42°16'47.23''	12°17'56.47''
Yo A6	42°16'47.17''	12°17'55.69''	**Yo C1**	42°16'47.31''	12°17'55.81''
Yo A7	42°16'47.17''	12°17'55.56''	**Yo C2**	42°16'47.32''	12°17'55.94''
Yo A8	42°16'47.16''	12°17'55.43''	**Yo C3**	42°16'47.34''	12°17'56.08''
Yo A9	42°16'47.15''	12°17'55.31''	**Yo C4**	42°16'47.34''	12°17'56.21''
Yo A10	42°16'47.14''	12°17'55.17''	**Yo C5**	42°16'47.35''	12°17'56.34''
Yo B1	42°16'47.35''	12°17'56.47''	**Yo C6**	42°16'47.21''	12°17'56.34''
Yo B2	42°16'47.37''	12°17'56.60''	**Yo C7**	42°16'47.20''	12°17'56.21''
Yo B3	42°16'47.37''	12°17'56.73''	**Yo C8**	42°16'47.19''	12°17'56.09''
Yo B4	42°16'47.38''	12°17'56.86''	**Yo C9**	42°16'47.19''	12°17'55.94''
Yo B5	42°16'47.39''	12°17'56.99''	**Yo C10**	42°16'47.17''	12°17'55.82''

Table 3 - ID and geographic coordinates (WGS84 GD) of the selected plants for tree geometry reconstruction and pruning.

While the ten plants for each pruning thesis were treated to evaluate their anatomical and eco-physiological response to the applied training systems, the UGV acquisitions and the relative elaborations for the plant three-dimensional reconstruction and for the development of the pruning algorithm were focused on three replications per thesis, and respectively on the plants A6, A7, A8 for the regular bush at four stems, B5, B6, B7 for the sapling-shape and C7, C9, C10 for the multi-stemmed bush.

At the end of the plant winter rest, slightly before bud break, in February 2019 when the plants were almost ready for starting their four leaf on ground, the first pruning interventions were manually applied by the UNITUS team in order to establish the chosen shapes. In that stage, all plants were disorderly bushes showing also many suckers one year old at the base of the plants.

Figure 9, Figure 10, and Figure 11 show the three replications for the thesis A, B and C used for UGV acquisitions, not yet pruned.

During the second half of February 2019 all plants where pruned according to the three different chosen shapes, the removed wood was weighed separately from removed suckers, and the pruned plants were periodically photographed and measured during the following growing season.

Figure 12, Figure 13, and Figure 14 show the same replications just after pruning applications, meanwhile Figure 15 reports the overview of the implemented trials for plant shaping and pruning at the beginning of March 2019.

Similarly, Figure 16, Figure 17, and Figure 18 show the same replications during the growing season 2019, after pruning applications, to highlight the different vegetative growing of the plants according to the different shaping applied.

Figure 9 - Un-pruned multi-stemmed plants A6, A7, A8 before the first year of manual pruning application (training system: regular bush at four stems). Early January 2019.

Figure 10 - Un-pruned multi-stemmed plants B5, B6, B7 before the first year of manual pruning application (training system: single trunk). Early January 2019.

Figure 11 - Un-pruned multi-stemmed plants C7, C9, C10 before the first year of manual pruning application (training system: multi-stemmed bush). Early January 2019.

Figure 12 - Plants A6, A7, A8 after the first year of manual pruning application (training system: regular bush at four stems). Late February 2019.

Figure 13 - Plants B5, B6, B7 after the first year of manual pruning application (training system: single trunk). Late February 2019.

Figure 14 - Plants C7, C9, C10 after the first year of manual pruning application (training system: multi-stemmed bush). Late February 2019.

Figure 15 - Overview of the shaping and pruning trials after the first year of winter pruning applications. Multi-stemmed bushes (C_n - on left), regular bushes at four stems (A_n - in the middle) and single trunk plants (B_n - on right). March 2019.

Figure 16 - Plants A6, A7, A8 after the first year of manual pruning application (training system: regular bush at four stems). Middle July 2019.

Figure 17 - Plants B5, B6, B7 after the first year of manual pruning application (training system: single trunk). Middle July 2019.

Figure 18 - Plants C7, C9, C10 after the first year of manual pruning application (training system: multi-stemmed bush). Middle July 2019.

Similarly to the winter 2019, in middle February 2020 the second year of pruning were applied to the trial. In this case, the interventions were not only aimed at the shaping and pruning of plants, but also at reconstructing the 3D geometry of the plants before and after pruning. These 3D image acquisitions have been very useful for developing the algorithm for pruning.

Before to start with the manual pruning application, in late January 2020 some random 3D acquisitions were carried out to set the field use of the UGV.

These preliminary acquisitions were very useful as they allowed us to note that the presence of catkins in the shoots represented a hindrance in the subsequent processing of the 3D acquisitions for the correct geometric reconstruction of the tree. Thus, before to apply the different pruning protocols the catkins were removed by hand using small scissors (Figure 19). Anyway, it is important to remark that catkins tend to drop naturally after blooming and that will facilitate the future 3D acquisitions in commercial hazelnut orchards, when the tool will be ready to be applied at large-scale.

After a first round of 3D images acquisition using the UGV, carried out in middle February on un-pruned plants, the team UNITUS pruned all 30 plants of the trial according to the three different chosen shapes, weighed the removed wood per plant and therefore the team UNIROMA3 carried out the second round of UGV acquisitions for reconstructing the geometry of the plants, before and after pruning applications.

Figure 20, Figure 21, and Figure 22 show the three replications for the thesis A, B and C used for UGV acquisitions and tree reconstruction, not yet pruned in the second year of the trial.

Figure 23, Figure 24, and Figure 25 show the same replications just after pruning applications, meanwhile the Figure 26 reports the overview of the implemented trials for plant shaping and pruning at the beginning of April 2020. The pruned plants were periodically photographed and measured during the growing season 2020. Furthermore, in early August 2020 the pruned plants were 3D scanned again for monitoring the "growth effect" due to the different shape of the plants according to their training.

Figure 27, Figure 28, and Figure 29 show the same replications during the growing season 2020, to highlight the different vegetative growing of the plants according to the different shaping applied. Furthermore, Table 4, Table 5, and Table 6 report the linear measurements of the plants carried out at the end of the seasonal vegetative growth, to determine the volumetric development of the plant crown according to the different plant training and pruning.

Figure 19 - Plant C9 before (on left) and after (on right) the catkins removal by hand. January 2020.

Figure 20 - Plants A6, A7, A8 before the second year of manual pruning application (training system: regular bush at four stems). Early February 2020.

Figure 21 - Plants B5, B6, B7 before the second year of manual pruning application (training system: single trunk). Early February 2020.

Figure 22 - Plants C7, C9, C10 before the second year of manual pruning application (training system: multi-stemmed bush). Early February 2020.

Figure 23 - Plants A6, A7, A8 after the second year of manual pruning application (training system: regular bush at four stems). Late February 2020.

Figure 24 - Plants B5, B6, B7 after the second year of manual pruning application (training system: single trunk). Late February 2020.

Figure 25 - Plants C7, C9, C10 after the second year of manual pruning application (training system: multi-stemmed bush). Late February 2020.

Figure 26 - Overview of the shaping and pruning trial after the second year of winter pruning applications. Multi-stemmed bushes (C_n - on left), regular bushes at four stems (A_n - in the middle) and single trunk plants (B_n - on right). Early April 2020.

Figure 27 - Plants A6, A7, A8 after the second year of manual pruning application (training system: regular bush at four stems). Early August 2020.

ID Plant	Plant height (m)	Inter-row plant length (m)	Intra-row plant length (m)
Yo A1	2.80	1.55	2.00
Yo A2	2.75	1.65	2.05
Yo A3	3.05	1.90	1.40
Yo A4	3.00	2.30	2.00
Yo A5	3.05	2.20	1.60
Yo A6	3.25	1.85	2.65
Yo A7	3.20	2.00	1.95
Yo A8	3.10	1.40	1.60
Yo A9	2.75	1.80	1.55
Yo A10	3.05	1.50	1.70
Mean value ± s.d.	**3.00 ± 0.18**	**1.82 ± 0.29**	**1.85 ± 0.36**

Table 4 – Biometric traits of the plants trained as regular bush at four stems, measured at the end of the seasonal vegetative growth (year 2020).

Figure 28 - Plants B5, B6, B7 after the second year of manual pruning application (training system: single trunk). Early August 2020.

ID Plant	Plant height (m)	Height of branches insertion (m)	Inter-row plant length (m)	Intra-row plant length (m)
Yo B1	2.50	1.10	1.60	1.70
Yo B2	2.30	1.20	1.50	1.20
Yo B3	2.40	1.05	1.50	1.55
Yo B4	2.80	1.10	1.25	1.05
Yo B5	2.70	1.15	1.15	1.25
Yo B6	2.60	1.25	1.10	1.25
Yo B7	2.75	1.00	1.80	1.30
Yo B8	2.70	1.20	1.40	1.35
Yo B9	2.40	1.20	1.10	1.15
Yo B10	2.65	1.30	1.25	1.35
Mean value ± s.d.	**2.60 ± 0.17**	**1.16 ± 0.09**	**1.36 ± 0.23**	**1.31 ± 0.19**

Table 5 - Biometric traits of the plants trained as sapling shape, measured at the end of the seasonal vegetative growth (year 2020).

Figure 29 - Plants C7, C9, C10 after the second year of manual pruning application (training system: multi-stemmed bush). Early August 2020.

ID Plant	Plant height (m)	Inter-row plant length (m)	Intra-row plant length (m)
Yo C1	2.20	1.50	1.45
Yo C2	3.20	2.50	2.75
Yo C3	3.00	2.35	2.35
Yo C4	3.10	2.55	2.80
Yo C5	3.20	2.40	2.55
Yo C6	3.00	2.10	2.25
Yo C7	3.30	2.30	2.20
Yo C8	3.25	1.75	1.95
Yo C9	3.10	1.95	2.00
Yo C10	3.40	2.05	2.15
Mean value ± s.d.	**3.17 ± 0.13**	**2.22 ± 0.27**	**2.33 ± 0.31**

Table 6 - Biometric traits of the plants trained as multi-stemmed bush, measured at the end of the seasonal vegetative growth (year 2020).

The last three figures of the paragraph (Figure 30, Figure 31, and Figure 32) describe an example of the 2D "cloud" reconstruction of the UGV data acquisition of the plants trained at different shapes before and after pruning, respectively.

Figure 30 - 2D "cloud" reconstruction of the UGV data acquisition of the plant Yo A7 before (on left) and after (on right) manual pruning carried out in February 2020.

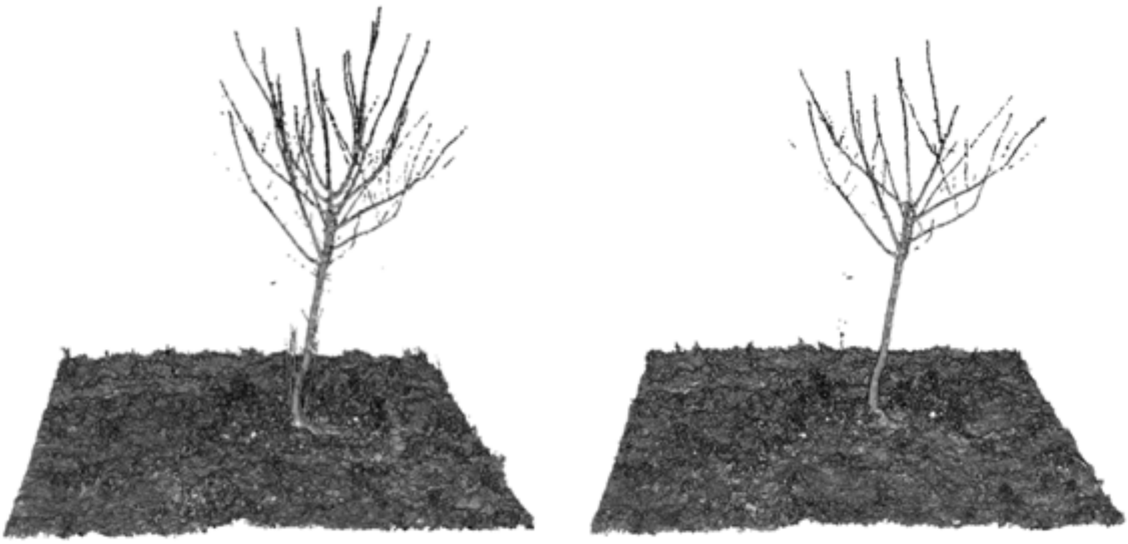

Figure 31 - 2D "cloud" reconstruction of the UGV data acquisition of the plant Yo B5 before (on left) and after (on right) manual pruning carried out in February 2020.

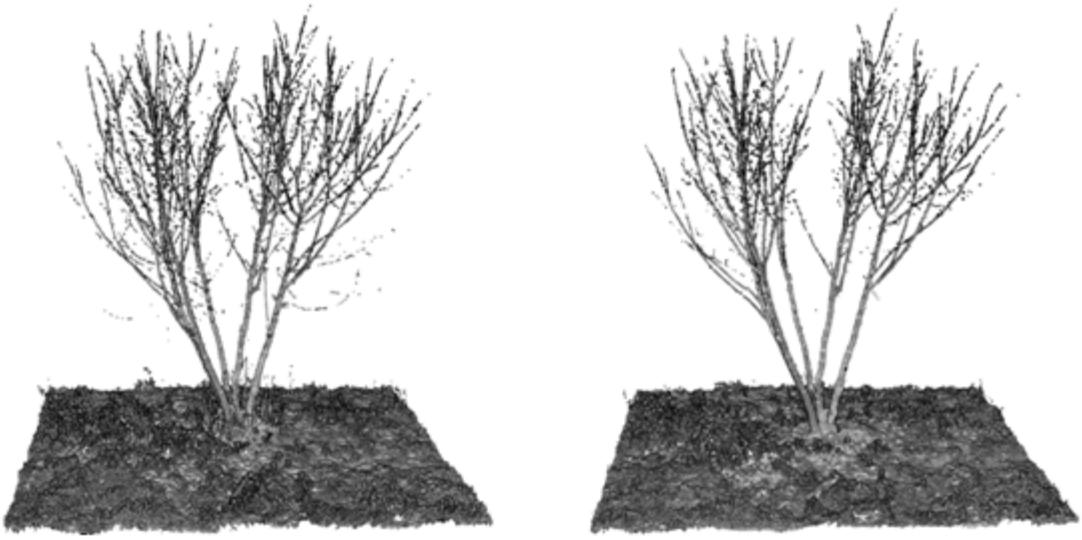

Figure 32 - 2D "cloud" reconstruction of the UGV data acquisition of the plant Yo C7 before (on left) and after (on right) manual pruning carried out in February 2020.

2.2 Ecophysiological response of plants and expected results

In order to evaluate the agronomic behavior of the plants trained with different shapes, the yield per plant and some eco-physiological measures were carried out over the two growing seasons starting from the first pruning application.

Table 7 and Table 8 report the removed wood with pruning applications and the yield of each plant of the trial in the growing season 2019 and 2020, respectively. These values are useful for the algorithm development as they show the real amount of pruned wood for every single plant.

ID Plant	**Pruned wood** (kg plant^{-1})	**Yield (in-shell nuts)** (kg plant^{-1})
Yo A1	1.30	0.071
Yo A2	1.85	0.074
Yo A3	2.20	0.463
Yo A4	2.11	0.236
Yo A5	2.97	0.389
Yo A6	3.41	0.673
Yo A7	6.22	0.489
Yo A8	1.23	0.123

Yo A9	0.95	0.171
Yo A10	1.21	0.132
Yo B1	5.17	0.230
Yo B2	5.09	0.062
Yo B3	4.22	0.130
Yo B4	6.79	0.142
Yo B5	4.27	0.161
Yo B6	7.16	0.167
Yo B7	5.28	0.072
Yo B8	5.98	0.137
Yo B9	5.35	0.110
Yo B10	6.45	0.167
Yo C1	0.25	0.046
Yo C2	0.69	0.310
Yo C3	0.74	0.845
Yo C4	0.50	0.582
Yo C5	0.74	0.448
Yo C6	0.45	0.080
Yo C7	0.56	0.267
Yo C8	0.41	0.343
Yo C9	0.65	0.798
Yo C10	1.12	0.867

Table 7 - Amount of pruned wood and in-shell nuts per plant obtained in the year 2019.

ID Plant	**Pruned wood** (kg plant^{-1})	**Yield (in-shell nuts)** (kg plant^{-1})
Yo A1	1.34	0.860
Yo A2	1.20	1.070

Yo A3	1.88	1.950
Yo A4	0.80	3.120
Yo A5	1.16	2.970
Yo A6	0.66	4.494
Yo A7	2.02	2.629
Yo A8	0.92	2.356
Yo A9	0.78	1.700
Yo A10	1.78	0.670
Yo B1	0.42	1.900
Yo B2	0.26	0.440
Yo B3	0.26	1.048
Yo B4	0.74	2.055
Yo B5	0.56	0.760
Yo B6	0.26	1.393
Yo B7	0.84	1.613
Yo B8	0.38	1.916
Yo B9	0.22	1.458
Yo B10	0.68	1.684
Yo C1	0.38	0.850
Yo C2	1.26	4.350
Yo C3	0.86	3.470
Yo C4	0.80	4.220
Yo C5	1.28	3.760
Yo C6	0.98	1.660
Yo C7	1.23	5.787
Yo C8	1.08	2.120
Yo C9	1.52	4.842
Yo C10	0.70	5.426

Table 8 - Amount of pruned wood and in-shell nuts per plant obtained in the year 2020.

Furthermore, Figure 33 and Figure 34 show the mean values of the removed wood and yield over the two years of investigation. These elaborations of the raw data are of high agronomic interest because very few trials are available in literature for comparing different training systems on hazelnut [4], [7].

Considering the wood removed annually (Figure 33), it is evident that in 2019 the pruning interventions were very intensive for treatment B (sapling-shape) because the plants not yet pruned were as bushes. Once the planned pruning protocol had been applied, in the second year the interventions were instead very light and aimed only at maintaining the plant shape.

The thesis C (multi-stemmed bush), as the most widespread plant shape currently used in hazelnut growing, showed the least amount of wood removed in two years, thus predisposing the plants to develop an excessively canopy, which will probably affect in the future the penetration of light into its inner portions, with possible negative effects on yield.

The average in-shell nuts production per plant was, as expected, higher in thesis C, subject to "rich" pruning, while thesis B was the most penalized, although it showed a significant yield recovery in the second year.

Considering the planting design of field 16, that is 4.5m x 3m for a total of 740 plants per hectare, the calculation of cumulative yield per hectare in the two-year period was 1.82, 1.15 and 3.00 tons of in-shell nuts per hectare in thesis A, B and C, respectively.

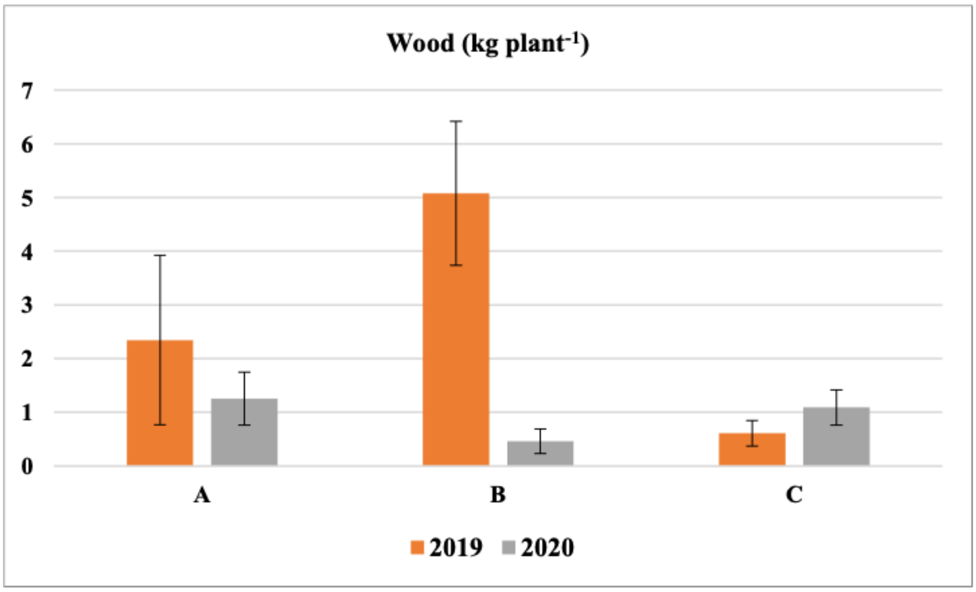

Figure 33 - Mean values of removed wood per plant over the two years of investigation.

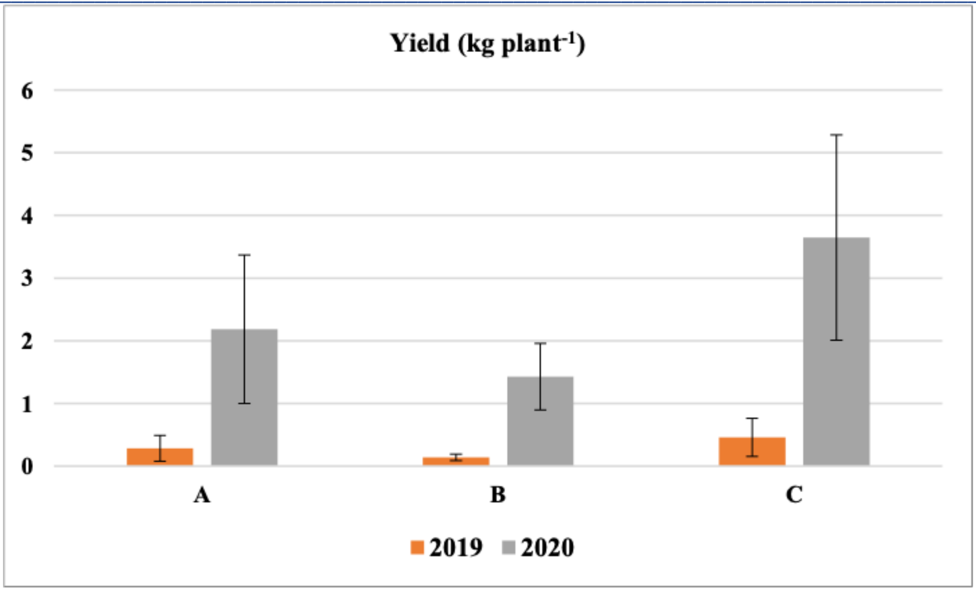

Figure 34 - Mean values of yield per plant over the two years of investigation.

Finally, for the completeness of investigation, during the growing seasons of the current trial, some eco-physiological parameters are also monitored, such as the chlorophyll content (Figure 35) and the NBI (Figure 36) of the leaves. These parameters, together with the other data acquired, will allow a full evaluation of the physiological response of the plants to the various pruning applications.

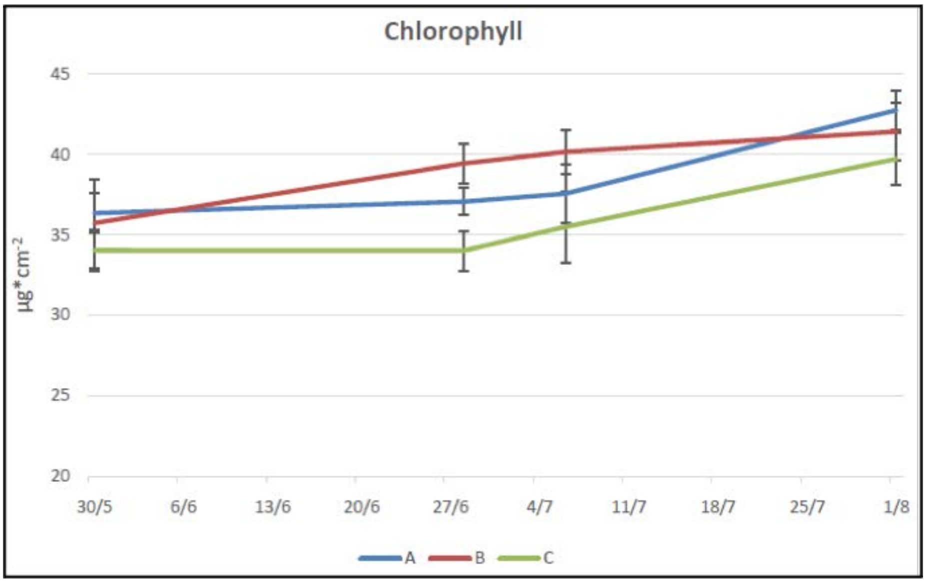

Figure 35 - Mean content of chlorophyll measured in the adult leaves of the pruned trees in the three different shape form (growing season 2020).

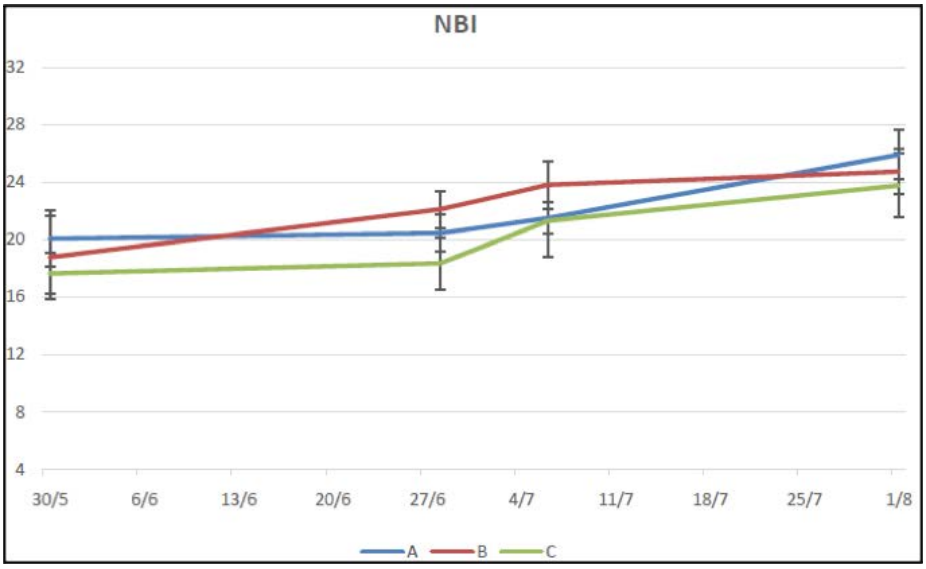

Figure 36 - Mean values of NBI measured in the adult leaves of the pruned trees in the three different shape form (growing season 2020).

These observations, to be continued also in the last year of activity, will help to guide growers and agronomists in the choices of plantation design and plant shape, in order to get new hazelnut orchards more suitable for PA applications.

3 Automated pruning protocol design

This section details the development of an automatic pruning protocol developed by the team of UNIROMA3 in collaboration with the team of UNITUS. The contents are organized as follows: section 3.1 details the development of virtually constructed hazelnut trees that have been used to check the correctness of the protocol; in section 3.2 the pruning protocol and its experimental validation are discussed; finally, in section 3.3 the outcomes of the protocol applied to the virtually reconstructed hazelnut trees of the orchard are presented. In the following the pruning protocol will also be referred to as pruning algorithm.

3.1 Agronomic and eco-physiological guidelines for the elaboration of the synthetic tree

The teams of UNIROMA3 and UNITUS decided to develop together a systematic way to build virtual models of hazelnut trees to facilitate the prototyping and numerical validation of the proposed algorithm. The planning and subsequent generation of the "synthetic tree - case 0", i.e., the first virtually generated tree model, was carried out through a constant interaction between the researchers of the two teams (UNITUS and UNIROMA3), to reconstruct a virtual three-dimensional structure as representative as possible of the bush growth system typical of the hazelnut tree.

Through a series of videoconference meetings aimed to share the model's progress states, the researchers of UNITUS (horticulturists) guided the researchers of UNIROMA3 (engineers) in understanding the vegetative habitus and growth system of hazelnut trees, in determining the frequency of the insertion angles of the main branches on the main trunks according to the multi-stemmed bush shape, and in reconstructing the representative plant architecture. During the building phase of the synthetic tree, for operational reasons, it was decided to omit, from the construction, the small size shoots, which are normally removed during the cutting of the branches of more than one year of age. In fact, the small size shoots are the most relevant portion of wood that is removed during pruning operations, both to maintain the plant shape and to promote the light penetration into the inner portion of the crown [14].

3.1.1 Synthetic tree generation

The software that generates the synthetic tree models has been developed in Python, starting from a base version developed by the TRIER team. The software consists of functionalities that randomly replicate the behaviour of a tree, such as generating seeds of the plant, generating buds, and growing. In particular, the following functionalities are included:

- Seed function that randomly generates a certain number of seeds with different length and radius from which new suckers are developed;
- Growth function that increases the radii of the current branches and the length of the current leaves of the tree. If the updated branches are too long, each overextended branch is split in two different bended segments;
- Bud function that randomly generates buds from which new branches sprout.

The software includes the possibility to model both natural hazelnut trees, i.e., trees that are not managed by any farmer and can hence have many suckers, and controlled hazelnut trees, i.e., trees that are managed and pruned regularly.

3.1.2 Experts feedback

Once the "synthetic tree - case 0" was obtained and validated by the UNITUS team as representative of the hazelnut tree architecture, it was decided to submit it to the attention of several experts in hazelnut cultivation, to get their opinion on the fidelity reconstruction of the synthetic tree.

In the following it is reported the query proposed to the researchers and agronomists involved in the hazelnut chain, to get their impression about the fidelity of reconstruction of the synthetic tree, in the early stages of the algorithm development.

> "Dear Colleague, dear Friend,
>
> within the PANTHEON project (H2020, grant n. 774571), we are developing an algorithm that will manage the pruning of hazelnut trees.
>
> The first phase of this work involves the realization of a 3D structure that reliably simulates the architecture of the hazelnut tree, at least in its primary structure.
>
> Before proceeding with the next steps, we would like to receive your feedback on the reliability of the 3D reconstruction.
>
> We attach a series of random reconstruction files of the plants, displayed in 2D image mode and realized by algorithms, flanked by real images to be used as a control.
>
> Do you think that this reconstruction can be reliable to represent the hazelnut tree grown at multi-stemmed bush?
>
> Thank you in advance for your feedback.
>
> Best Regards
>
> The Pantheon Team"

In Table 9 the most relevant answers are summarized. Figure 37 represents an example of the images sent to the interviewed so that they could judge the fidelity of the reconstruction of the hazelnut synthetic tree.

Expert interviewed	**Answer**	**Institution**
Dr. Merce Rovira	Firsts of all, thank you for sharing your project and ideas. I'm surprised about how you can "construct" a tree from algorithms! In my opinion the pictures show that the reconstruction is reliable to	IRTA - Institute of Agrifood Research and Technology (Spain)

	represent a hazelnut tree. Although, more than a multi-stemmed bush, for me is a tree with few stems (4-5). As you know, hazelnut trees grown in Spain are a multi- stemmed bush, different from your real pictures.	
Dr. Miguel Ellena	I congratulate you for your interesting project with an important contribution to the research in this species. Like Mercé I'm very surprised about how you can construct a tree from algorithms. In Chile multi-axis training systems (3 -5 axes) are similar from your real pictures. However, the future trend will be the single axis system, particularly with the use of rootstocks without suckers.	INIA - Instituto de Investigaciones Agropecuarias - Ministerio de Agricoltura (Chile)
Dr. David C. Smith	What a fascinating concept! I would say that the algorithms are doing a reasonably good simulation of primary branch structure. Will the next effort be to simulate higher order branching, where fruit production occurs, or to relate 1st order branching to productivity? I look forward to seeing more of your project in the future!	Department of Horticulture, Oregon State University, 4017 Ag and Life Sciences Building, Corvallis, OR 97331 (USA)
Dr. Gianluca Grisieri	I believe that the proposed reconstruction of the multi-stemmed system is substantially correct. Will the same work be done on the single-trunk system?	www.nocciolservice.com Nocciolo Service. Local extension service. Piedmont (Italy)
Dr. Giacomo Santinelli	I find the 2D reproductions very accurate and conform to the real morphology of the plant.	ASSOFRUTTI.SRL - Technical assistance. Viterbo (Italy)
Dr. Gianluca Santinelli	I think the work is very interesting and analysing in detail the 3D reconstruction I think the constituent parts of the hazelnut bush are well represented. I would just have a small note to make in the last 3D image represented, where the lower branches have in my opinion a too wide angle of inclination compared to the classic one that our varieties usually have.	C.P.N. – Cooperativa Produttori Nocciole. Ronciglione, Viterbo Province (Italy)

	For the rest I would say that the work is excellent.	

Table 9 - Summary of the main answers obtained during the interview on the reconstruction of the synthetic tree.

Figure 37 - An example of images sent to the interviewed for the comparison of the synthetic tree with a real multi-stemmed bush of hazelnut.

After the opinions of the interviewed experts have been collected and positively acknowledged, the two teams decided to proceed with the development of the pruning protocol, which will be detailed in the following section.

3.2 Pruning protocol

The automatic pruning protocol has been developed in MATLAB, a numerical computing software developed by MathWorks that allows to manipulate matrices, import and visualize data, and implement algorithms in the homonym programming language, among many things. The development of the proposed protocol consisted of four phases:

1. Gathering of pruning guidelines from a set of agronomical experts;
2. Development and implementation of a mathematical model able to represent the hazelnut trees in MATLAB;
3. Implementation on the tree model of the pruning guidelines suggested by the agronomical experts;
4. Validation of the protocol on a set of 1000 synthetic trees.

3.2.1 Graph theory

The natural way to represent a tree in a schematic model is through the usage of lines and dots that represent the branches and the forks of a tree. The mathematical tool that easily fits such graphical representation is the theory of graphs. A graph is an ordered pair $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ composed of a set $\mathcal{V}$ of vertices, also referred to as nodes, and a set of edges $\mathcal{E}$ such that $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$, i.e., the edge set is composed of elements that are pairs of vertices. The elements of the vertices set $\mathcal{V}$ are usually denoted as $\mathcal{V} = \{ v_1, \dots, v_n\}$ or $\mathcal{V} = \{ 1, \dots, n\}$ where n is the total number of vertices in the graph, whereas the elements of the edge set $\mathcal{E}$ are usually denoted as $e_{ij} = (i, j)$ with $i, j \in \mathcal{V}$ representing a link between the i-th and j-th vertices. If the links can be travelled in both directions the graph is said undirected, otherwise it is said directed. As hinted above, a graph can be represented by drawing a dot for each vertex and a line for every edge that exists between two dots. The line possesses a single tip if the edge is directed and has none (or two) if the edge is undirected. Figure 38 depicts two small graphs $\mathcal{G}$ with $n = 5$ vertices $\mathcal{V} = \{1, 2, 3, 4, 5\}$. The first one is a directed graph on edge set $\mathcal{E}_d = \{(1,2), (1,3), (2,4), (2,5)\}$ (Figure 38.a) whereas the second one is an undirected graph on edge set $\mathcal{E}_u = \{(1,2), (1,3), (1,5), (2,1), (2,3), (3,1), (3,2), (3,4), \dots,$ $\dots, (3,5), (4,3), (4,5), (5,1), (5,3), (5,4)\}$ (Figure 38.b).

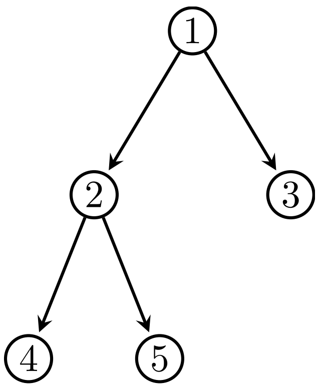

Figure 38.a - A directed graph on 5 nodes.

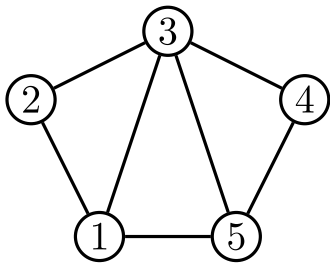

Figure 38.b - An undirected graph on 5 nodes.

Figure 38 - Example of directed and undirected graphs.

From Figure 38 some notions on graphs can be grasped: two vertices i and j are said adjacent, or neighbors, if there exists the edge e_{ij} connecting them. Moreover, the vertices i and j are said the endnodes of the incident edge e_{ij}. The degree of a vertex is the number of its adjacent vertices, e.g., in the example depicted in Figure 38.b vertex 1 has degree equal to 3 because it is adjacent to three vertices, i.e., nodes $\{2, 3, 5\}$. Another graph notion that can be noticed in the above example is the path that consecutive vertices and edges made up to connect different vertices in the graph. Formally, a path $P = \{v_0, v_1, \dots, v_m\}$ is a sequence of vertices joined by edges that link two vertices in the graph. A path is said directed if it can be travelled only in one direction, e.g., as in Figure 38.a, or undirected if it can be travelled in both directions, e.g., as in Figure 38.b. A path is called cycle, or loop, if it starts and ends at the same vertex, e.g., $P_c = \{1,2,3,1\}$ in Figure 38.b. An undirected graph is said connected if there exists an undirected path between each pair of vertices; a directed graph is said strongly connected if there exists a directed path from any node to any other node, whereas it is said weakly connected if it is connected considering the paths as undirected, i.e., ignoring the directions of the edges.

A particular kind of graph that is connected and does not have any cycles is called tree. The vertices of degree 1 in a tree are said leaves. A connected graph on n vertices is a tree if and only if it has exactly $n - 1$

edges. The directed graph considered in Figure 38.a is indeed a tree. The vertex from where the other vertices descend is called root, e.g., node 1. Following the descending structure of the tree, a vertex j that follows a vertex i is called children, whereas node i is called father. Two nodes that have the same father are called brothers. All the vertices (children) encountered while exploring all the paths starting from a vertex i and reaching the possible leaves of the tree, are called descendant of i. For example, in Figure 38.a vertex 2 is father of the vertices $\{4, 5\}$, whereas vertex 3 is children of the root 1. The vertices $\{2, 3\}$ and $\{4, 5\}$ are brothers. In this case vertices $\{3, 4, 5\}$ are also the leaves of the tree since they have no descendants (they have degree equal to 1). The nodes $\{2, 3, 4, 5\}$ are all said descendants of vertex 1.

In virtue of what has been explained until now, hazelnut trees will be modelled as directed graph trees. The graph will have a growing topological structure, with the root located at the bottom of the plant and the leaves at the top. The vertices of the graph will model the leaves and the forks of the hazelnut tree, whereas the branches will naturally be modelled by the edges of the graph.

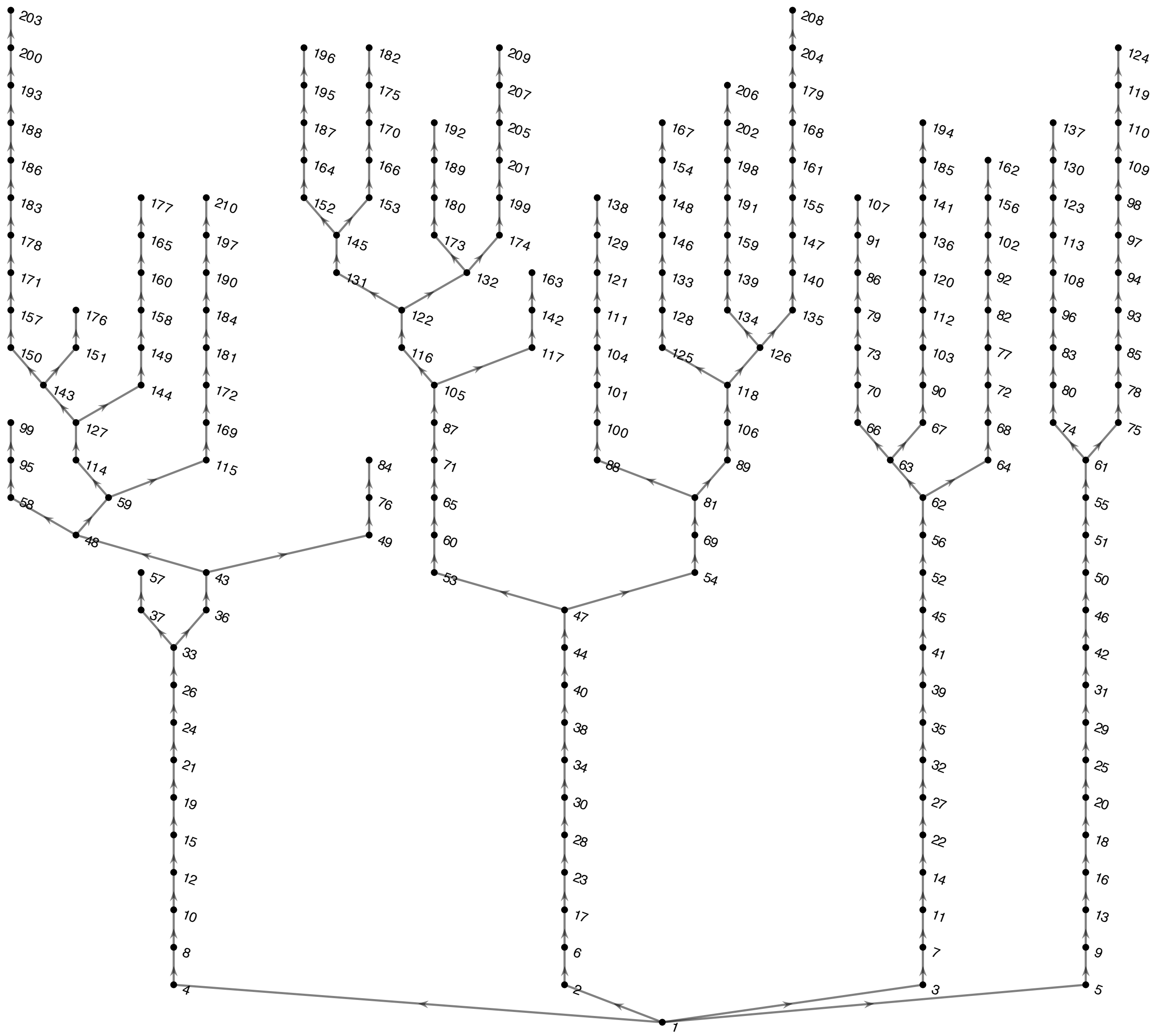

Figure 39 - Tree graph structure of a virtually reconstructed hazelnut plant.

Figure 39 depicts the tree graph structure of the A3 plant virtually reconstructed. Note that each vertex, here labelled with an integer number, possesses physical attributes such as position and radius that in this case have not been used to create the graphical representation. This physical information, along with the adjacent relationship of the nodes, are the basic elements that enable the methods utilized by the pruning algorithm.

3.2.2 Pruning guidelines

In order to correctly prune the hazelnut tree, the UNITUS team provided the UNIROMA3 team with different pruning guidelines, gathered from the opinion of a set of researchers and agronomic experts. The guidelines are the following:

1. The hazelnut tree can have up to a maximum number of main branches from which it can grow (depending on the shape of the plant);
2. Completely vertical or horizontal branches are not desired;
3. Branches oriented towards the centre of the hazelnut are not desired;
4. Branches that may obstruct the movements of the ground robots and tractors are not desired;
5. Short branches in the low-central area of the plant are not desired;
6. Pair of branches growing closely to each other are not desired;
7. Pair of high-altitude branches growing from the same fork should have similar length.

In the next section the working principles of the algorithm will be detailed.

3.2.3 Protocol description

The pruning protocol takes as input a .gexf file that details the graph topological structure of the tree that needs to be pruned and returns the IDs of the vertices and edges (branches) selected for pruning.

The .gexf file can be generated from virtually constructed trees, namely the synthetic trees, or from virtual reconstruction of the real hazelnut trees present in the orchard. For details of the virtual reconstruction the reader is referred to [15].

As explained above, each node is associated to a global position and a radius. The global position is expressed in meters in a UTM coordinate system, whereas the radius is expressed in meters. For easiness of work, the coordinates are translated with respect to the position of the root, i.e., the position of the root is subtracted to the coordinates of all other nodes so that the tree is actually centred with respect to the root system that is considered as the origin of the coordinate system.

The protocol is structured in the following logical steps:

- Setup phase in which the data is loaded, and the information is stored;
- First procedure used to compute the forks and the leaves of the tree along with their paths starting from the root;
- Second procedure that allows the algorithm to obtain for each edge additional information such as vertical orientation, number of descendants associated to the node from which the edge is leaving, and direction of the edge with respect to the centre of the tree (i.e., if the branch is directed towards the centre of the tree or outwards);
- Implementation of the selection pruning criteria listed in the pruning guidelines introduced in 3.2.2;
- Visualization of the output of the algorithm and computation of the potential biomass associated to the selected pruned branches.

In detail, the graph structure data is loaded with the help of the Python library NetworkX. For easiness of work the IDs of the vertices of the tree are first relabelled. Then, utilizing the adjacency information of the graph, the paths towards the leaves of the tree are computed. In doing so, the algorithm is able to establish the vertices associated to a fork in the hazelnut tree, i.e., vertices that have more than one child. Moreover, for each node j and consequently for each edge (i, j) from where node j is originated, the angle with respect to the vertical Z axis, the orientation with respect to the centre of the tree, and the number of descendants is computed. At this point the algorithm is ready to check the pruning guidelines introduced before.

The first selection made by the algorithm concerns the number of main branches from which the majority of the nodes grows. To this end, the algorithm determines the children of the root; if the children are more than a certain threshold, the algorithm selects the nodes that have fewer descendants and adds them (along with their descendants) to the list of pruned nodes. Every time a set of nodes is added to the list of pruned nodes, the structure of the graph is immediately updated, and the selected nodes (and edges) are removed in order to reduce the computational cost of the algorithm. Figure 40 depicts an example of a tree in which four suckers, highlighted in red, have been selected for pruning.

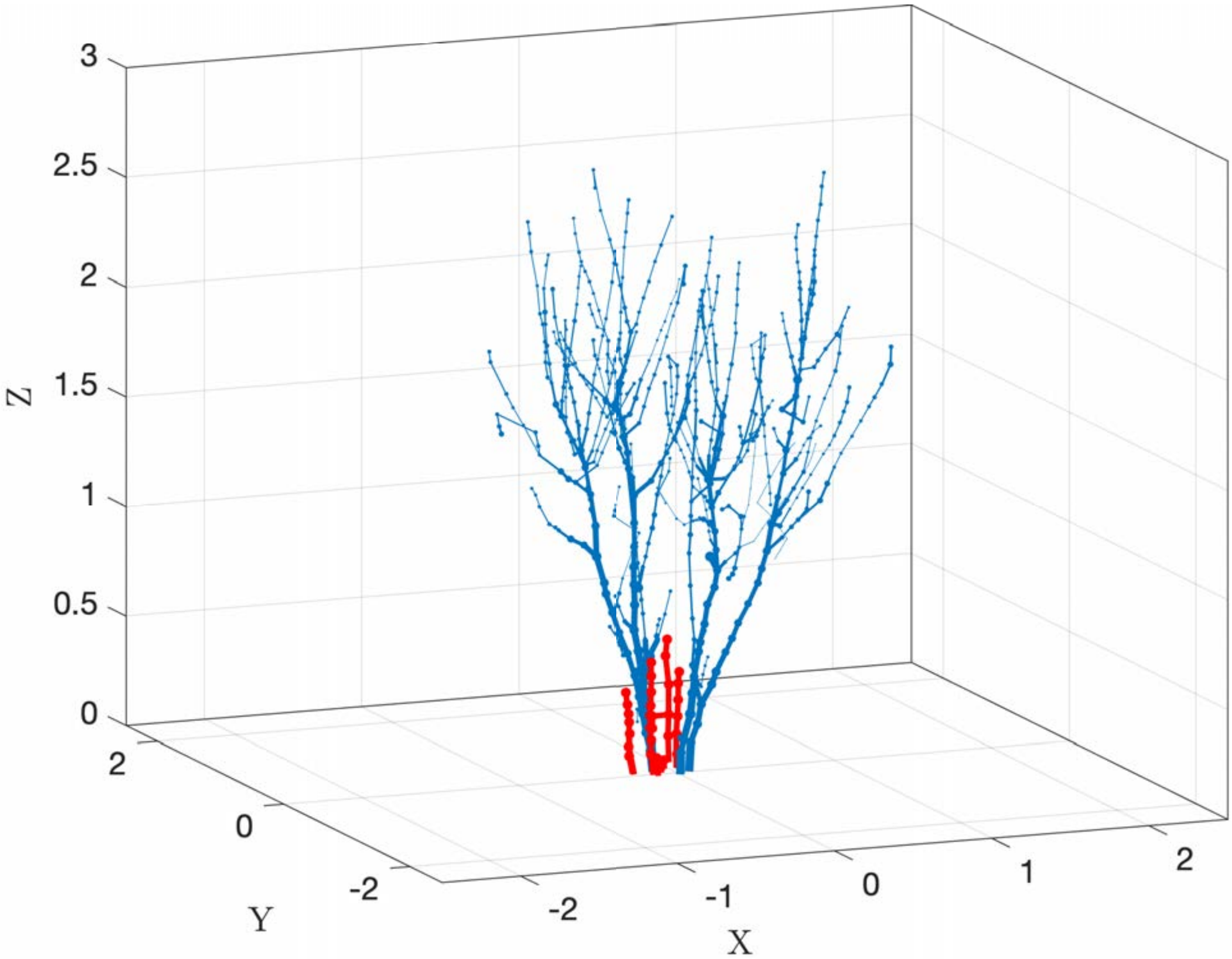

Figure 40 - Selection of excessive suckers at the base of the tree.

The second selection made by the algorithm concerns vertical and horizontal nodes. In detail, the algorithm considers as potential nodes to be pruned vertices that possess an angle with respect to the Z axis close to $k\frac{\pi}{2}$ with $k \in \mathbb{Z}$. Figure 41 depicts an example where the vertical nodes have been highlighted in red, whereas the horizontal ones are highlighted in magenta. Note that the descendants of the two selected nodes are selected as well with the same colour as their parents.

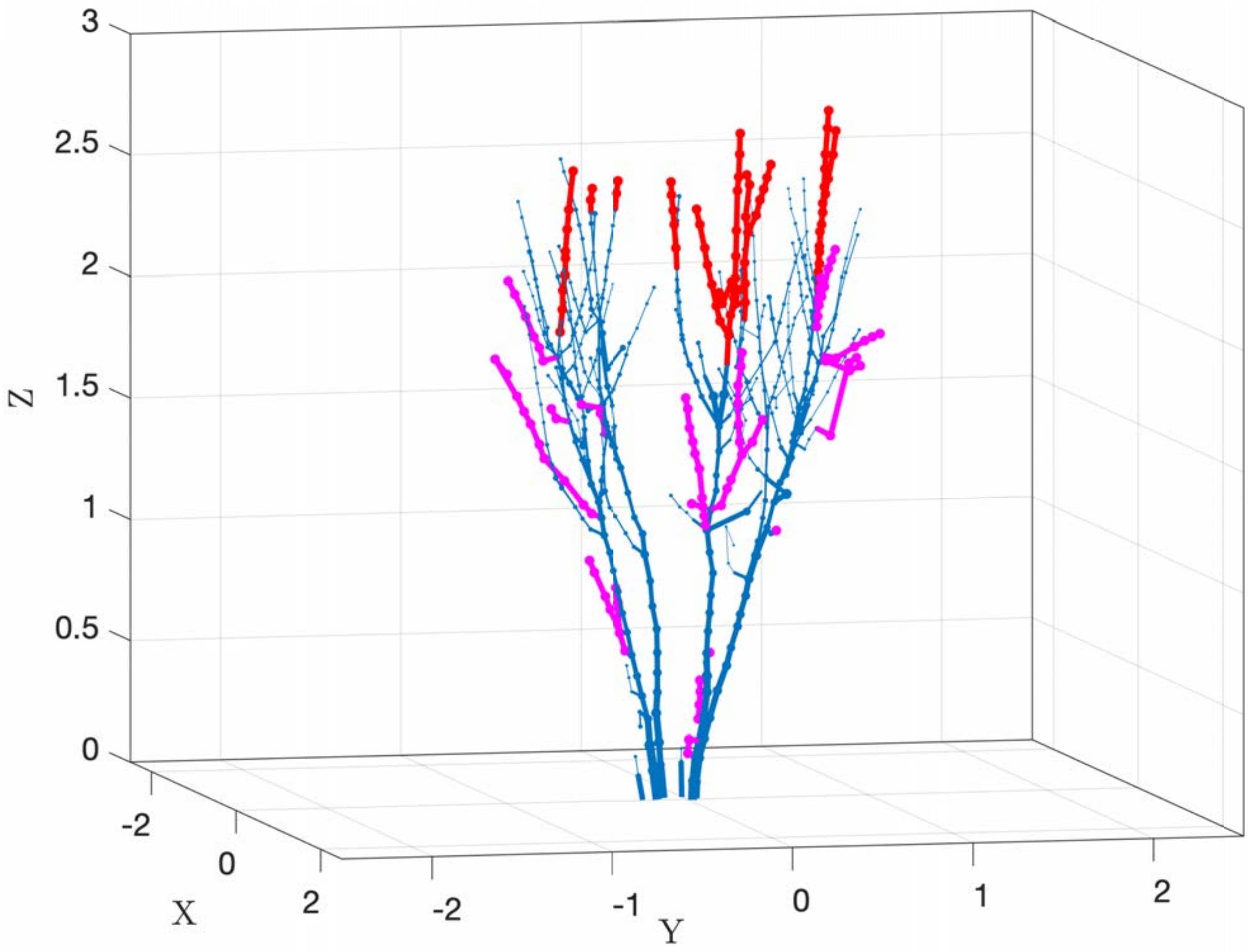

Figure 41 - Selection of vertical and horizontal nodes.

The third selection made by the algorithm regards leaves and branches that grow towards the interior of the plant rather than towards the exterior. In this case, using the information on the orientation of the branches previously elaborated, the algorithm selects the branches above a certain altitude that are directed towards the interior of the tree and that can cause obstruction to the growth of other branches. Figure 42 depicts a selection of such nodes, highlighted in red colour.

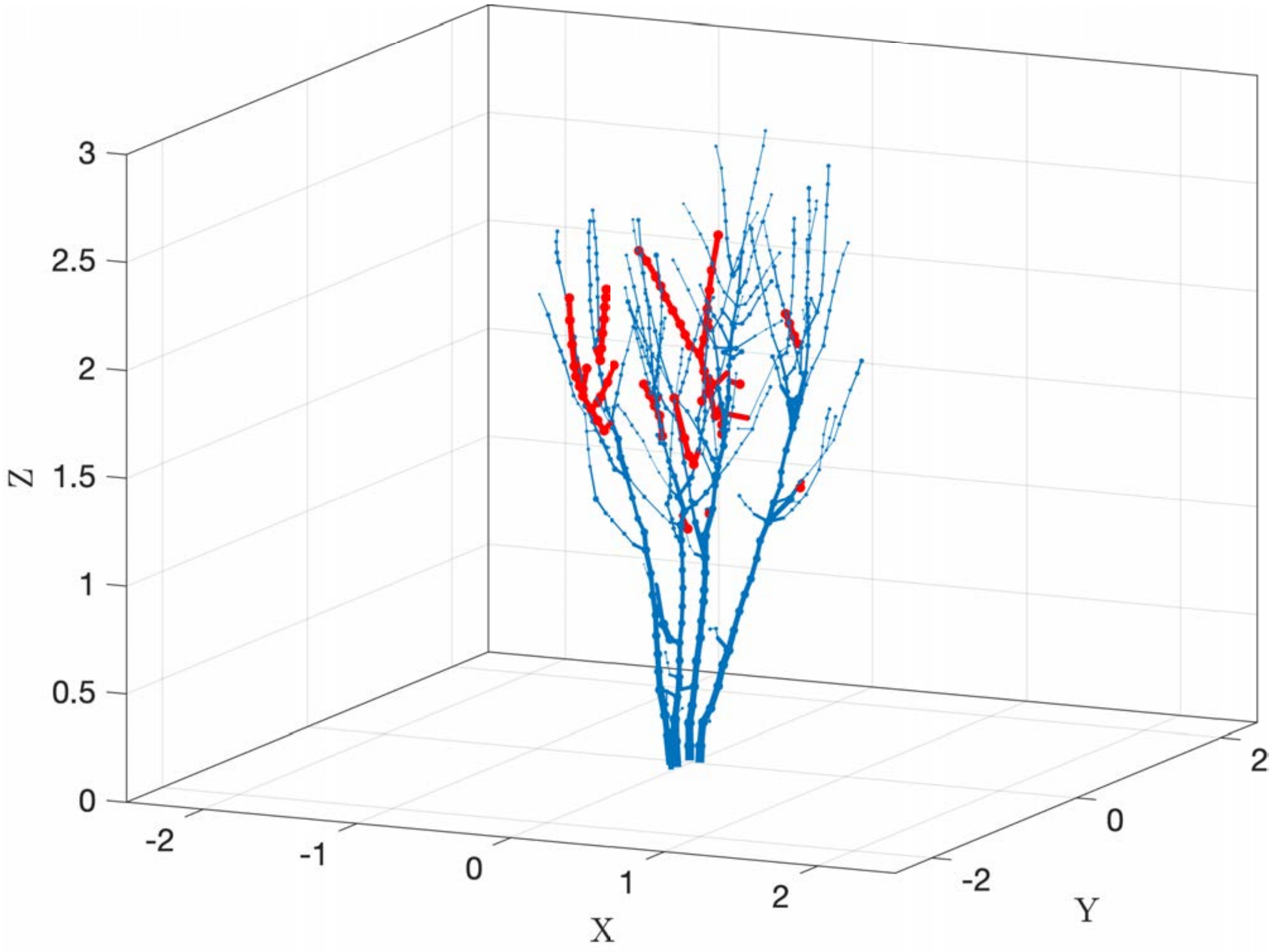

Figure 42 - Selection of nodes oriented towards the interior of the tree.

Since there could exists branches at certain altitude and with certain extension towards the exterior of the tree that could obstruct the movements of the ground robots in the orchard, a fourth selection criteria able to individuate such branches has been added. In detail, the algorithm can virtually construct a truncated three-dimensional cone around the tree and select for pruning all the nodes that are out of the cone, representing branches that could be a hazard for the robots. Figure 43 illustrates an example of this scenario, where the outside branches have been selected for pruning.

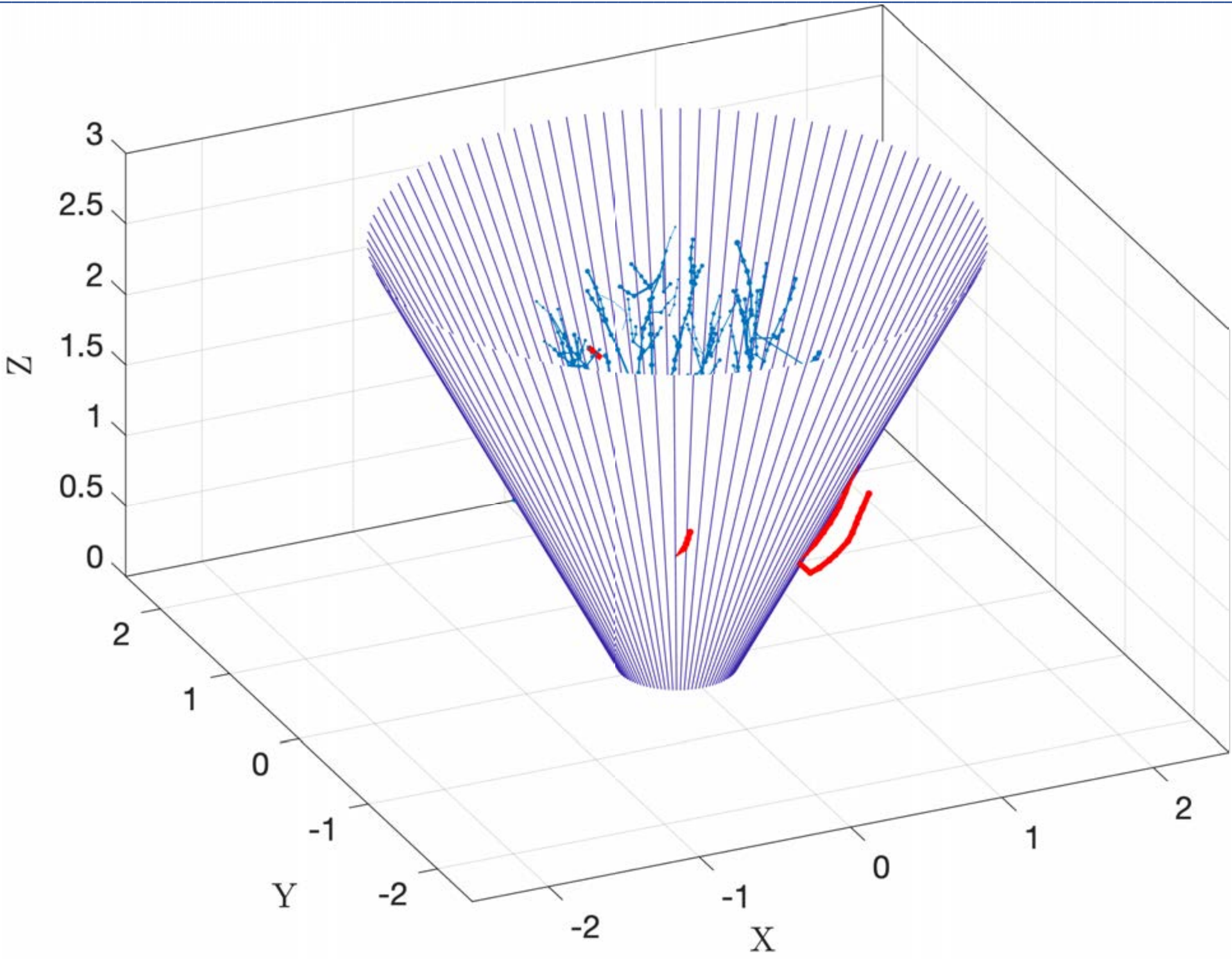

Figure 43 - Selection of nodes that are not inside a virtual truncated cone.

This selection, other than removing the potential obstacles to the movements of the ground robots, helps the tree to grow in a symmetrical structure, since all the branches and leaves are constrained to grow inside a virtual symmetrical figure. Note also that the virtual geometrical constraining figure could be chosen and sized differently according to the needs of the plant shape or the orchard design, e.g., cone with ellipsoidal base or cylinders with different dimensions could be implemented as well.

The fifth criterion implemented by the algorithm concerns the removal of medium-short branches that are located in the lower half of the tree. In detail, as first step leaves located below the centroid of the tree are individuated. Then, the paths starting from the selected leaves are checked backwards going towards the root until a first fork is met. The nodes between the leaf and the fork are then selected for pruning. This procedure is iterated until no more leaves that fit this criterion are found. Figure 44 depicts a selection that fits this criterion. Note that suckers at the base of the tree are also individuated. However, this selection is fundamentally different from the criterion introduced above aimed to select the main branches of the tree since this one is uncapable of selecting nodes that lie in the upper half of the tree.

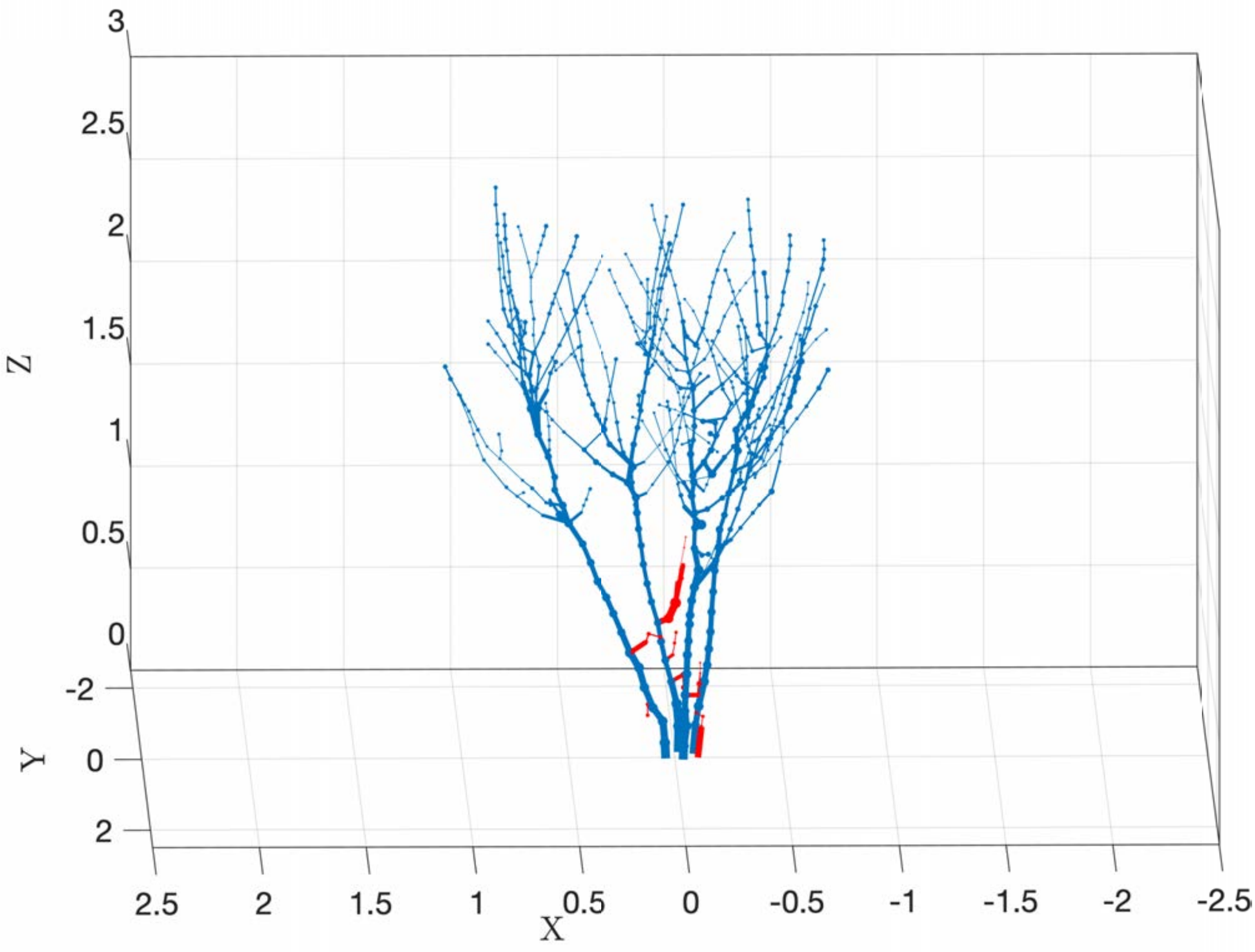

Figure 44 - Selection of short branches in the lower half of the tree.

The sixth selection criteria performed by the algorithm deals with branches that are growing close to each other or are colliding with each other. First, the algorithm checks the paths of every leaf of the tree and adds, to a temporary list, pairs of nodes of different paths that are spatially close to each other. Then the algorithm selects among such pairs of nodes the vertices that are more reasonable to prune, according to the following parameters: i) if one of the two nodes of the pair is a descendant of the other; ii) if one of the two nodes is a leaf; iii) if one node has more descendants of the other; iv) if one node has more descendants that can cause collision problem than the other; and finally, v) if one node is more higher than the other in the tree. Figure 45 depicts an example where nodes closer than 15 cm were considered candidates for pruning. The nodes highlighted in red are the ones among the possible candidates that have been then selected for pruning.

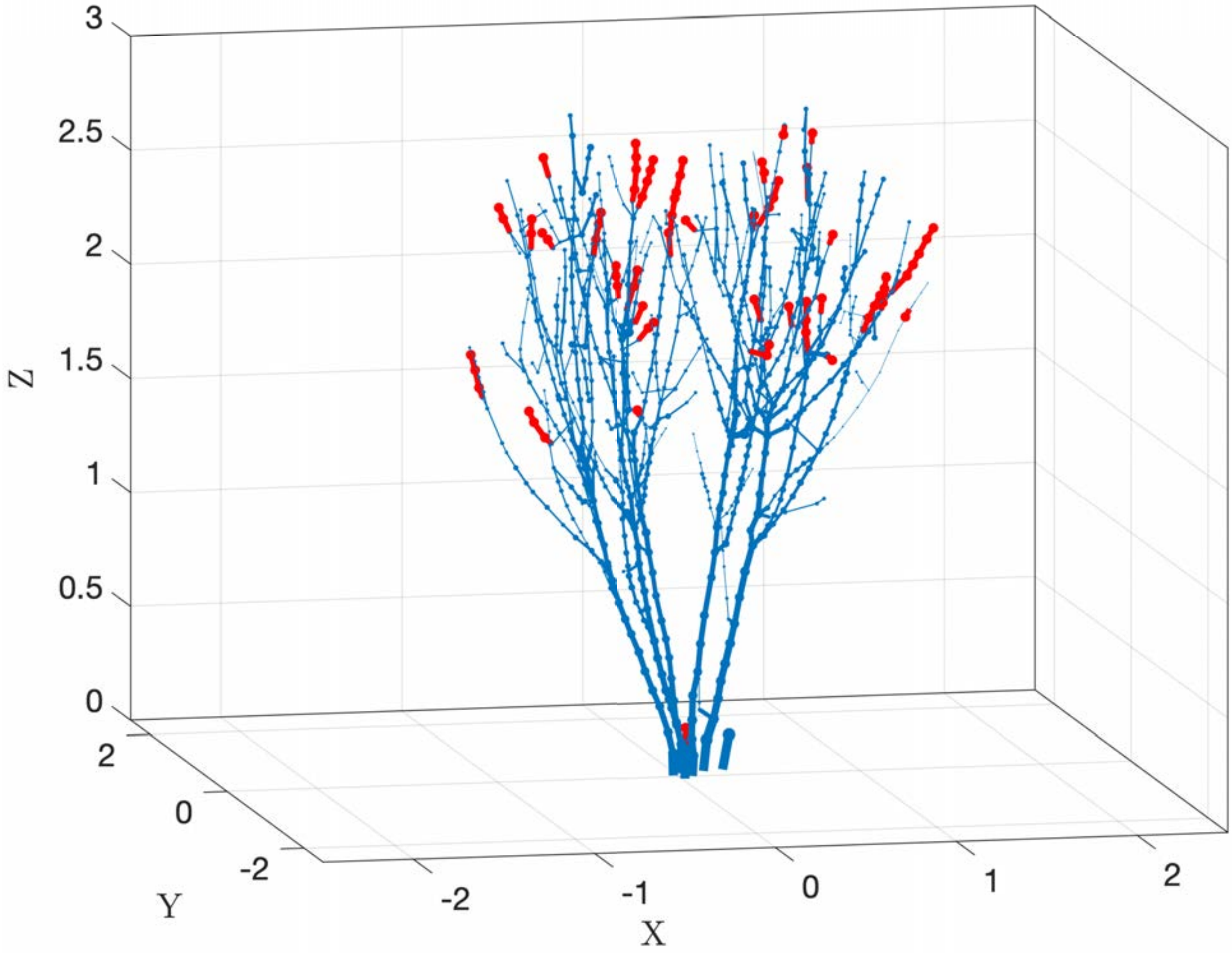

Figure 45 - Selection of potentially colliding nodes.

The last selection made by the algorithm concerns all the nodes that compose the branches that have as second endnode the leaves. In particular, the algorithm checks if branches of this kind that originate from the same father have similar length, otherwise part of the branch is removed. Figure 46 depicts an example where branches originating from the same father and with a difference in length greater than 40 cm have been selected for adjustment.

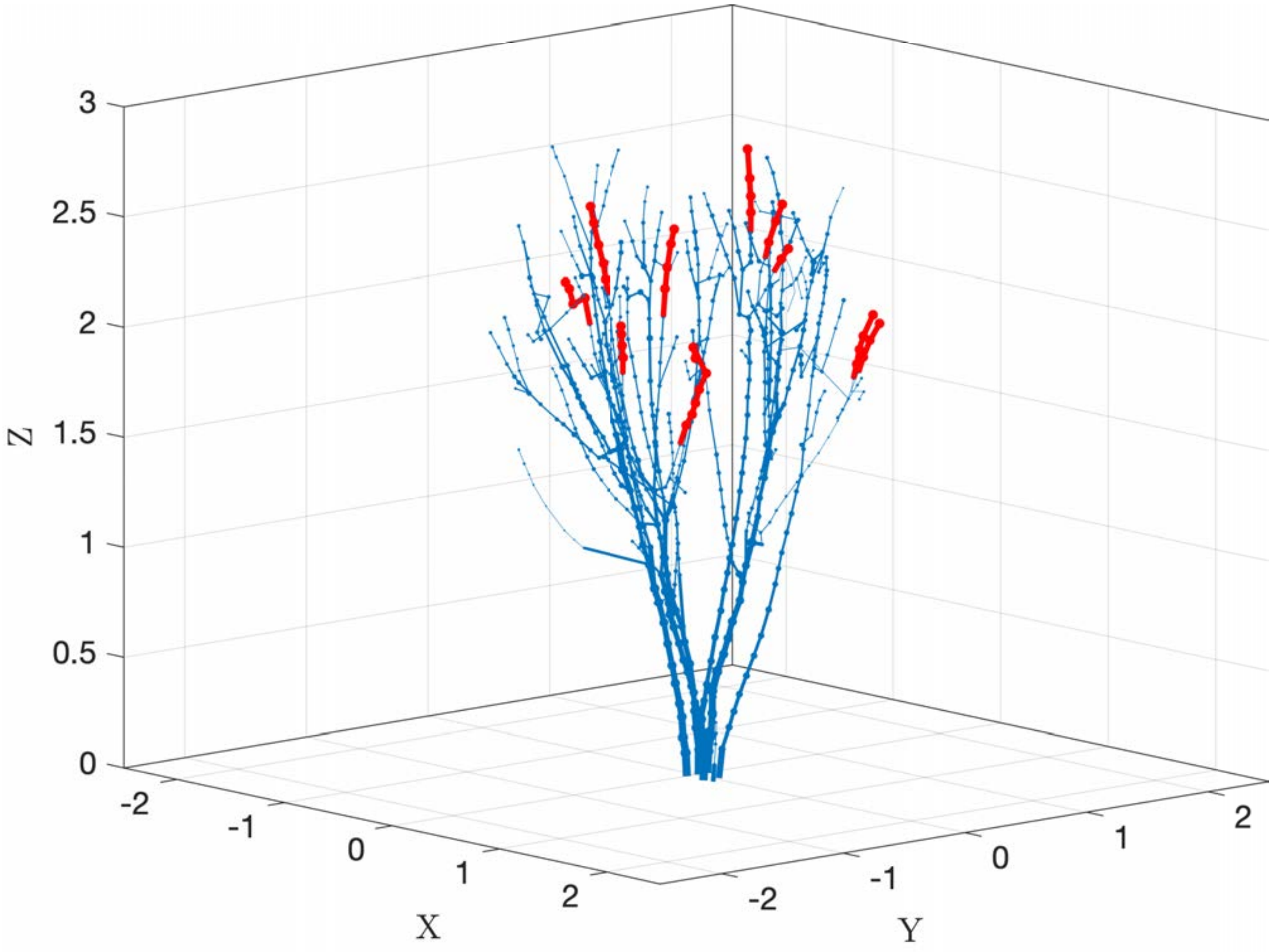

Figure 46 - Selection of pruned nodes to enhance the balance on the branches of the leaves of the tree.

Finally, the algorithm returns the IDs of the vertices that have been removed and provide a graphical comparison between the original tree in which the nodes and edges selected for pruning have been highlighted in red and the pruned tree where these edges have been removed, as shown in Figure 47 and Figure 48.

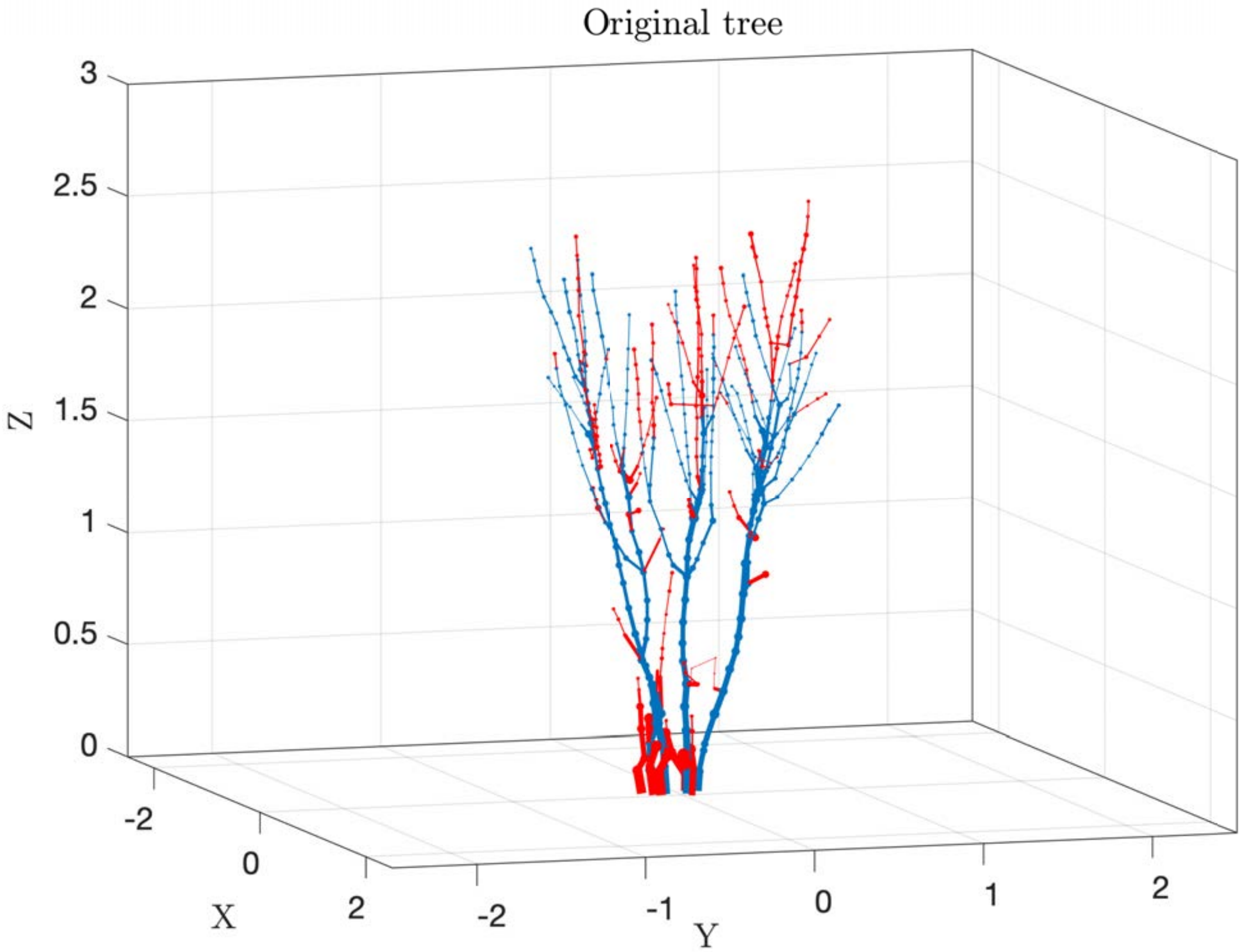

Figure 47 - Outcome of the pruning algorithm.

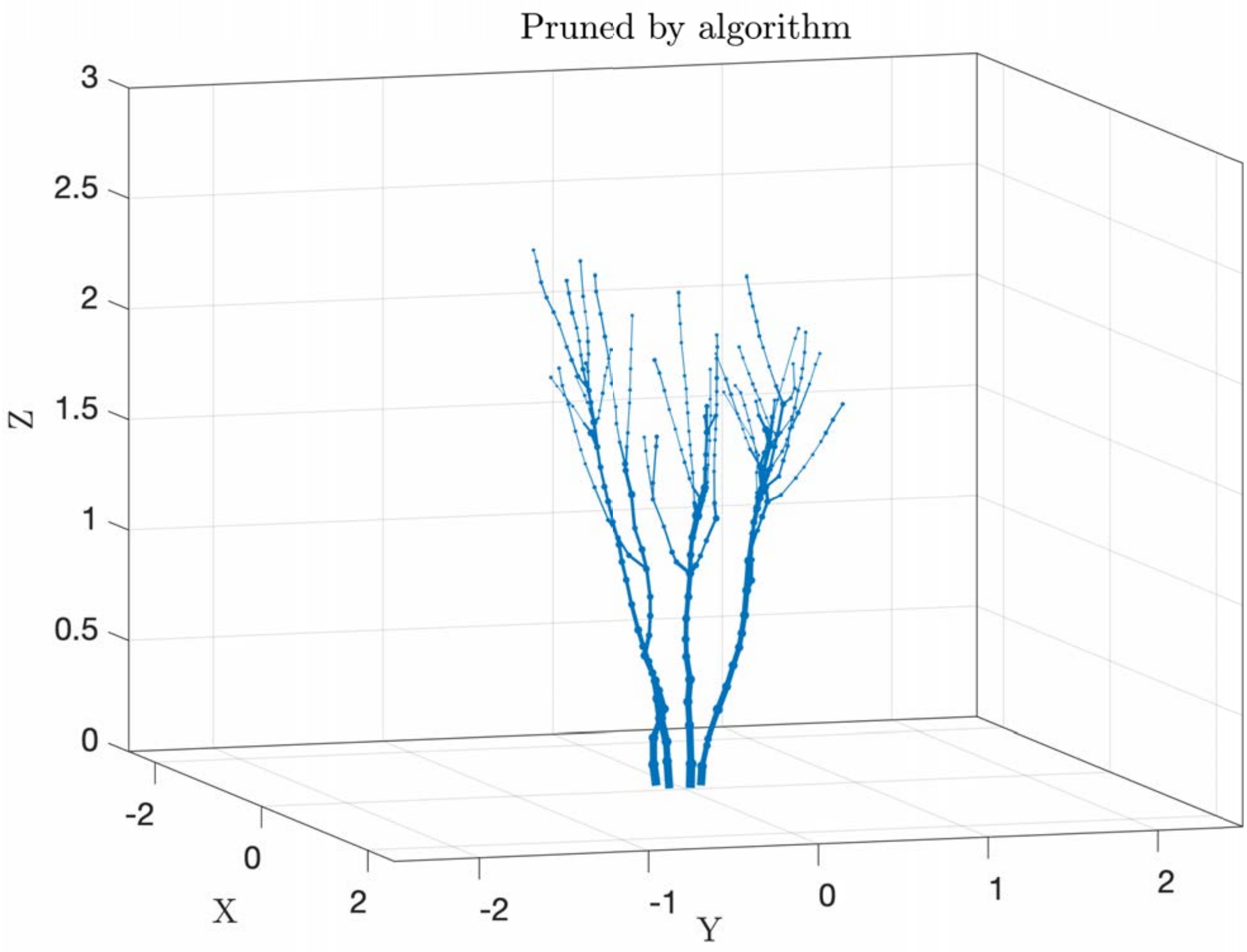

Figure 48 - Tree pruned according to the suggestions illustrated in Figure 47.

An estimation of the amount of pruned wood can be computed using the following equation

$$Pruned\ wood = Volume\ \times\ Density \qquad \text{Eq. 1}$$

where the volume of the branches can be approximated as the sum of volumes of cylinder with radius and altitude equal to the mean radius and distance of the two endnodes of the branch, and for the volumetric mass wood density the value of 650 kg/m^3 is used following the results of [6].

To conclude, all the parameters that describe the criteria selection methods implemented by the algorithm such as the maximum number of main branches, the vertical angles allowed, etc., can be edited in order to encode different types of tree structures and/or pruning methodologies.

3.2.4 Experimental validation

In order to validate the functionalities of the developed pruning algorithm, UNIROMA3 researchers generated 1000 synthetic hazelnut trees and asked UNITUS researchers to conduct a virtual pruning of branches and shoots, through a properly designed software able to highlight the portion of wood to be cut. 51

The designed software has been developed in C++ utilizing the library OlcPixelGameEngine. It provides a three-dimensional view of the tree with access to tools for both rotating the tree along its vertical axis and zooming into the image to increase the visibility of the branches. When the cursor of the user is hovering over a certain branch, the nodes of that branch and their descendants are highlighted with a white box on the image and their IDs are displayed on screen. The user can then click on the branch to add the displayed IDs to a .txt files containing the IDs of all pruned nodes.

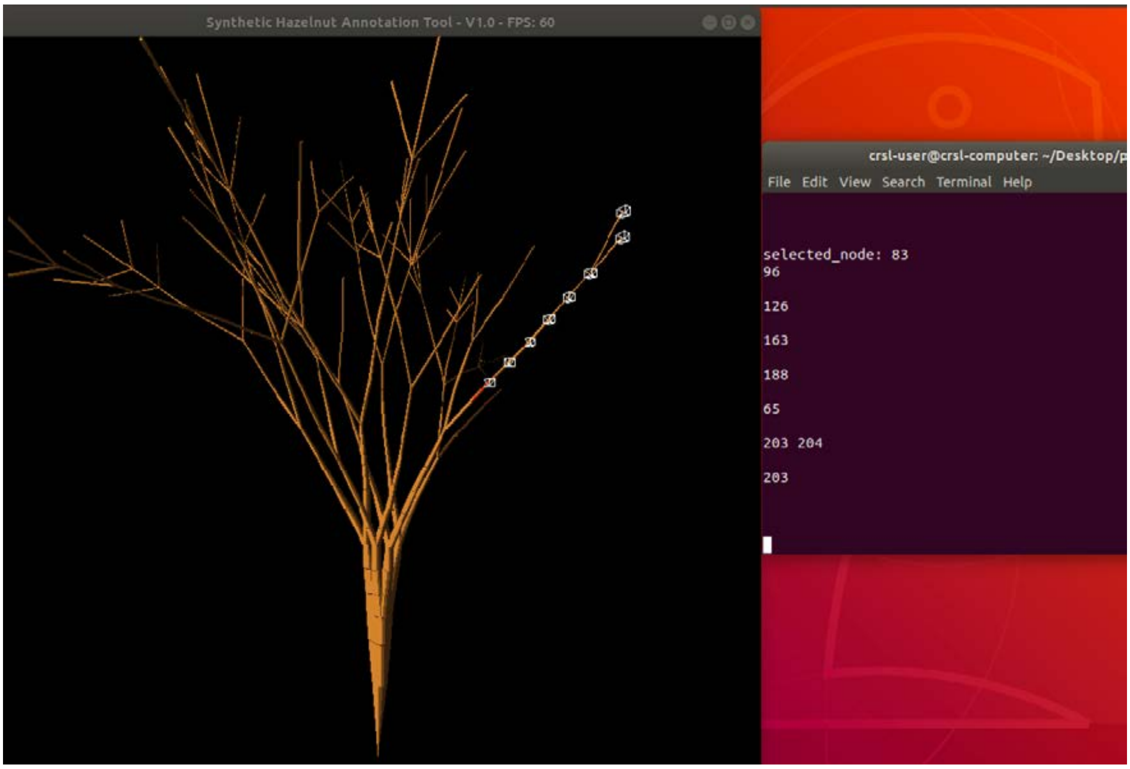

Figure 49 - Virtual pruning software interface.

Figure 49 depicts the user’s interface with a set of nodes highlighted both on screen and on the image.

The treatment of each case took about 3-5 minutes, including general observation of the tree and reporting of the cuts. Once all 1000 cases were pruned, the UNIROMA3 team was able to assert the correctness of the developed algorithm.

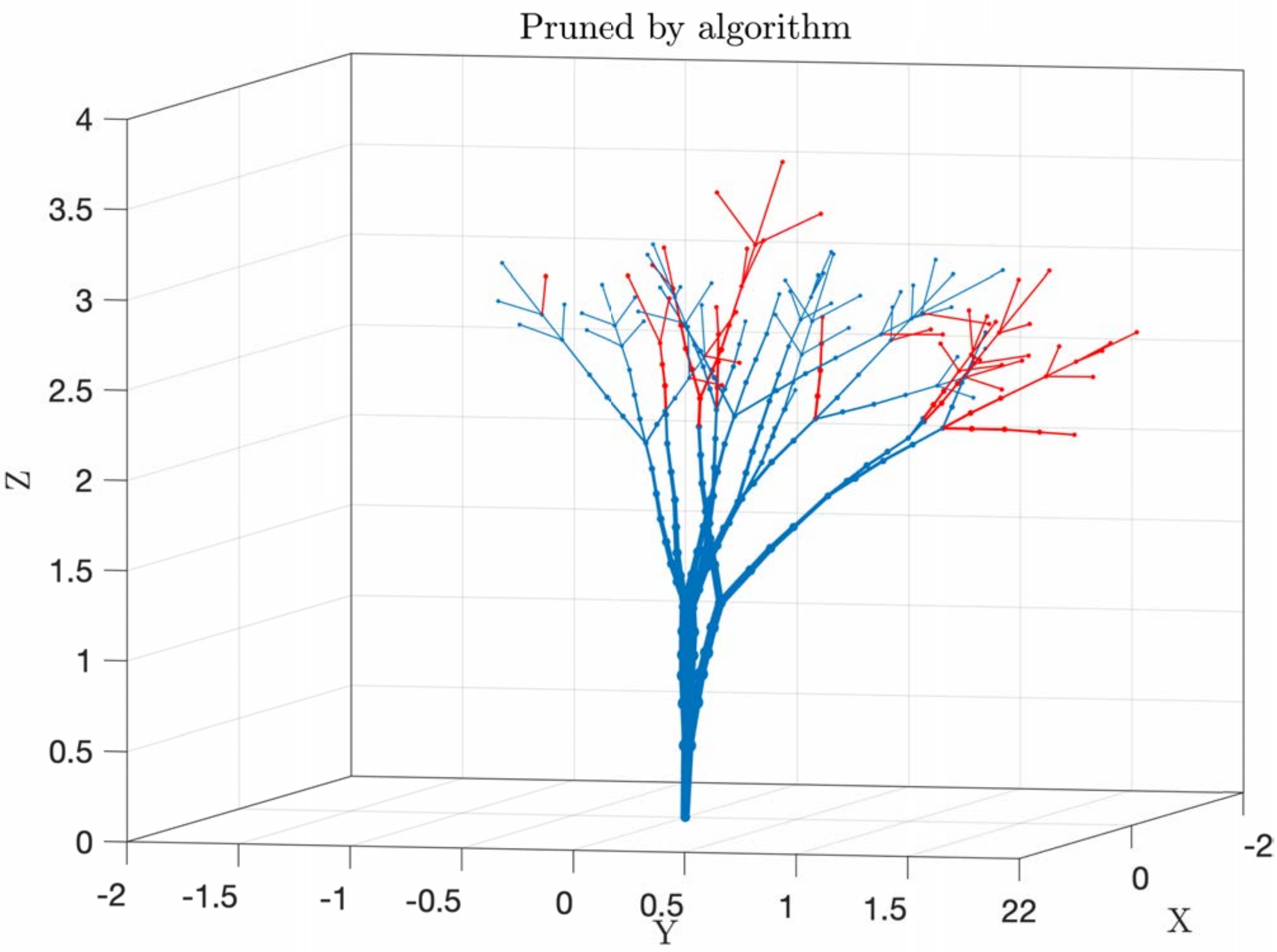

Figure 50 - Comparison between algorithm and agronomist selections on a synthetic tree. Algorithm selection.

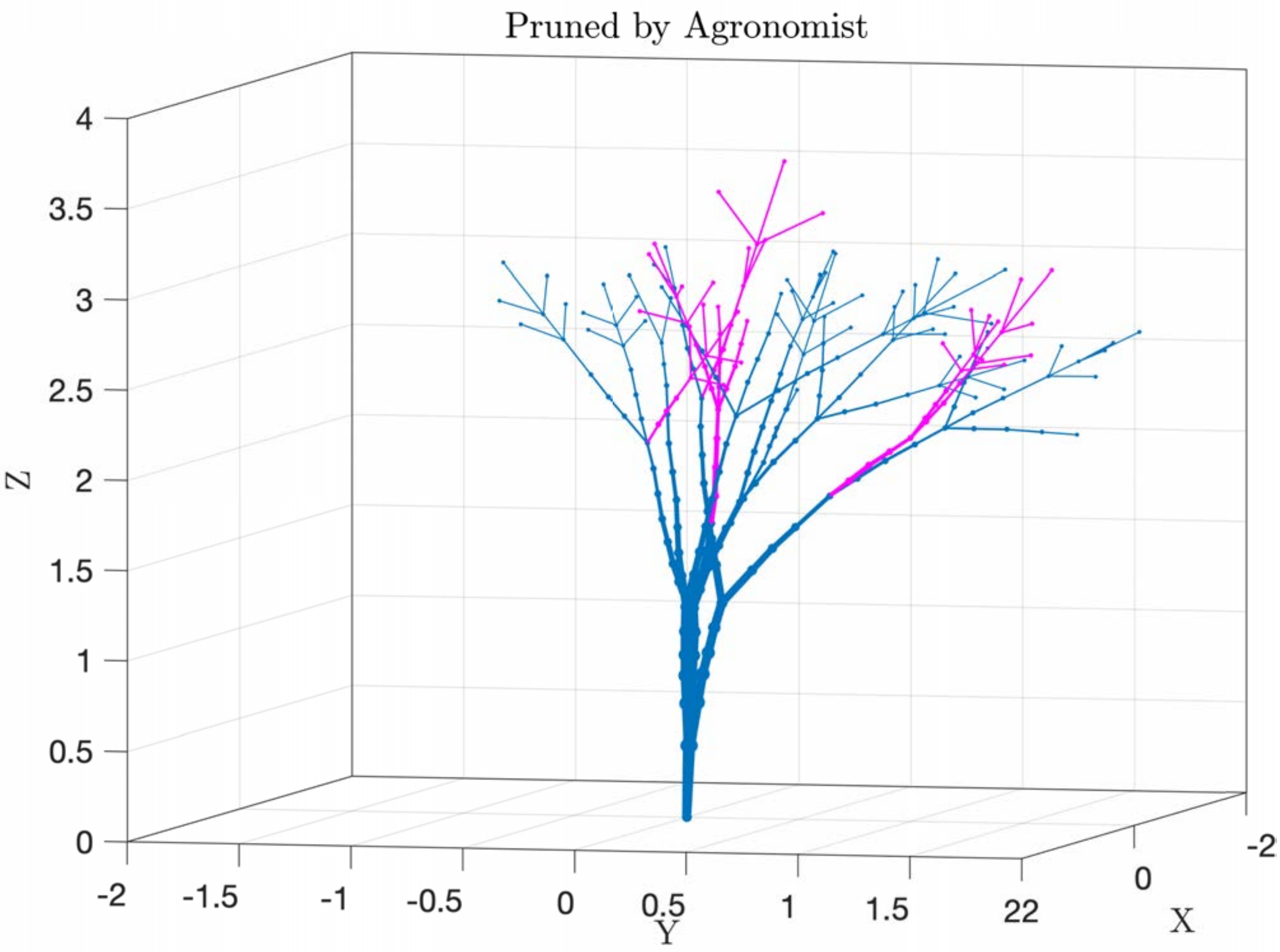

Figure 51 - Comparison between algorithm and agronomist selections on a synthetic tree. Agronomist selection.

Figure 50 and Figure 51 illustrate a comparison between the choice of the algorithm and the choice of an agronomical expert. Note that the logic replicated by the algorithm is similar to the one implemented by the agronomist, even if the amount of pruned wood is slightly different (0.68 kg versus 0.84 kg).

3.3 Outputs of the algorithm

In this section, the outcomes of the algorithm applied to three selected trees of the orchard are reported. The three selected trees represent different kind of pruning methods, i.e., the A, B, and C plant shapes. In particular, the outcomes of the plants A8, B6, and C10 plants are reported. In the Annex at the end of the document the outcomes of the plants A6, A7, B5, B7, C7, and C9 can be found as well.

For each plant five figures are presented: the first one illustrates a graphical visualization of the tree with the algorithm pruning selection highlighted in red; the second one depicts the tree pruned according to the selection of the algorithm; the third one depicts the pruning made by the horticulturists of the UNITUS team on the real tree in the orchard; finally, the fourth and fifth figures illustrate the output of a laser scan executed on the tree in the orchard, before and after the manual pruning. Moreover, for each plant, an estimate of the amount of pruned wood is given according to Eq. 1.

As a matter of fact, the task of reconstructing real trees from 3D LiDAR data is a challenging task and the outcome may not always be optimal. The underlying assumption of the proposed pruning protocol is that the tree must have a certain topological structure, i.e., a proper tree graph structure. As it will be shown later, there may be cases in which the reconstruction fails to fulfil this condition and thus a pre-processing step may be required. For now, minor topological alterations have been manually fixed and currently heuristics based on the a priori knowledge coming from the physical properties of hazelnut trees, that can fix those minor issues of the 3D reconstruction, e.g., missing connection between branches or the presence of outliers coming from neighbouring trees, are being developed. Nevertheless, at the end of the section, the results obtained from the proposed protocol applied to cases where the minor topological issued are not removed, are also presented. A discussion on the heuristics that are currently being developed to solve such minor issue will follow.

The amount of wood removed following the suggestions of the algorithm for all the considered trees (both the ones presented in this section and the ones illustrated in the Annex) is summarized in Table 10.

ID Plant	**Pruned wood** (kg plant^{-1})
Yo A6	1.261
Yo A7	1.495
Yo A8	1.298
Yo B5	0.170
Yo B6	0.628
Yo B7	0.600
Yo C7	1.748
Yo C9	1.089
Yo C10	1.009

Table 10 - Amount of wood removed according to the suggestions of the pruning protocol.

3.3.1 Plant A8

Figure 52 to Figure 56 concerns plant A8 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.298 kg.

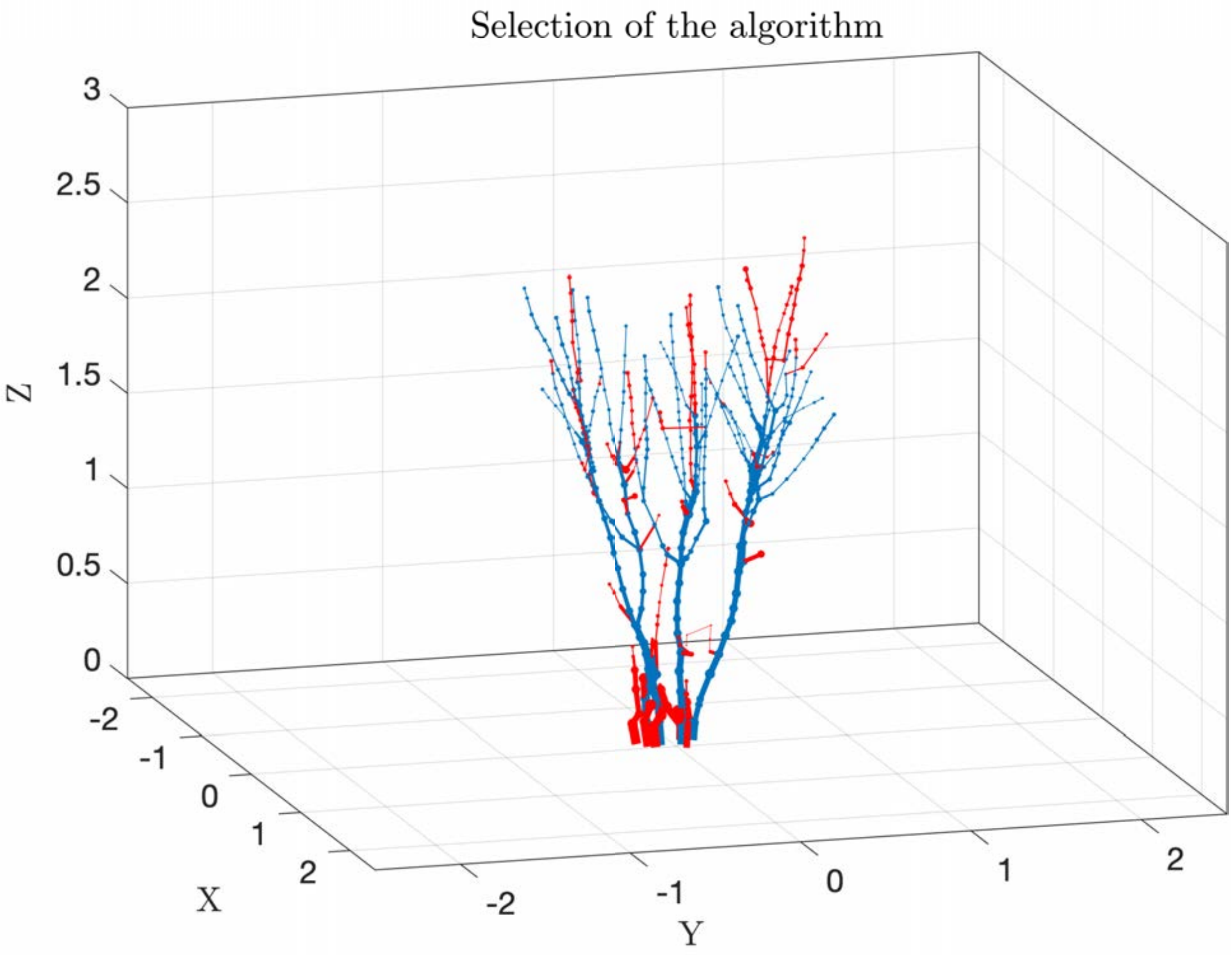

Figure 52 - Plant A8 where the algorithm has highlighted the branches to prune.

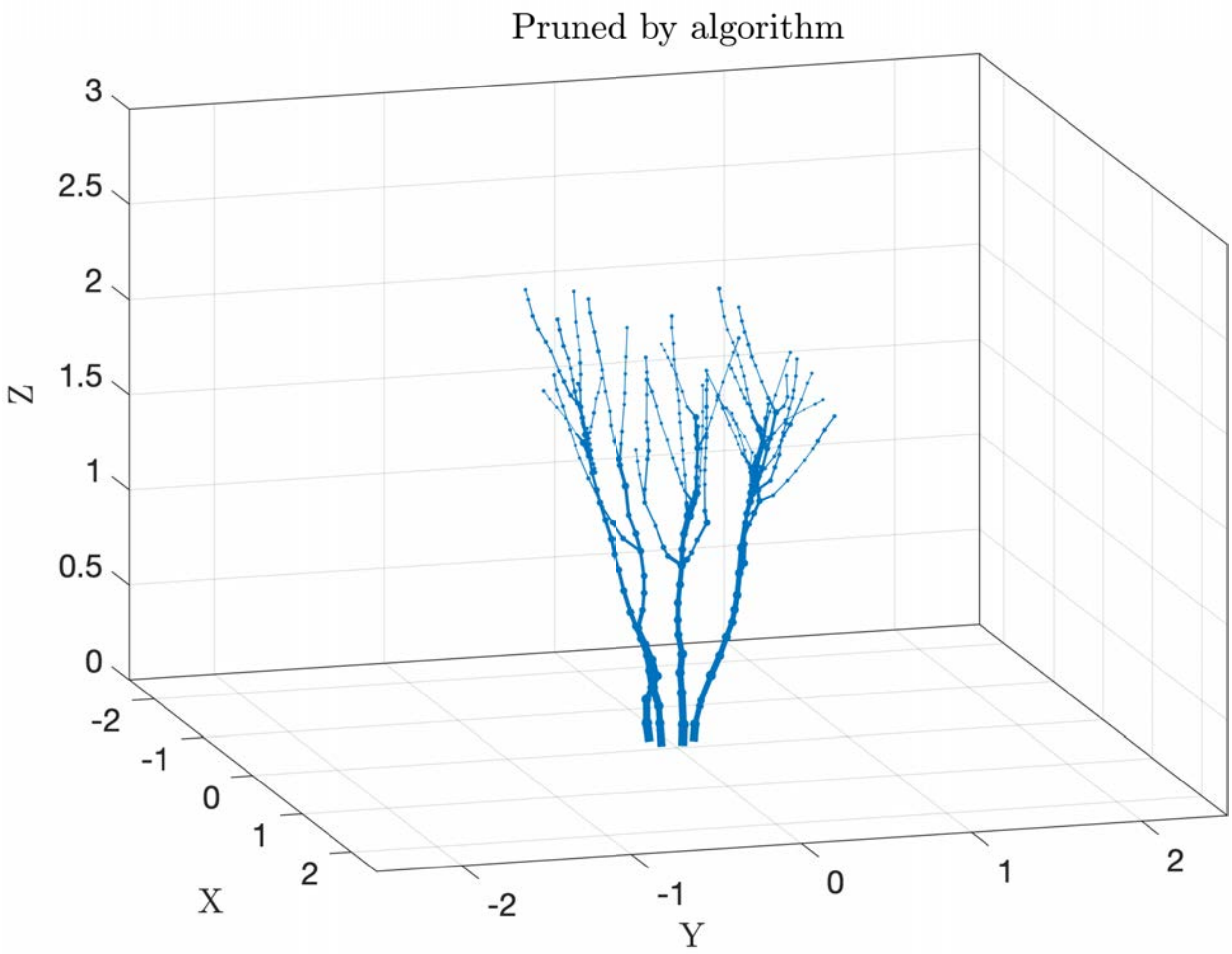

Figure 53 - Plant A8 pruned following the suggestions of the algorithm.

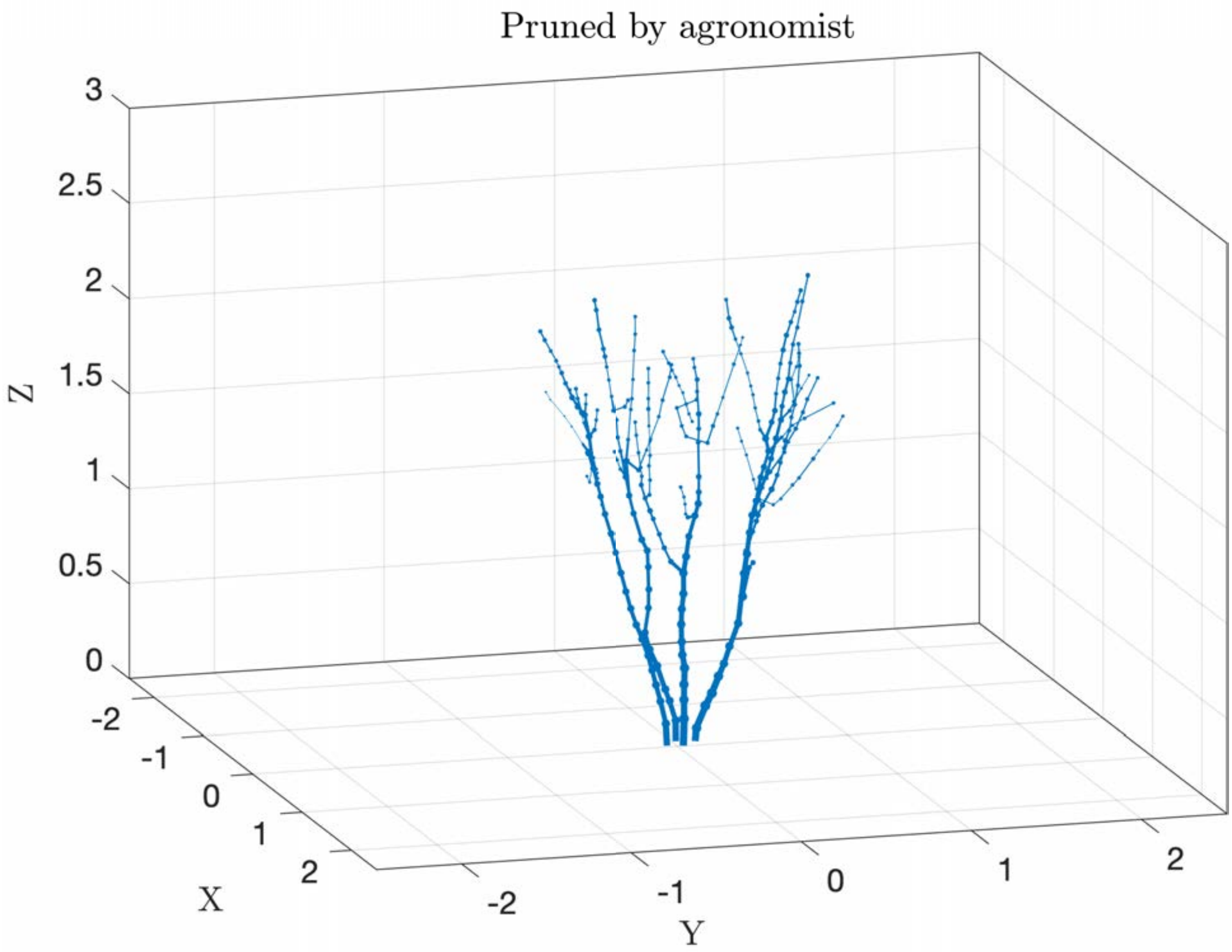

Figure 54 - Plant A8 pruned by an agronomical expert.

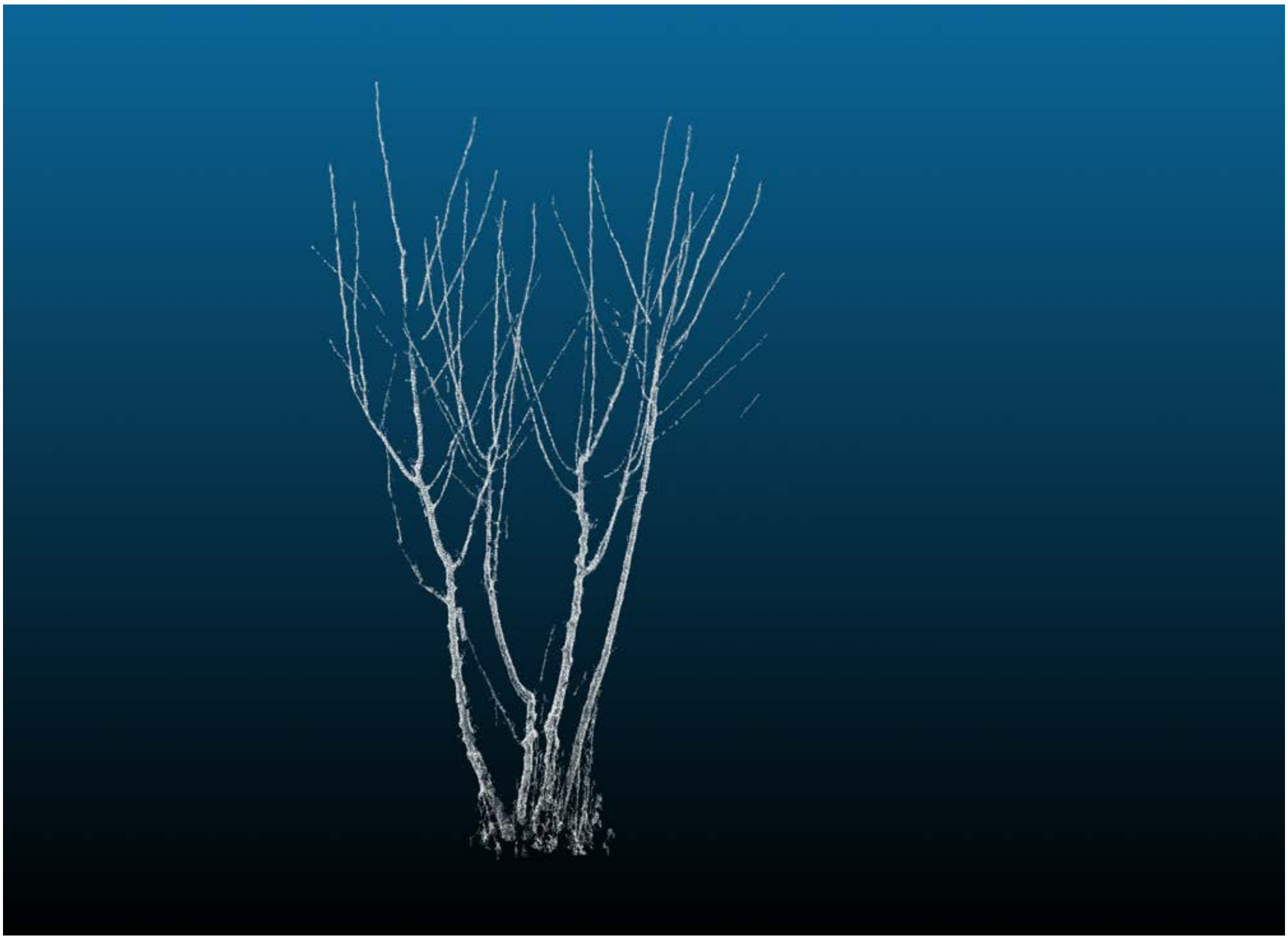

Figure 55 - 3D point cloud of A8 plant before pruning.

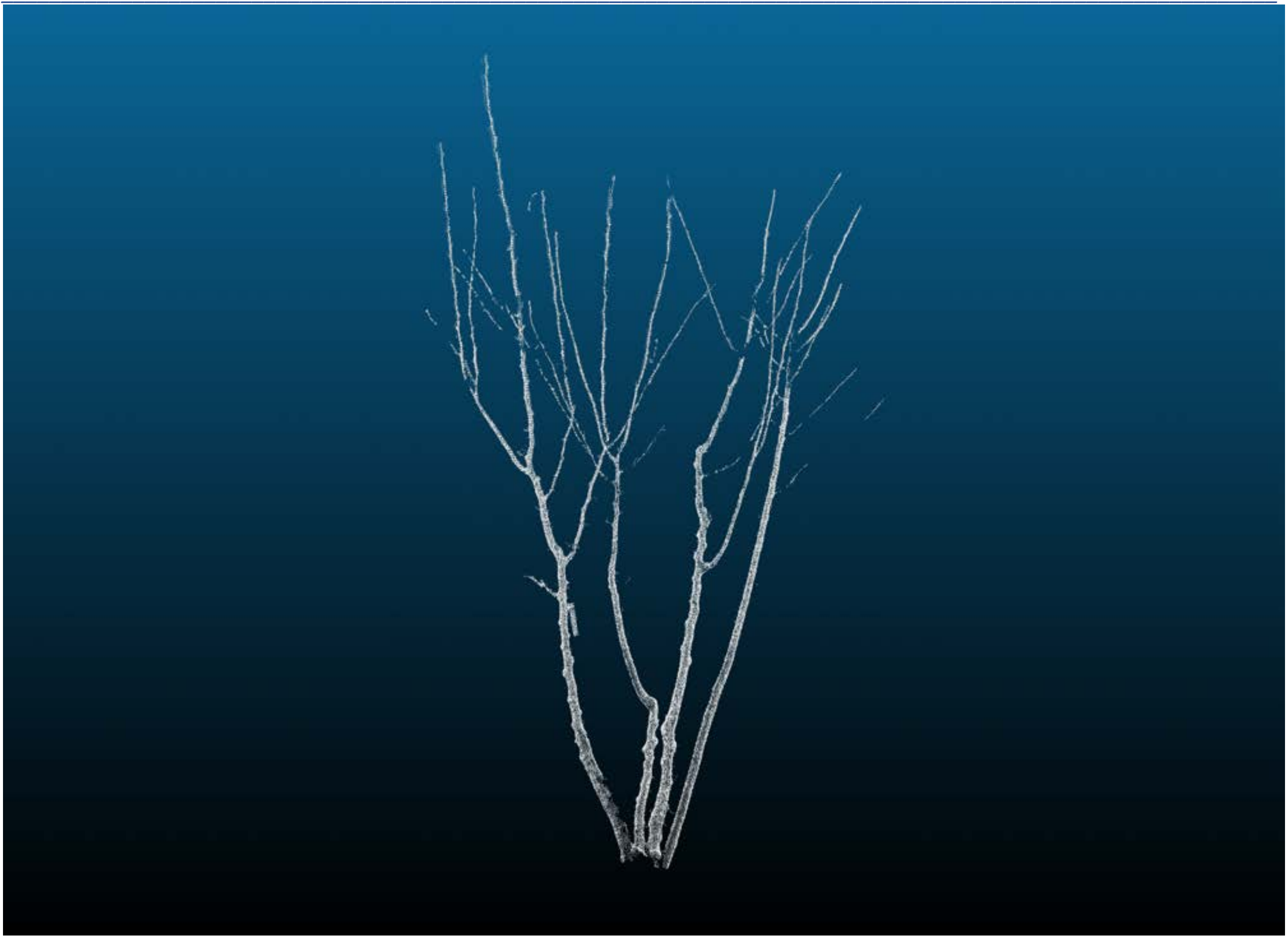

Figure 56 - 3D point cloud of A8 plant after pruning.

3.3.2 Plant B6

Figure 57 to Figure 61 concerns plant B6 of the orchard. The amount of pruned wood selected by the algorithm is equal to 0.628 kg.

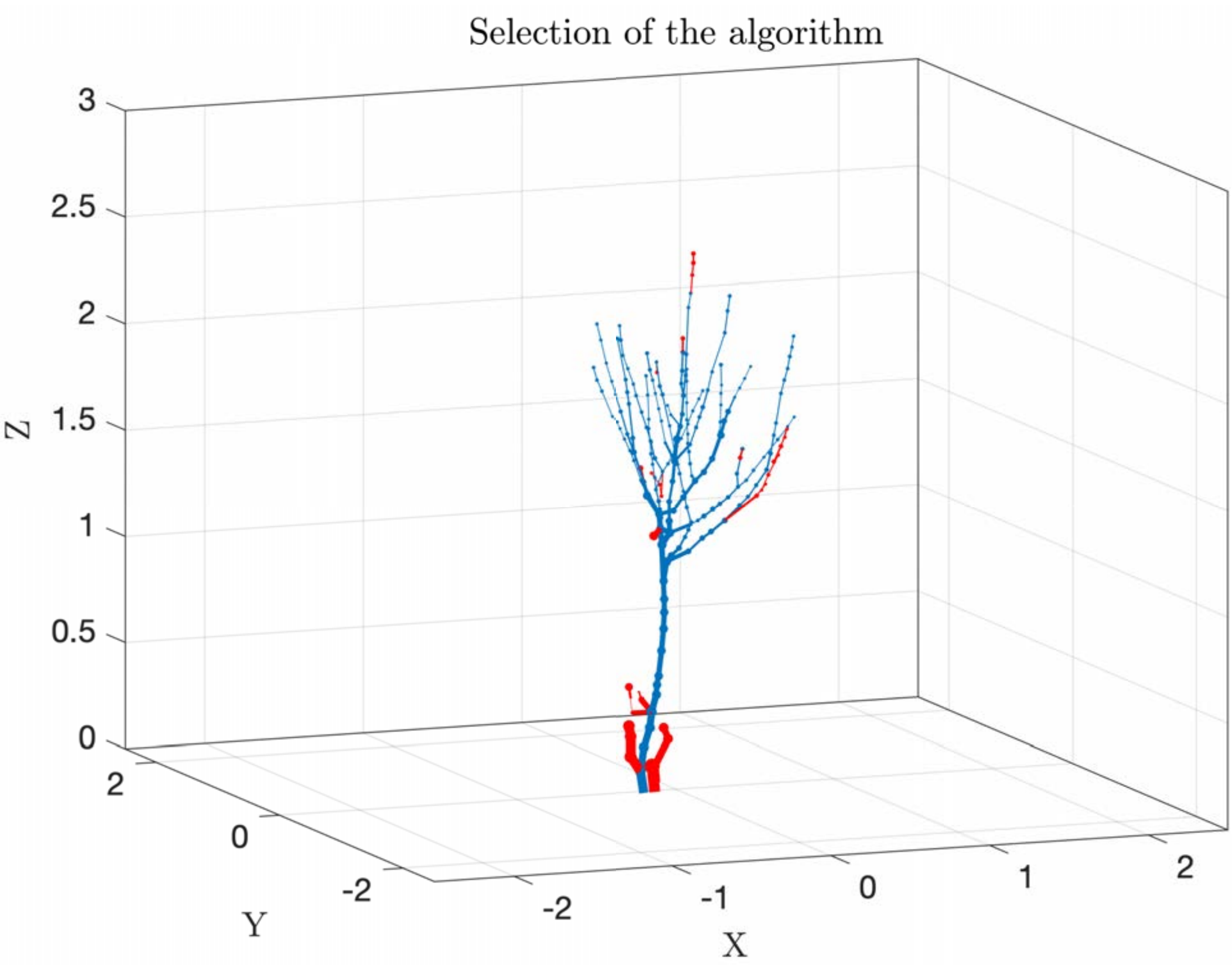

Figure 57 - Plant B6 where the algorithm has highlighted the branches to prune.

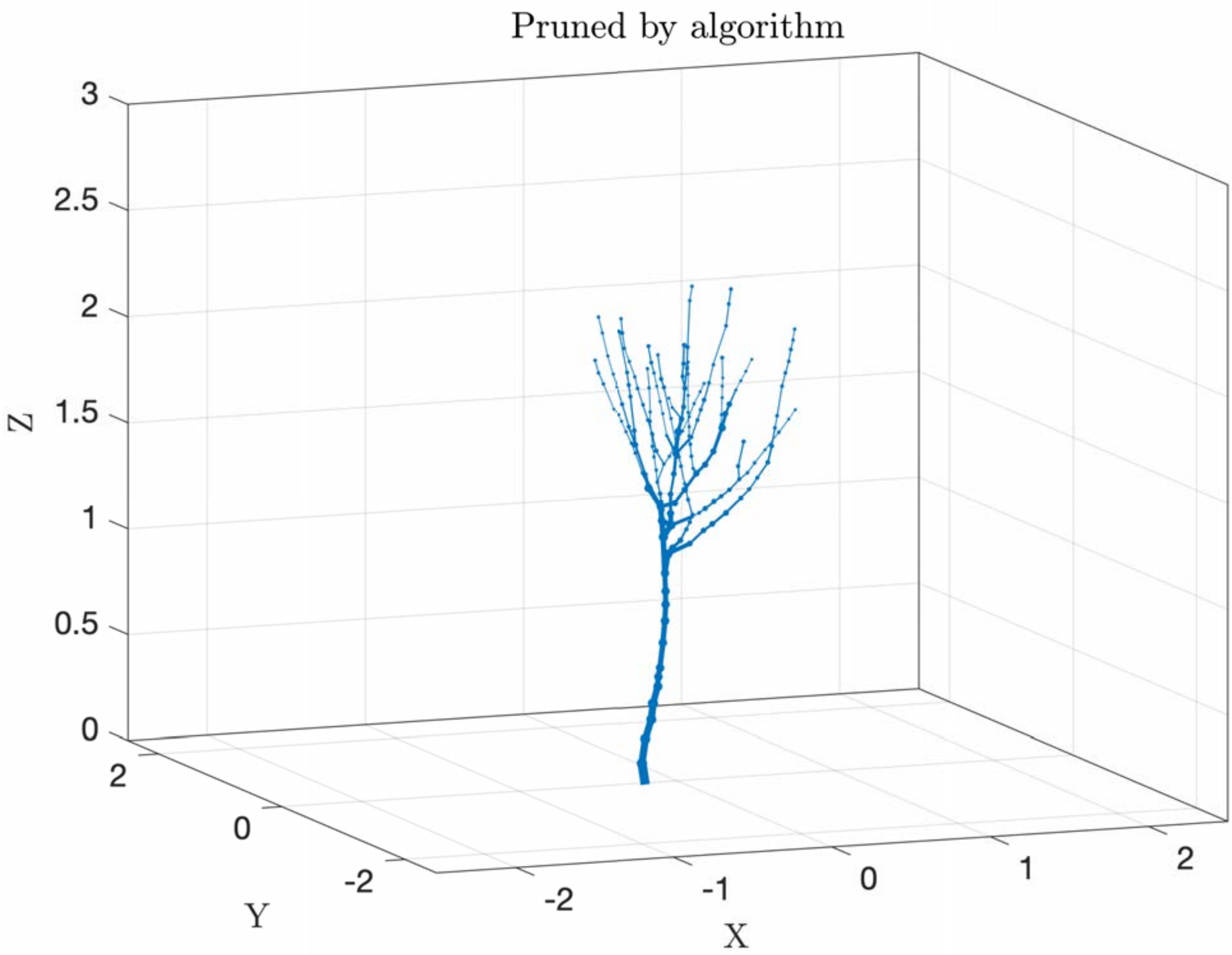

Figure 58 - Plant B6 pruned following the suggestions of the algorithm.

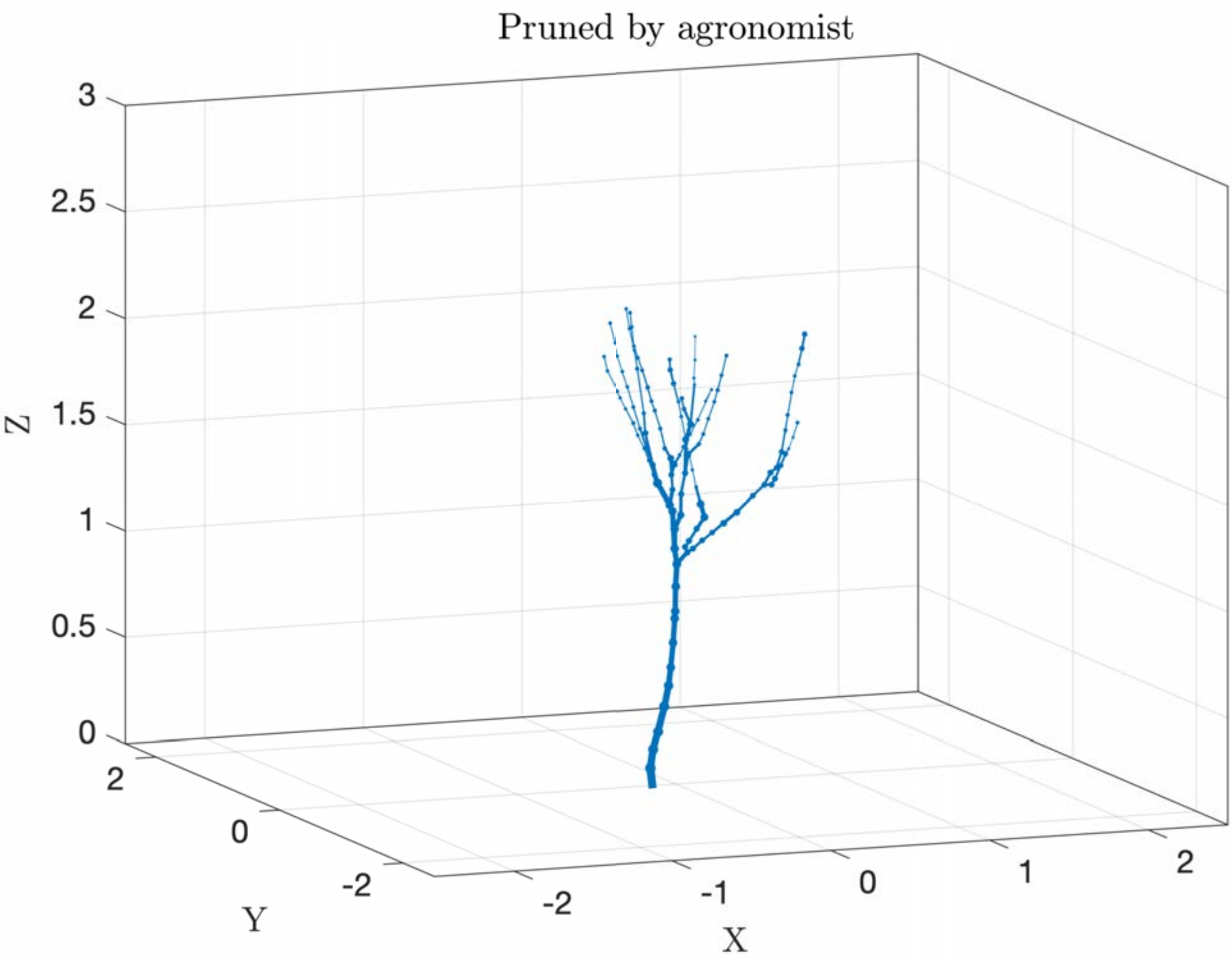

Figure 59 - Plant B6 pruned by an agronomical expert.

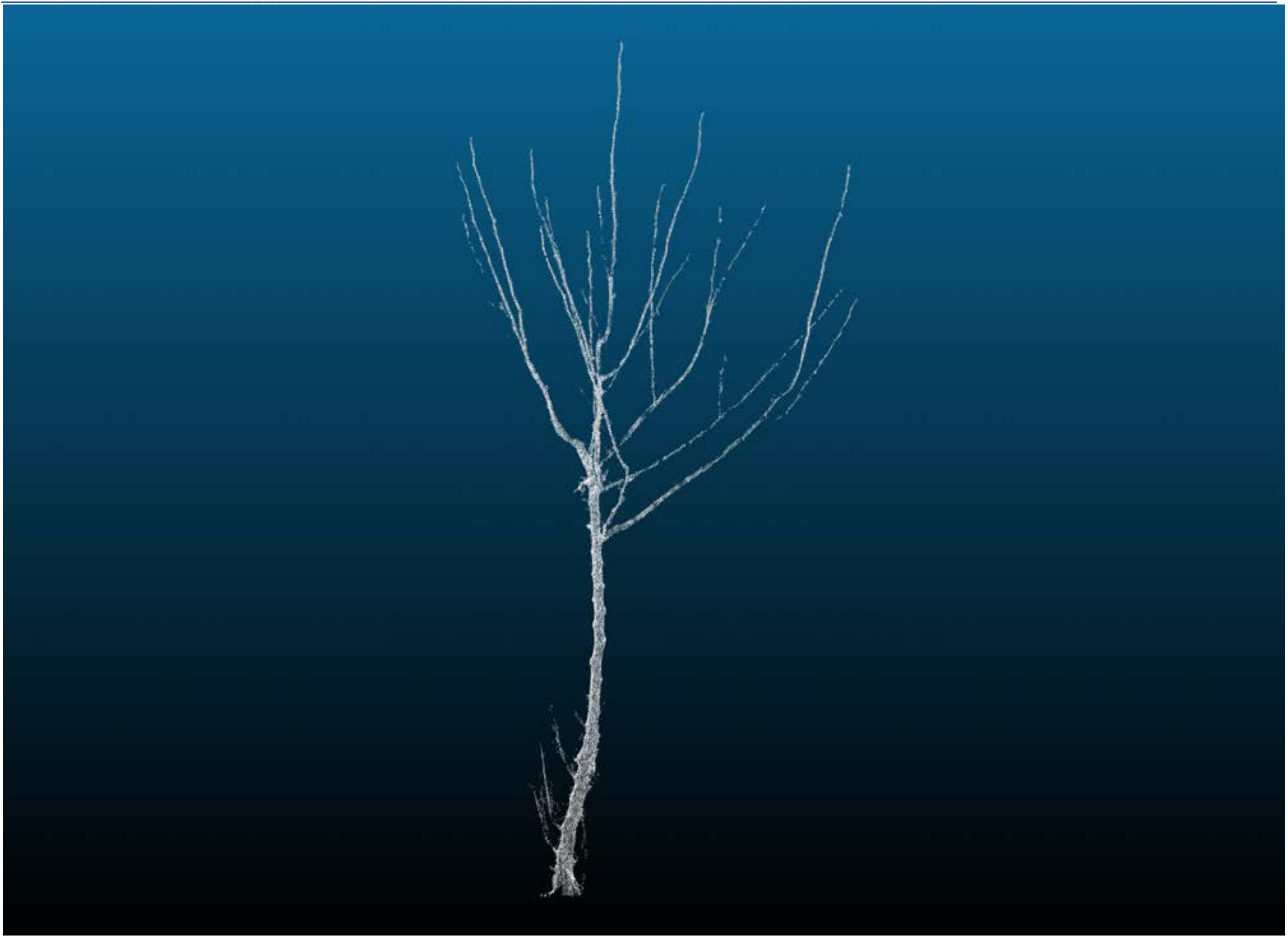

Figure 60 - 3D point cloud of B6 plant before pruning.

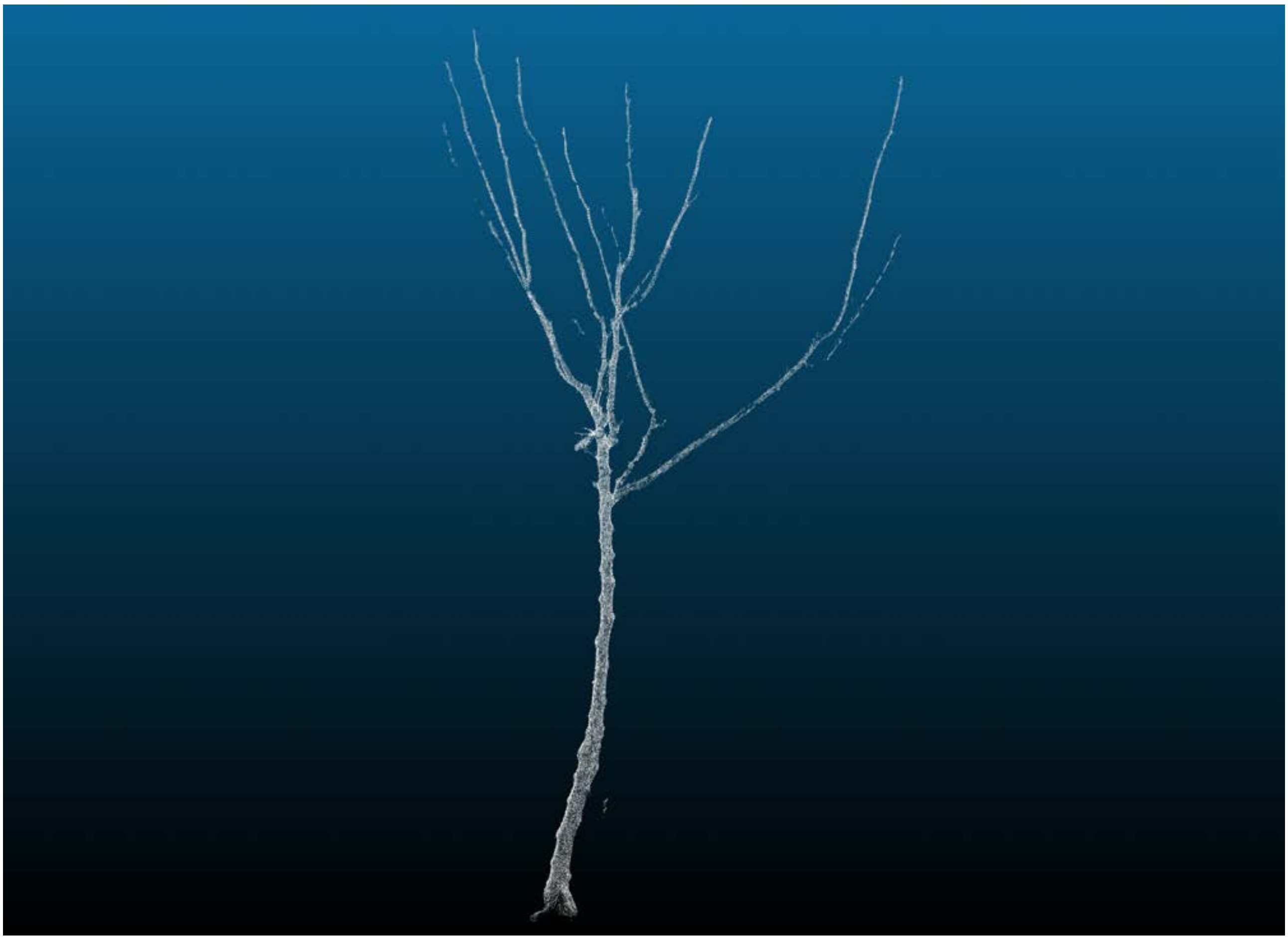

Figure 61 - 3D point cloud of B6 plant after pruning.

3.3.3 Plant C10

Figure 62 to Figure 66 concerns plant C10 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.009 kg.

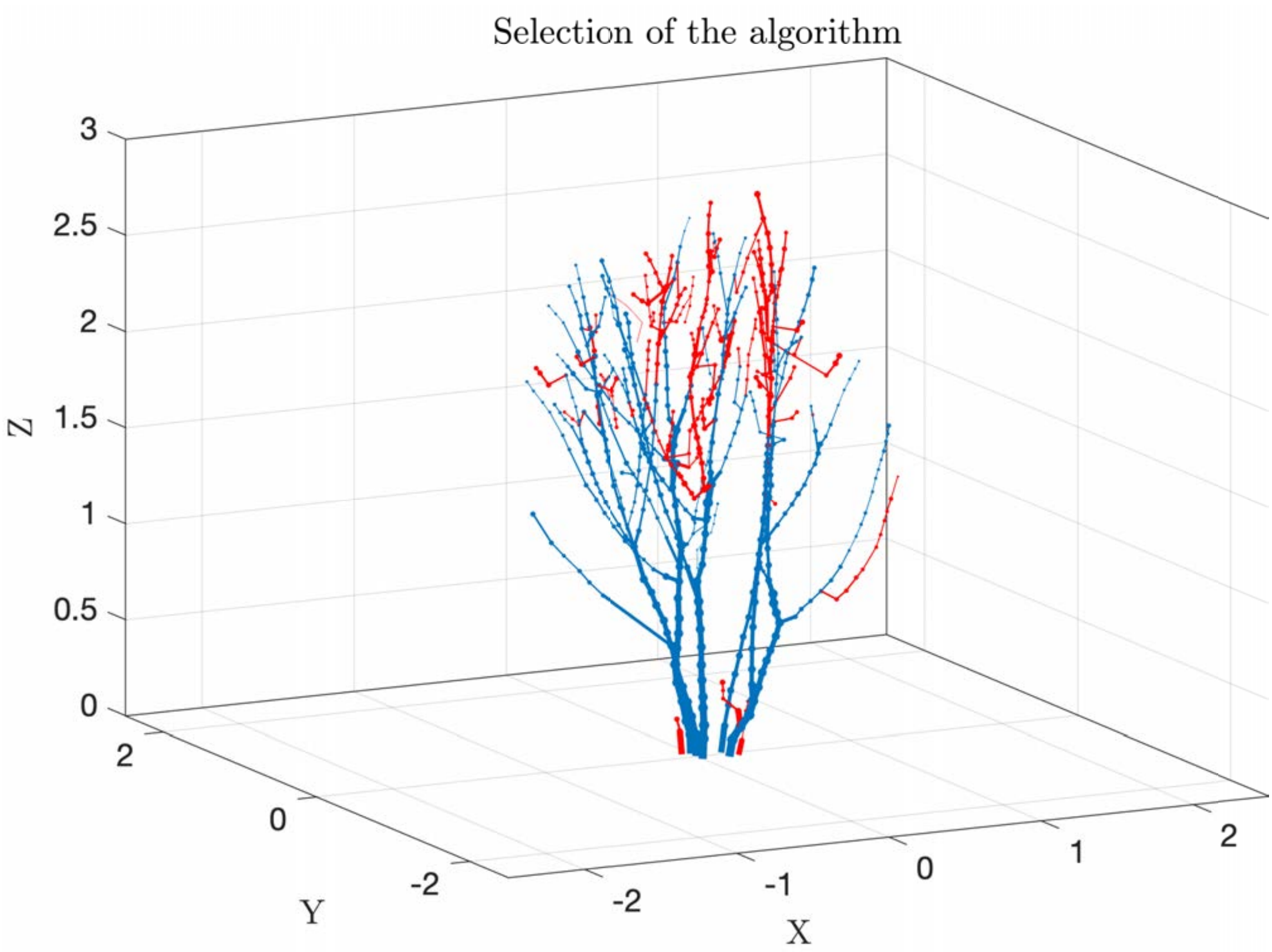

Figure 62 - Plant C10 where the algorithm has highlighted the branches to prune.

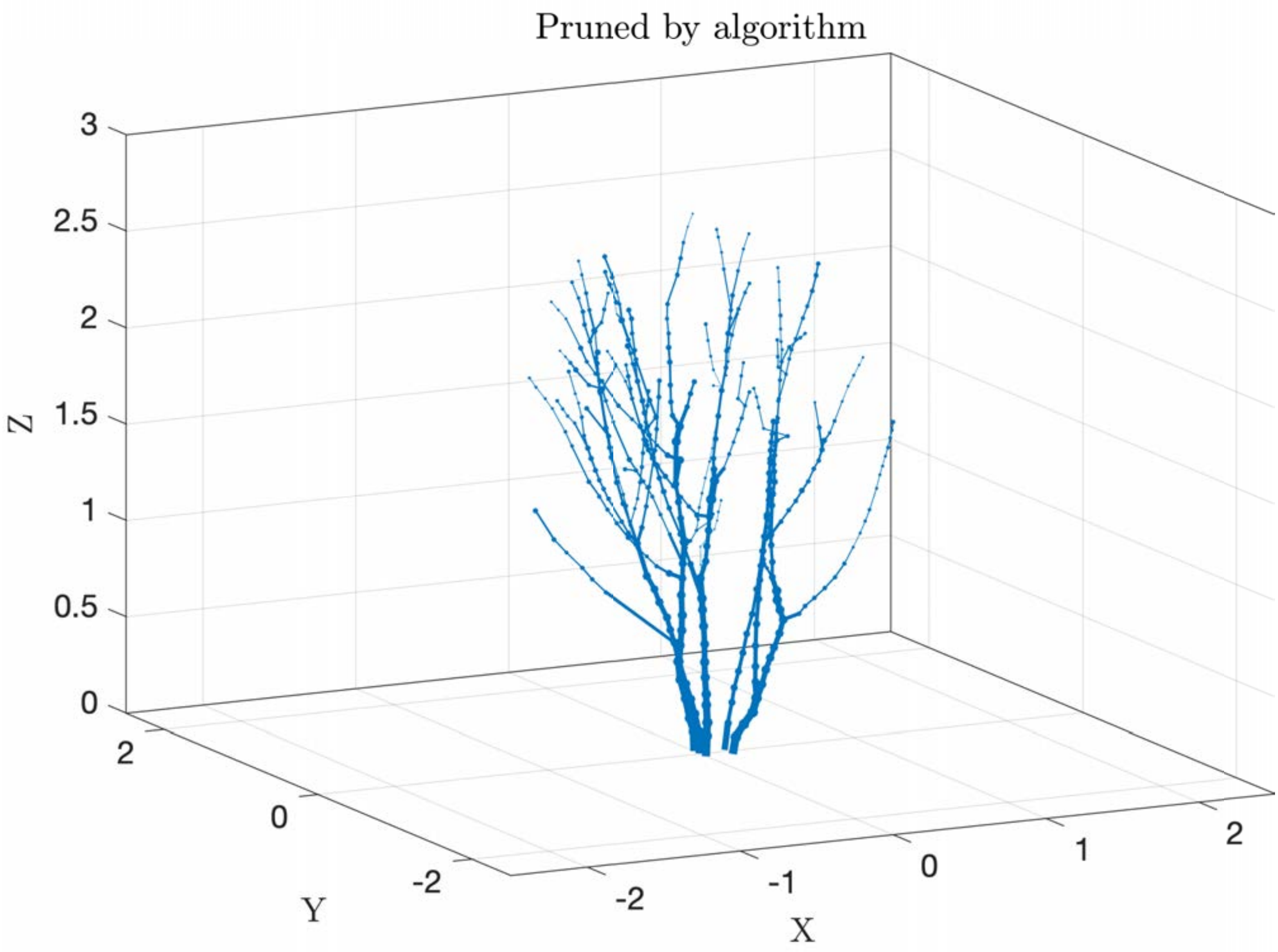

Figure 63 - Plant C10 pruned following the suggestions of the algorithm.

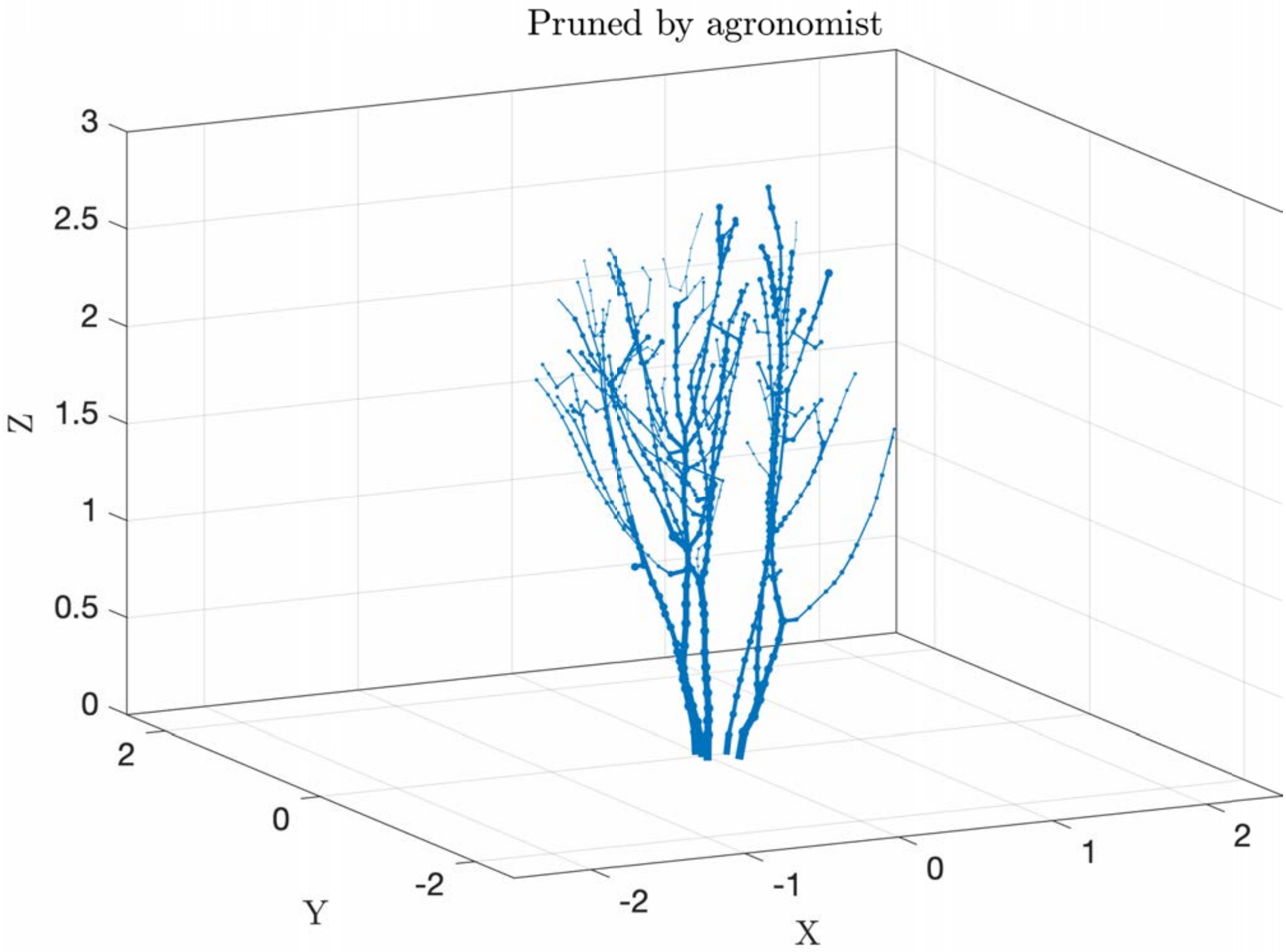

Figure 64 - Plant C10 pruned by an agronomical expert.

Figure 65 - 3D point cloud of C10 plant before pruning.

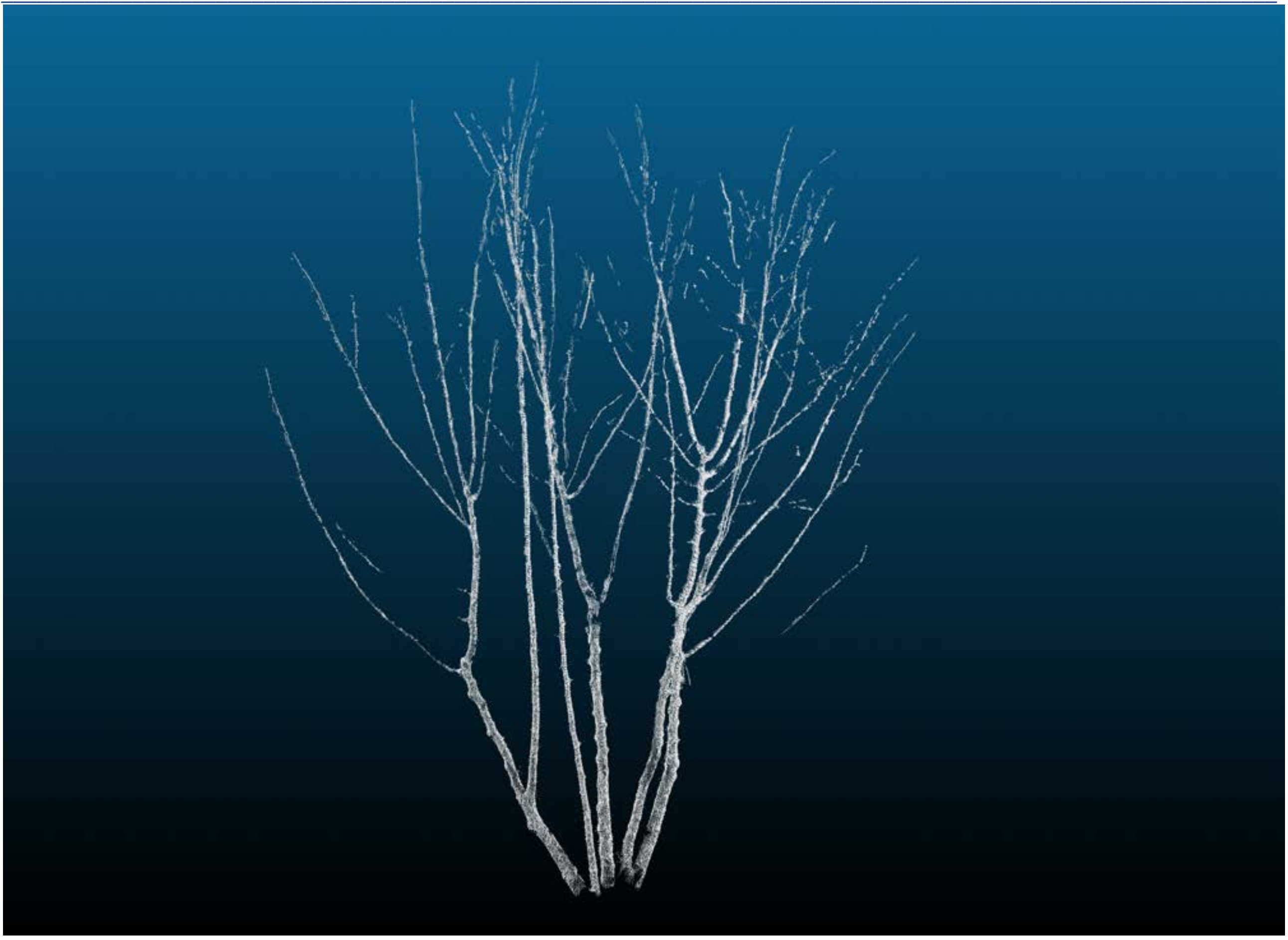

Figure 66 - 3D point cloud of C10 plant after pruning.

3.4 Ongoing work

As introduced earlier, reconstructing real trees from 3D LiDAR scans is a challenging task and the result of the reconstruction may not always be optimal. For this reason, pre-processing heuristics are being added to the algorithm in order to fix these potential minor issues. In the following the original outcome of the pruning algorithm without the pre-processing phase are reported. Suggestion on possible directions concerning how to design such pre-processing heuristics are also discussed.

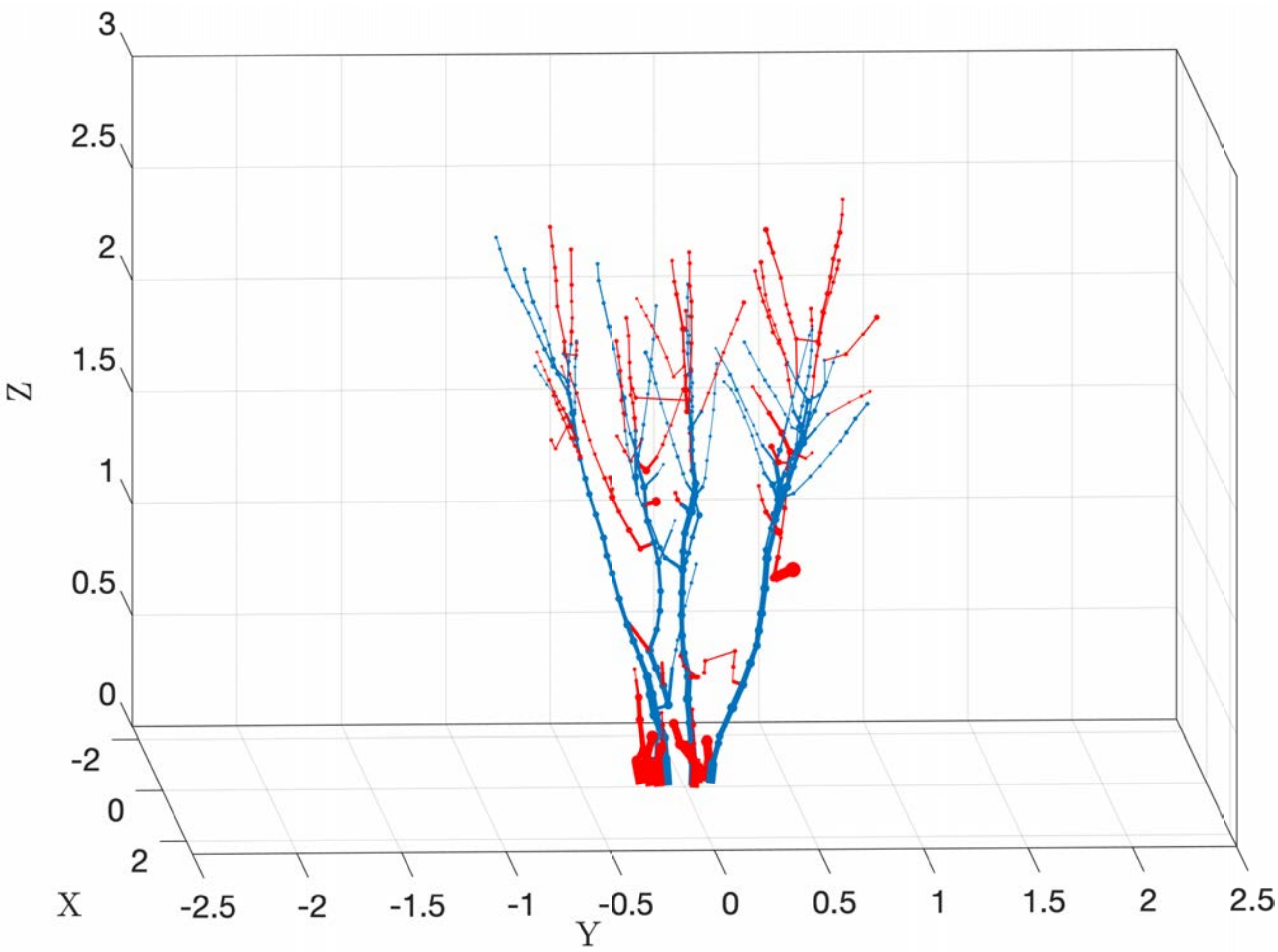

Figure 67 - Selection of the algorithm on the plant A8 where minor topological issues were not manually fixed.

Figure 67 depicts the application of the pruning algorithm to the original 3D reconstruction of the plant A8 where a couple of unusual topology connections can be noticed. Nevertheless, the unusual link connections that ideally represents unusual branch's structures are selected for pruning.

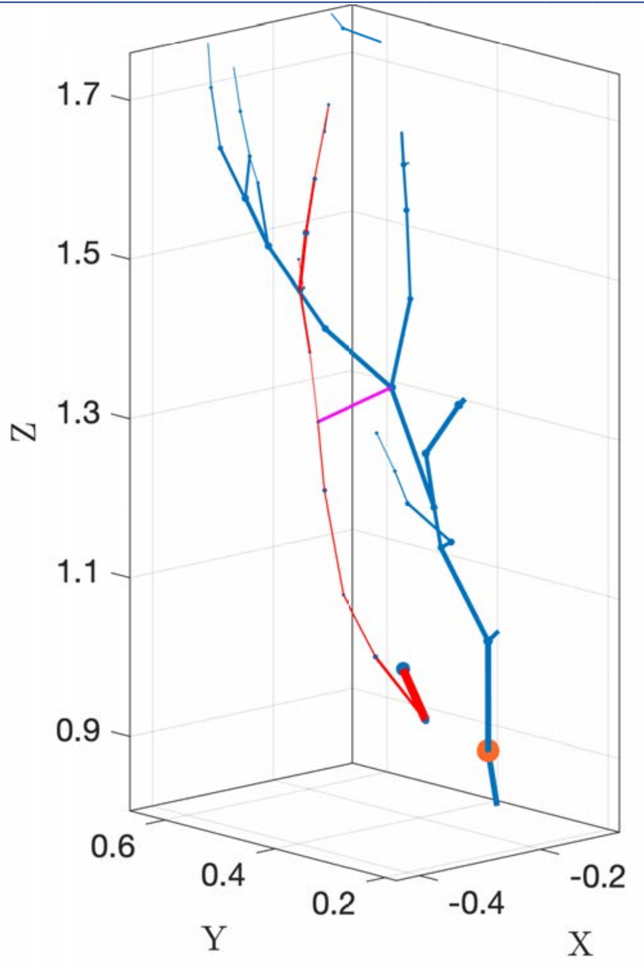

Figure 68 - Highlight of a questionable connection in the original reconstruction of plant A8.

Figure 68 shows the detail of a questionable connection made by the reconstruction procedure where the horizontal magenta branch is connecting the red branch to the rest of the tree. This connection, however, does not reflect the real structure of the tree as illustrated in Figure 55. A more valid connection would have linked the red branch to the orange node.

This kind of issue generates a secondary problem: the directions of the edges of the tree happen to be 'reversed' for certain edges, e.g., in this case all the links of the inferior part of the red branch are directed downwards whereas it would be expected in a usual tree to find edges directed upwards, following the natural growth of a tree. Naturally, it also possible that downwards branches exist in real life so in order to solve this kind of issue a specific pre-processing procedure needs to be implemented. Exploiting the fact that this issue usually involves two sudden changes of direction in space, e.g., as in this case the path towards a leaf is first directed upwards, then rotates 90° and then immediately rotates again for other 90°, an heuristic that checks all paths starting from the root of the tree and arriving to the leaves of the tree could notice this problem and find a better connection for the branch.

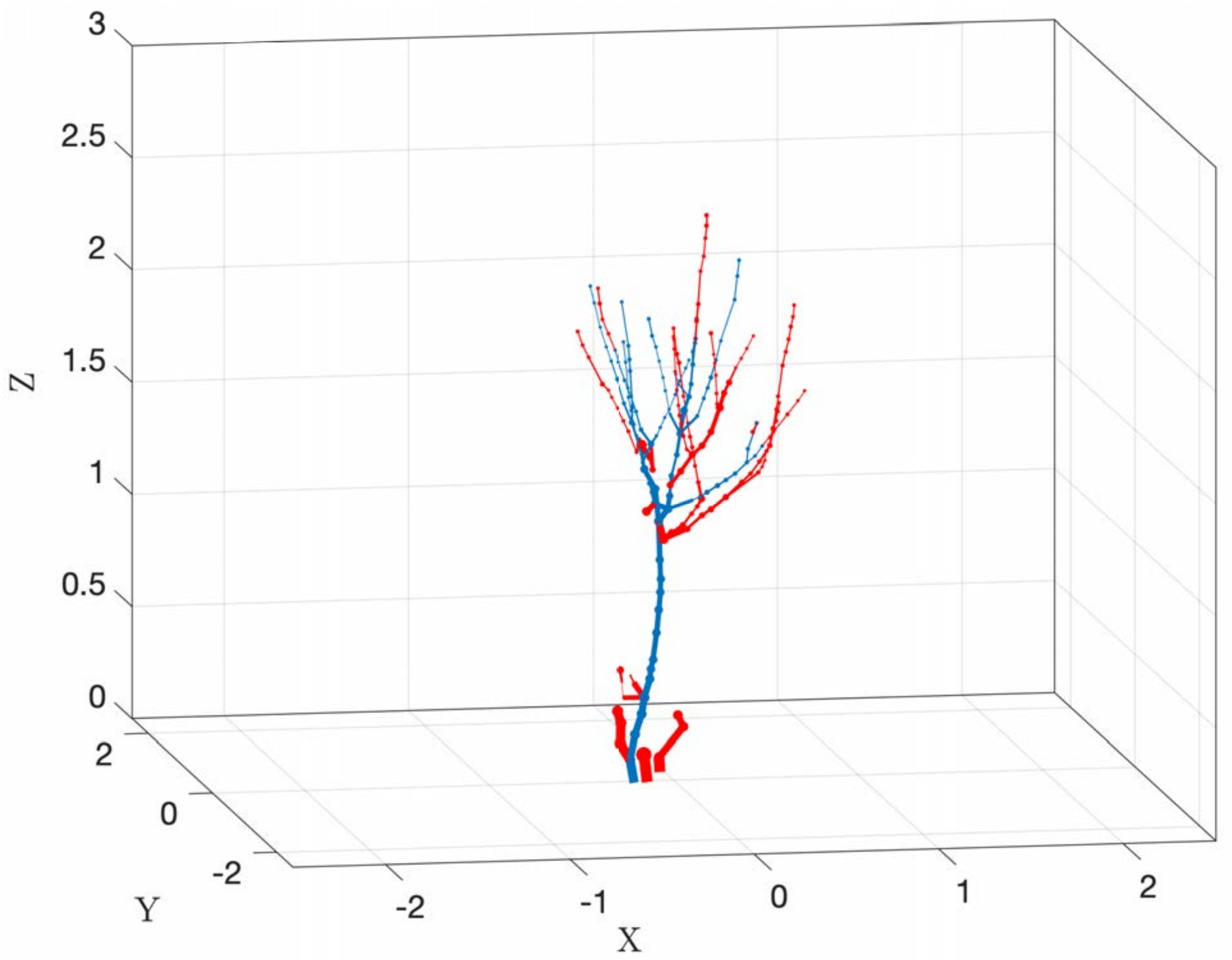

Figure 69 - Selection of the algorithm on the plant B6 where minor topological issues were not manually fixed.

Figure 69 illustrate the outcome of the pruning algorithm to the original 3D reconstruction of the plant B6. As shown, the result is quite different with respect to the one illustrated in Figure 57 since two more branches have been selected for pruning in the case shown here. The reason behind the different selection can be found in Figure 70. The branches that originate from the green node have been modelled as sprouted from a downward branch. This branch has been selected by the vertical criteria of the algorithm and hence all of its descendants have been selected for pruning as well. A better model would have added another node on the main branch of the tree and connected the two growing branches to such node. In this way, the red downward branch would have not existed, and the algorithm would have never selected it. In this case a pre-processing heuristic aimed to fix the issue, could check branches that grow in a horizontal direction (for example checking the differential increment for each segment of the branch) and try to attach them in a more suitable position.

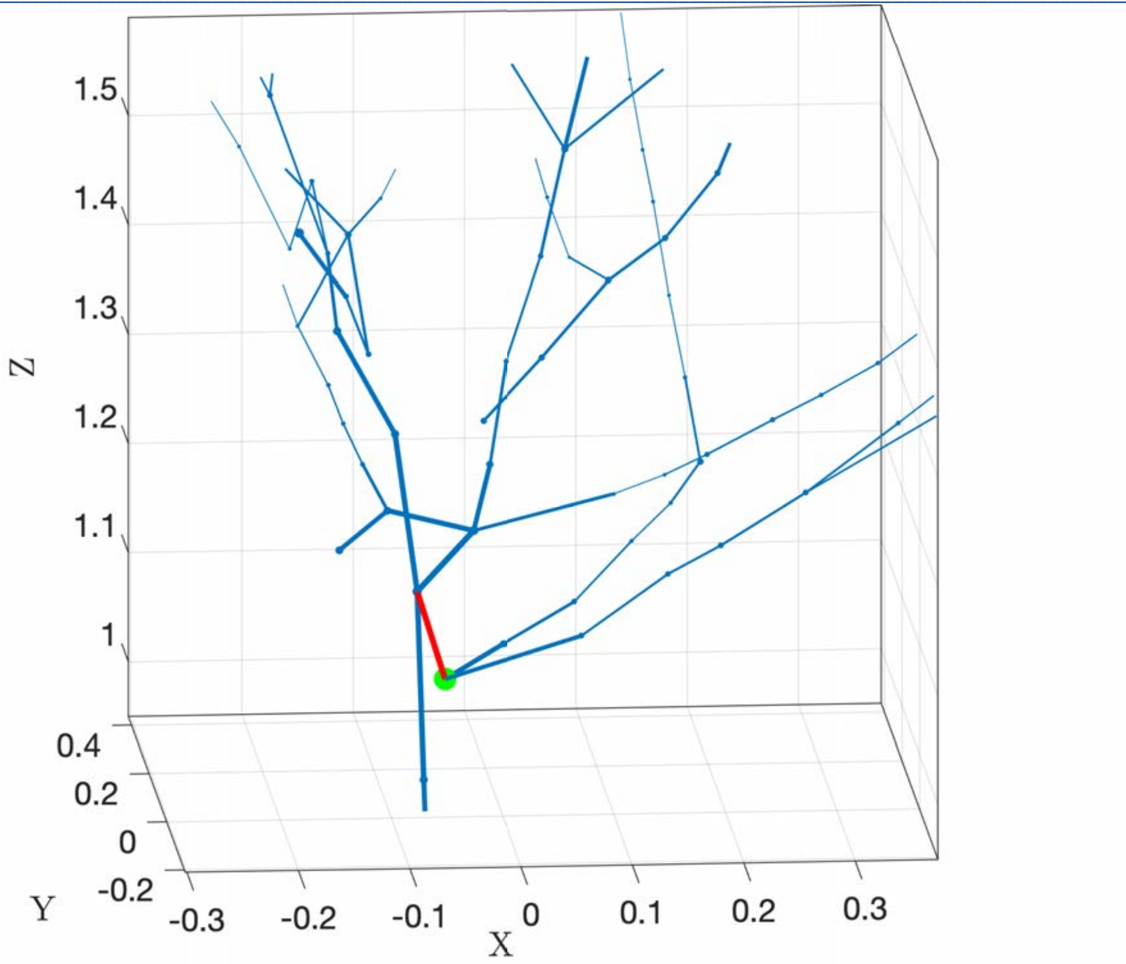

Figure 70 - Highlight of a questionable connection in the original reconstruction of plant B6.

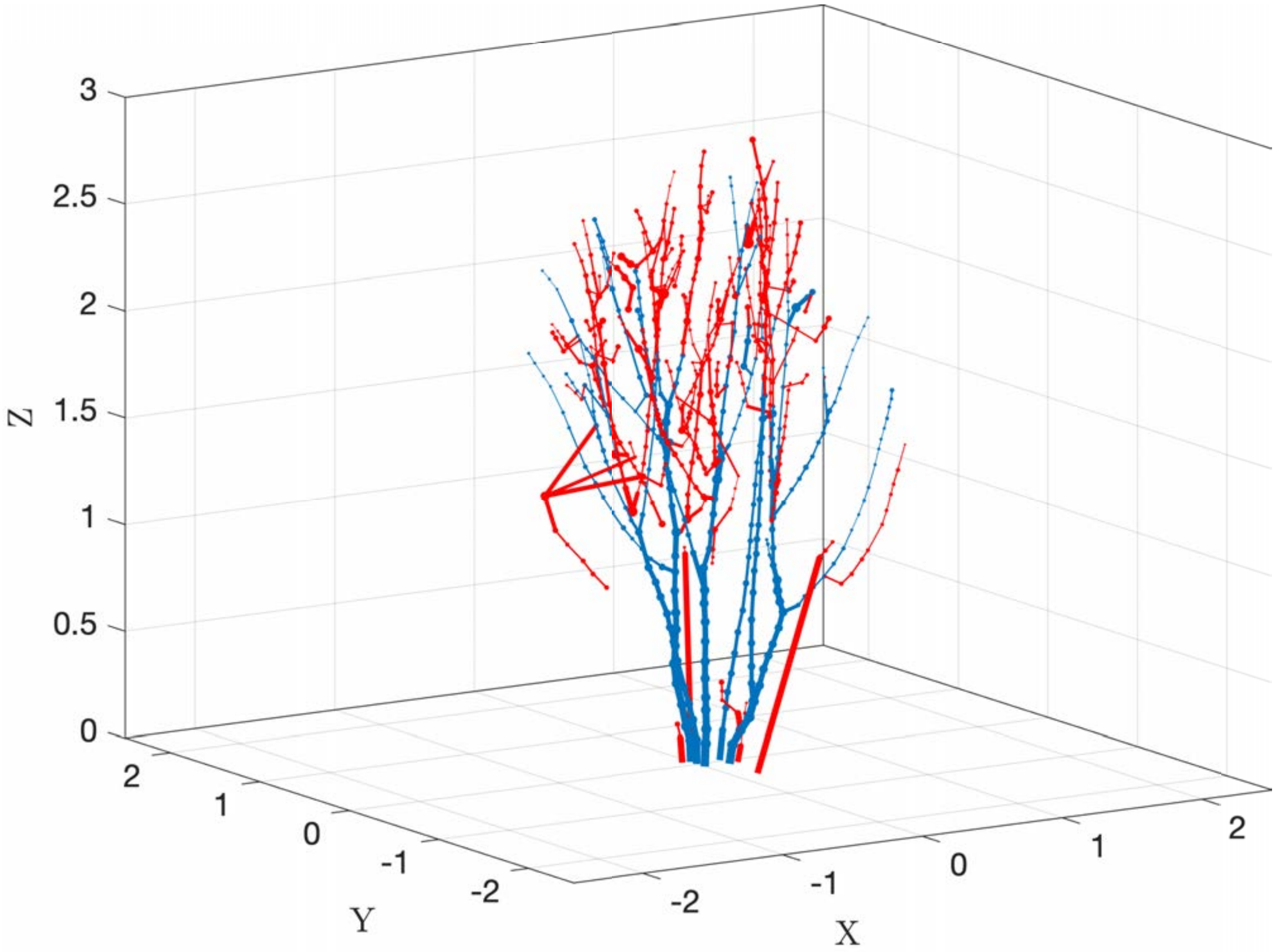

Figure 71 - Selection of the algorithm on the plant C10 where minor topological issues were not manually fixed.

Figure 71 shows the pruning suggestion of the algorithm in regard to the original reconstruction of plant C10 of the orchard. A few minor issues such as the presence of some outliers and questionable choice of connections between the nodes are present. Potential outliers however are correctly detected by the virtual truncated cone criteria, that can hence be used also as a pre-processing procedure to improve the quality of the model. Figure 72 illustrate a scenario how a different choice of connections could have been made. The suggested edits are highlighted with two orange arrows. In this case, similar to the case of plant A6, a pre-processing heuristic that checks the paths towards the leaves of the tree and their direction/orientation in space should be able to find and improve these connections.

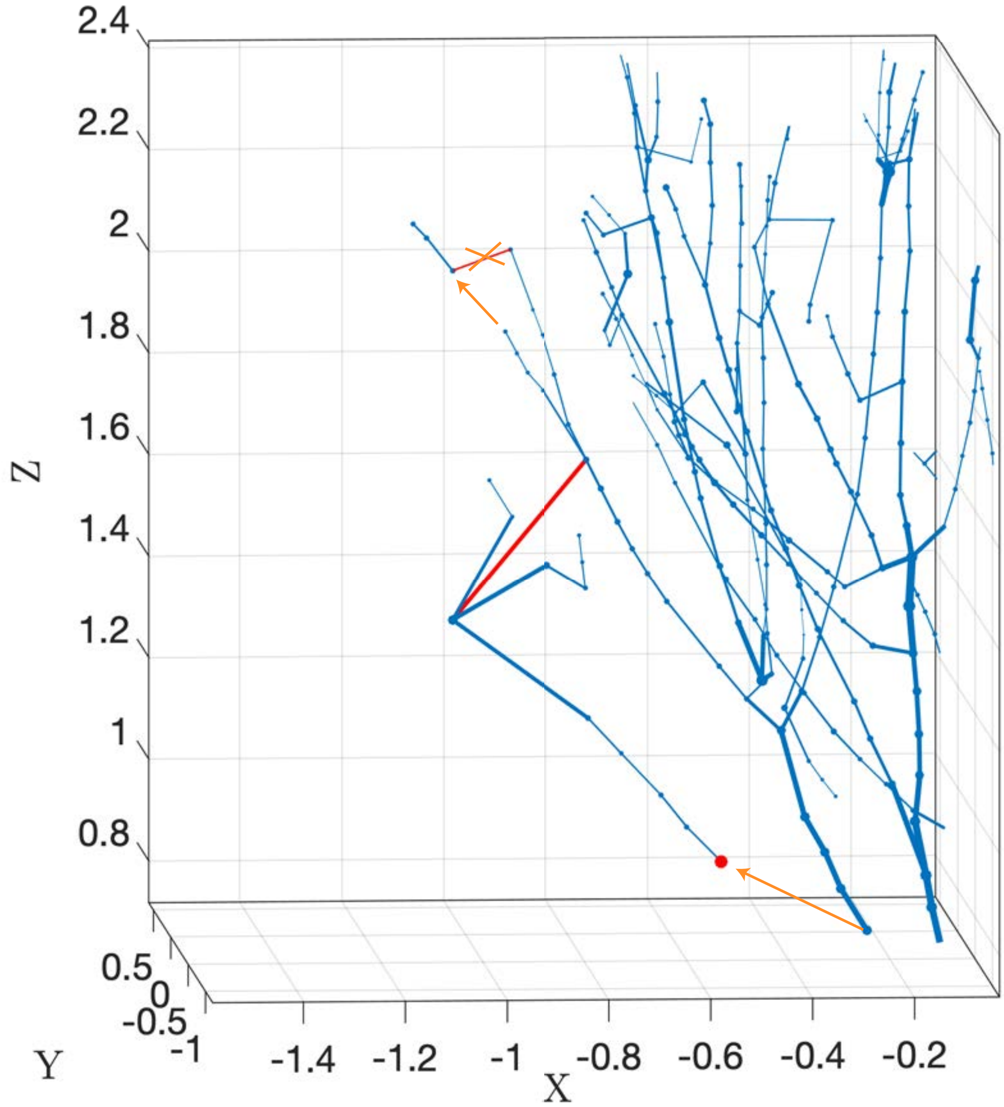

Figure 72 - Highlight of questionable connections in the original reconstruction of plant C10.

Other improvements that could benefit the adoption of the proposed algorithm concern the adaptation of the algorithm to other woody plants, especially for pome and stone species that are very often grown at hedgerow systems, easier to manage than shrubs. This extension should be quite easy given the fact that the algorithm works on topological graphs structures only, i.e., it is quite independent from the tree that the model represents.

4 Validation of the control protocol effectiveness

In order to validate the algorithm for tree geometry reconstruction and pruning guidance, in the following year, starting in January 2021, two different validation approaches will be carried out.

The first activity will concern the "test plants" already used in February 2020 (A6, A7, A8; B5, B6, B7; C7, C9 C10) through the application of the manual pruning protocol previously described, with acquisition of 3D scanning to be done before and after winter pruning, using the properly equipped UGV. This activity is aimed at further validating the protocol to the type of cuts to be recommended, which can be different from year to year, depending on the vegetative development of the plants.

The second activity will be exclusively aimed at validating the pruning protocol through a preliminary 3D scanning with UVG of the other plants of the trial, after eliminating the catkins, in order to obtain the automated indications of which portions of plants to cut, according to the different plant shapes, also through the use of the software developed for the pruning of synthetic trees. Once the information will be acquired, the UNITUS team will manually apply the cuts proposed by the pruning algorithm and once the pruning has been carried out, they will agronomically validate the post-pruning architecture of the treated plants.

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Annex

In this annex the outcomes of the algorithm and the 3D cloud reconstruction of the plants A6, A7, B5, B7, C7, and C9 are reported.

As discussed earlier for the illustrated A8, B6, and C10 plants, also in these cases minor fixes to the topological structure of the reconstructed 3D models have been made.

Plant A6

Figure 73 to Figure 77 concerns plant A6 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.261 kg.

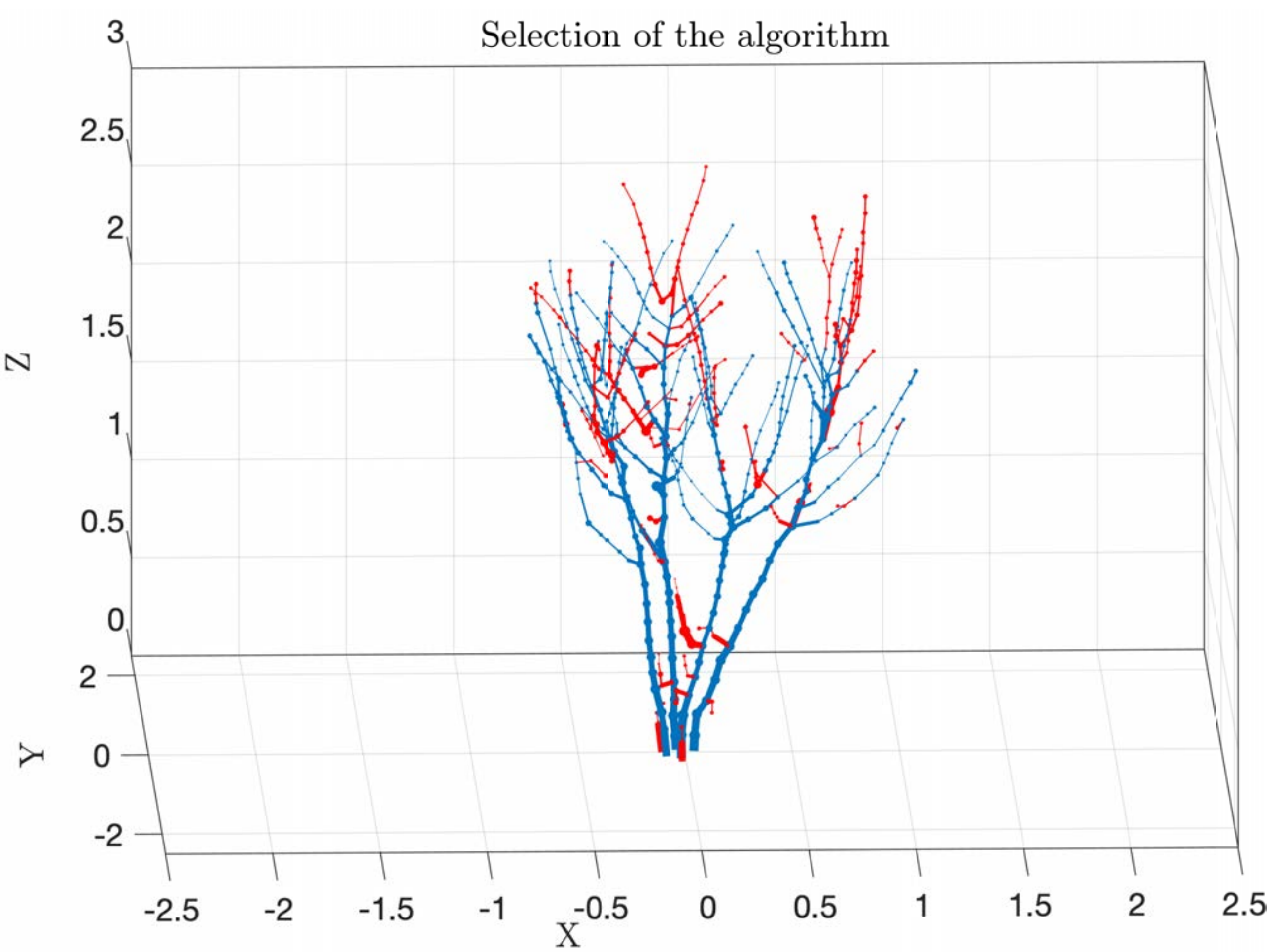

Figure 73 - Plant A6 where the algorithm has highlighted the branches to prune.

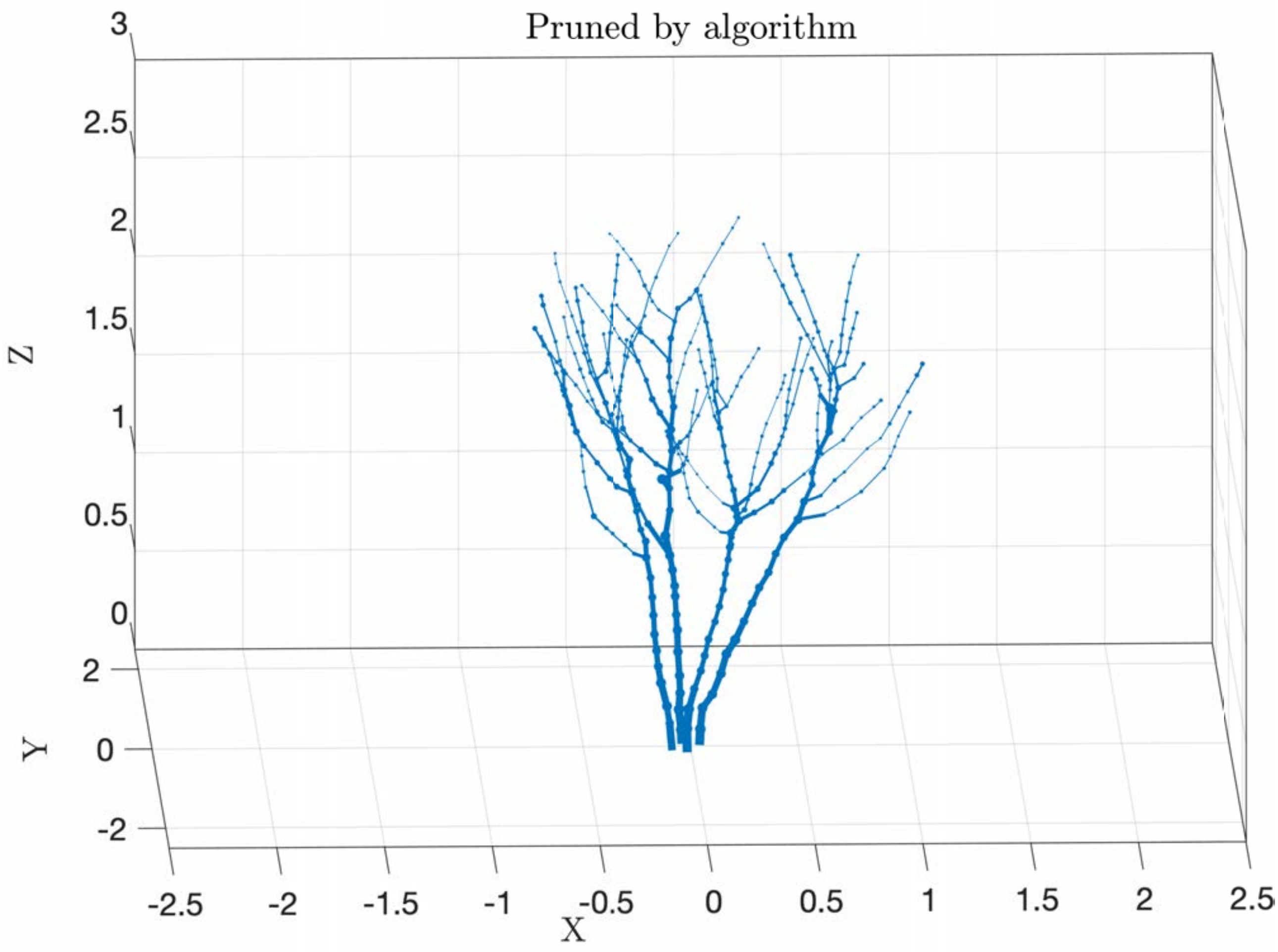

Figure 74 - Plant A6 pruned following the suggestions of the algorithm.

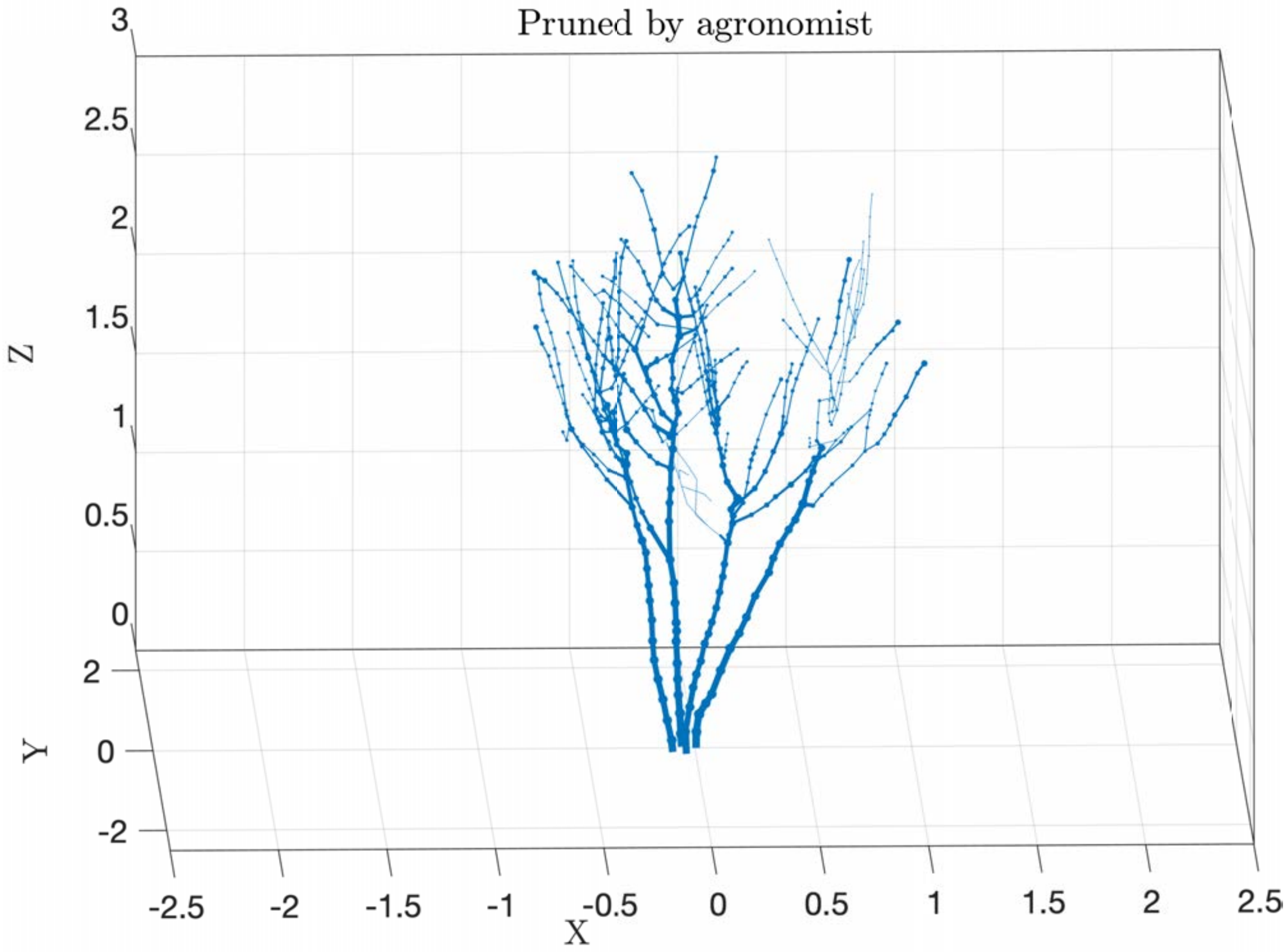

Figure 75 - Plant A6 pruned by an agronomical expert.

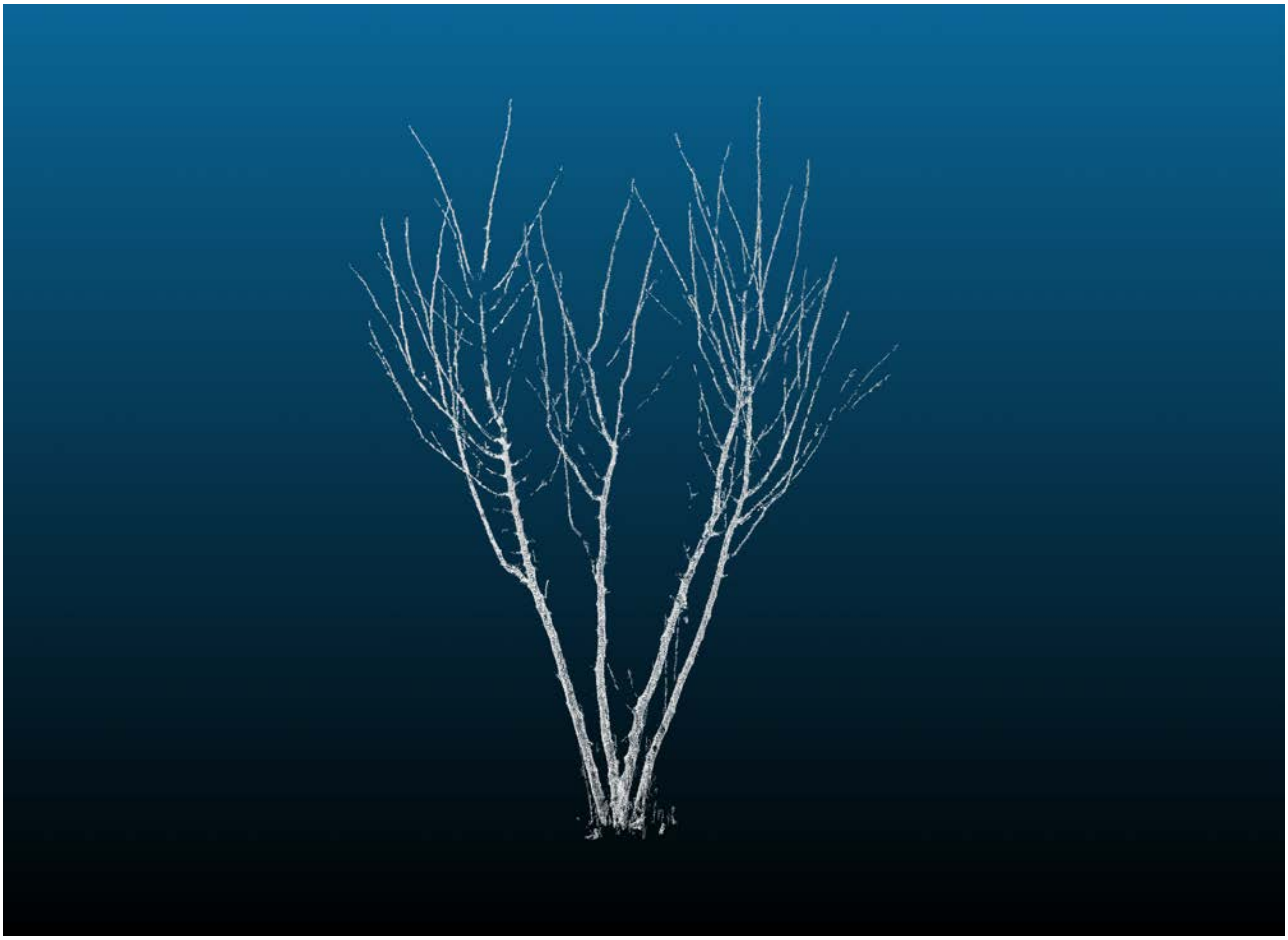

Figure 76 - 3D point cloud of A6 plant before pruning.

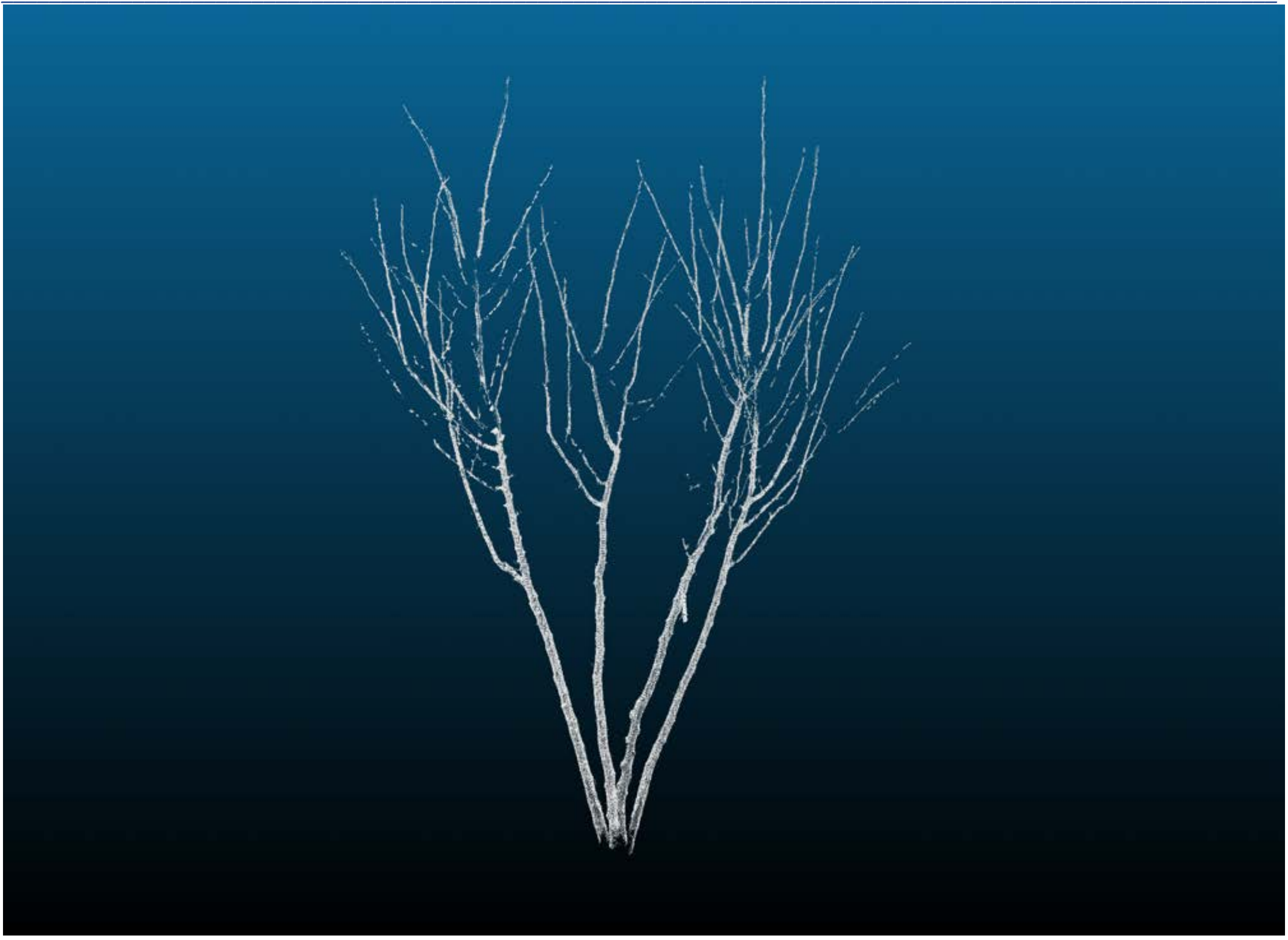

Figure 77 - 3D point cloud of A6 plant after pruning.

Plant A7

Figure 78 to Figure 82 concerns plant A7 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.495 kg.

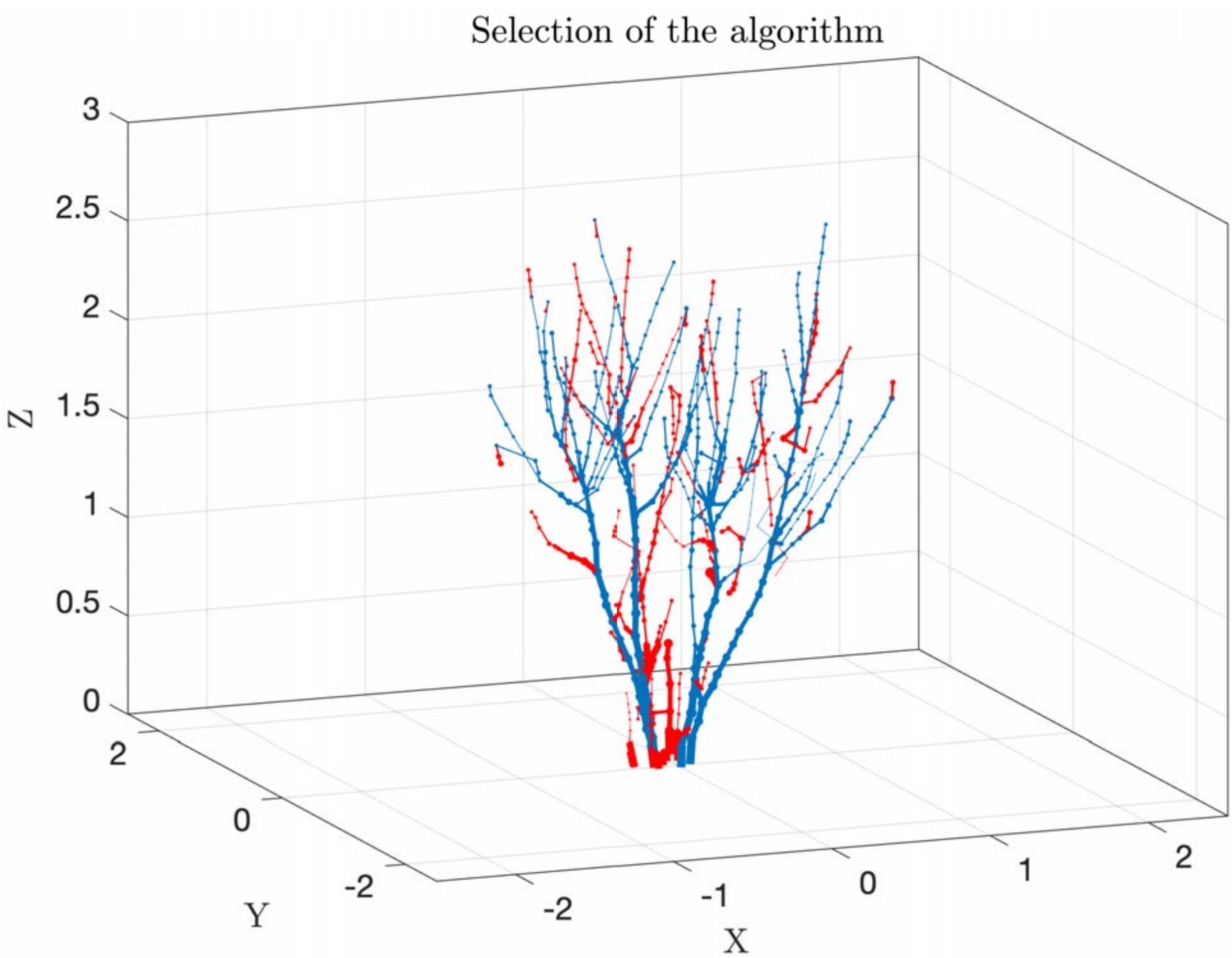

Figure 78 - Plant A7 where the algorithm has highlighted the branches to prune.

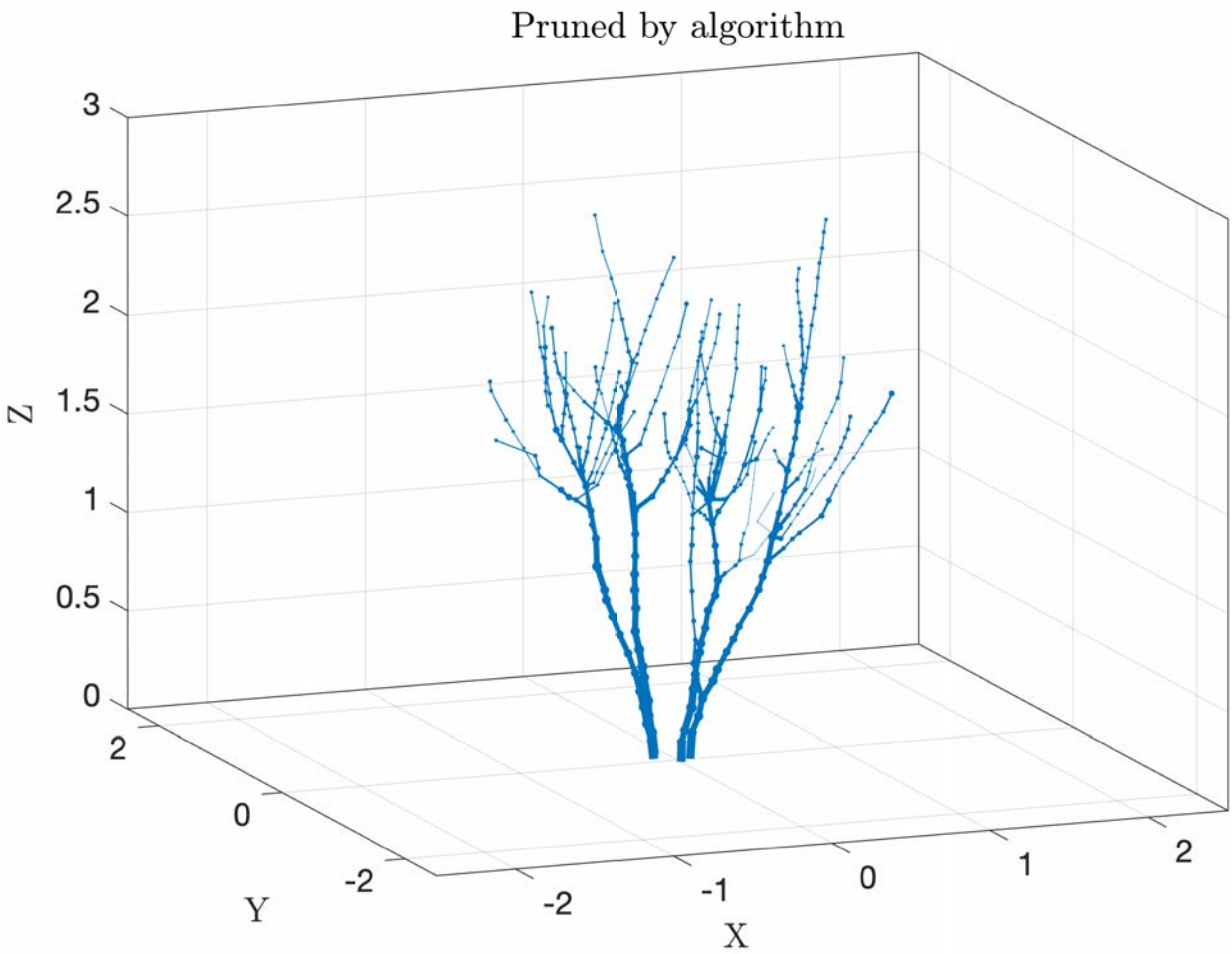

Figure 79 - Plant A7 pruned following the suggestions of the algorithm.

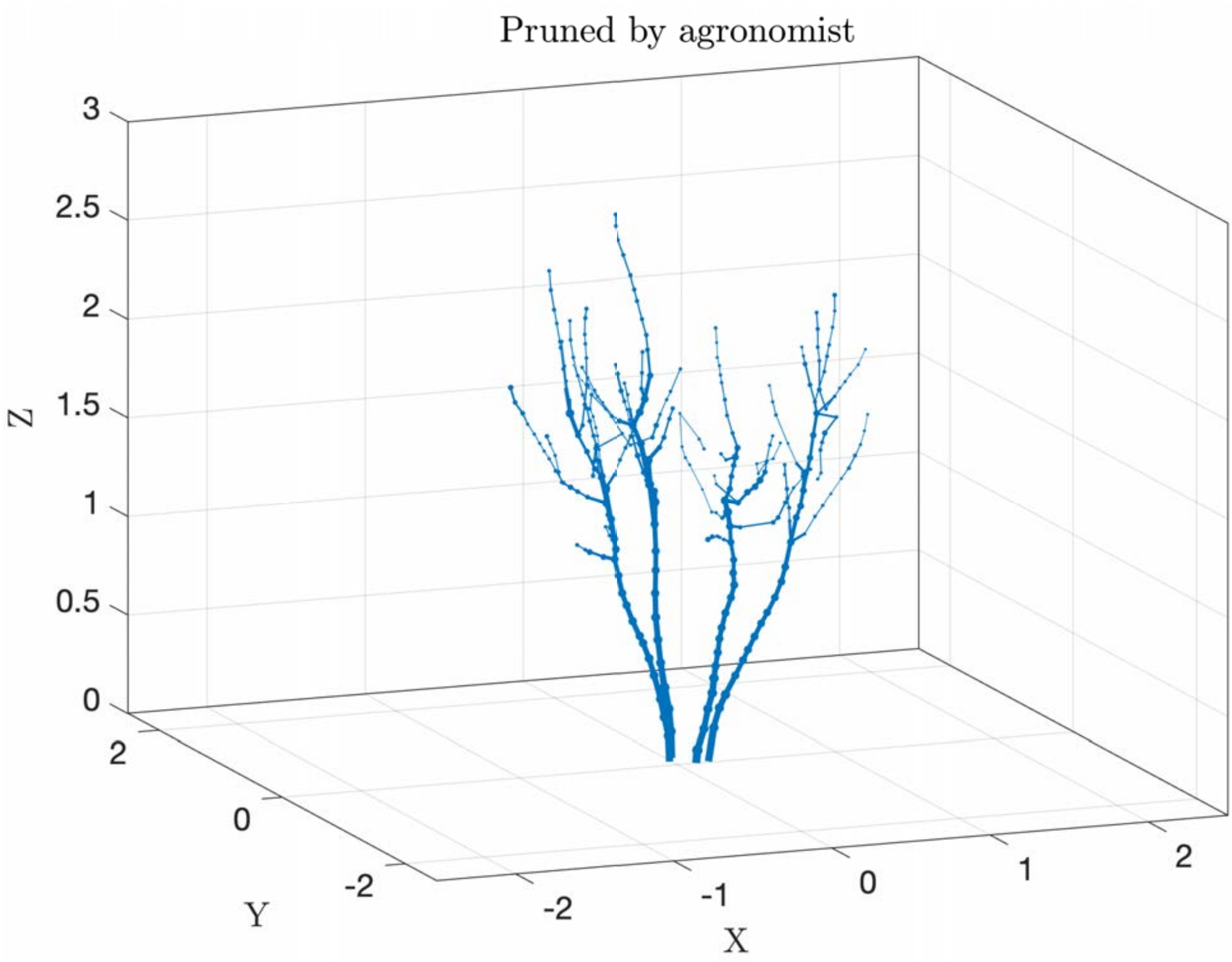

Figure 80 - Plant A7 pruned by an agronomical expert.

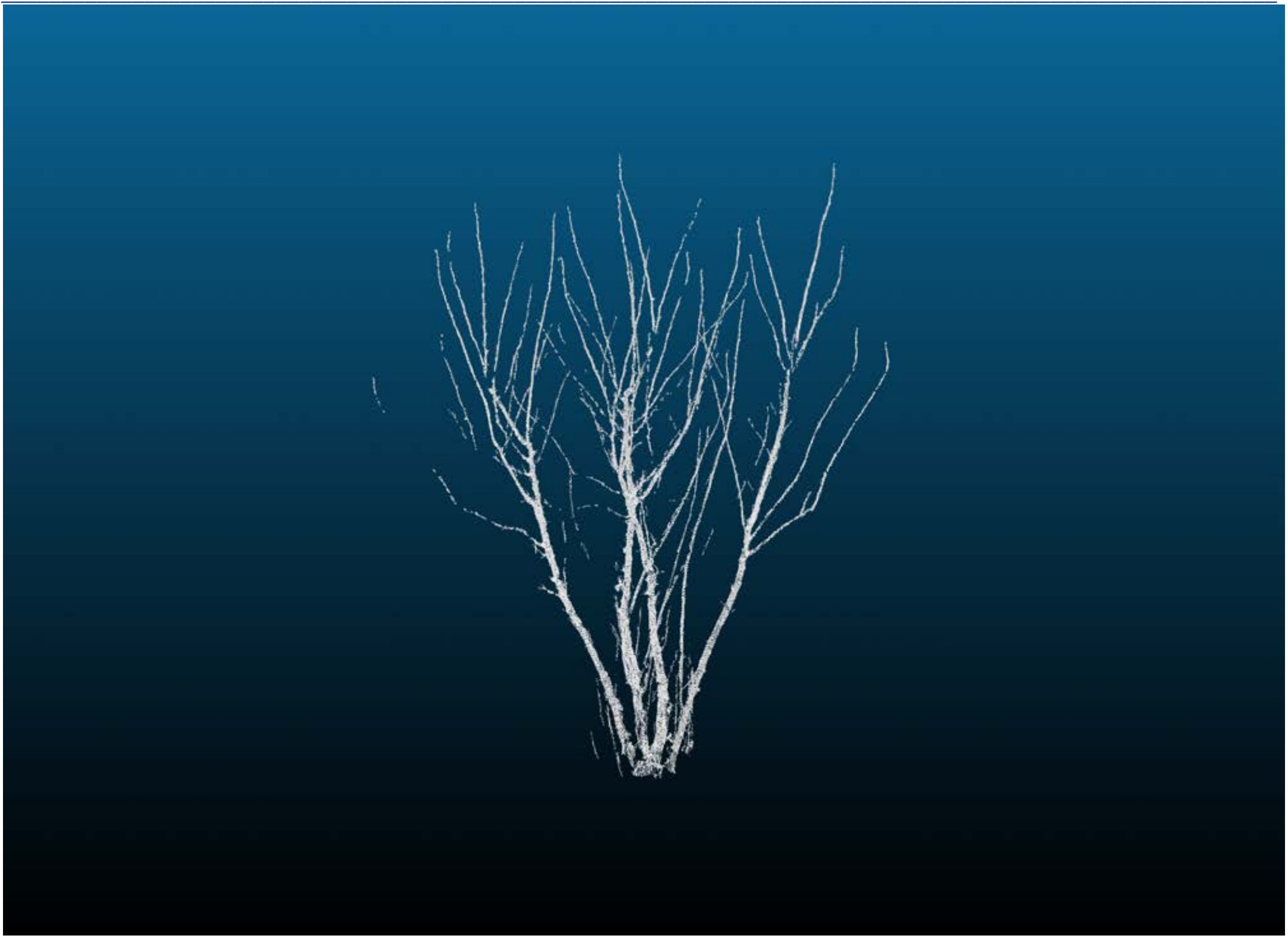

Figure 81 - 3D point cloud of A7 plant before pruning.

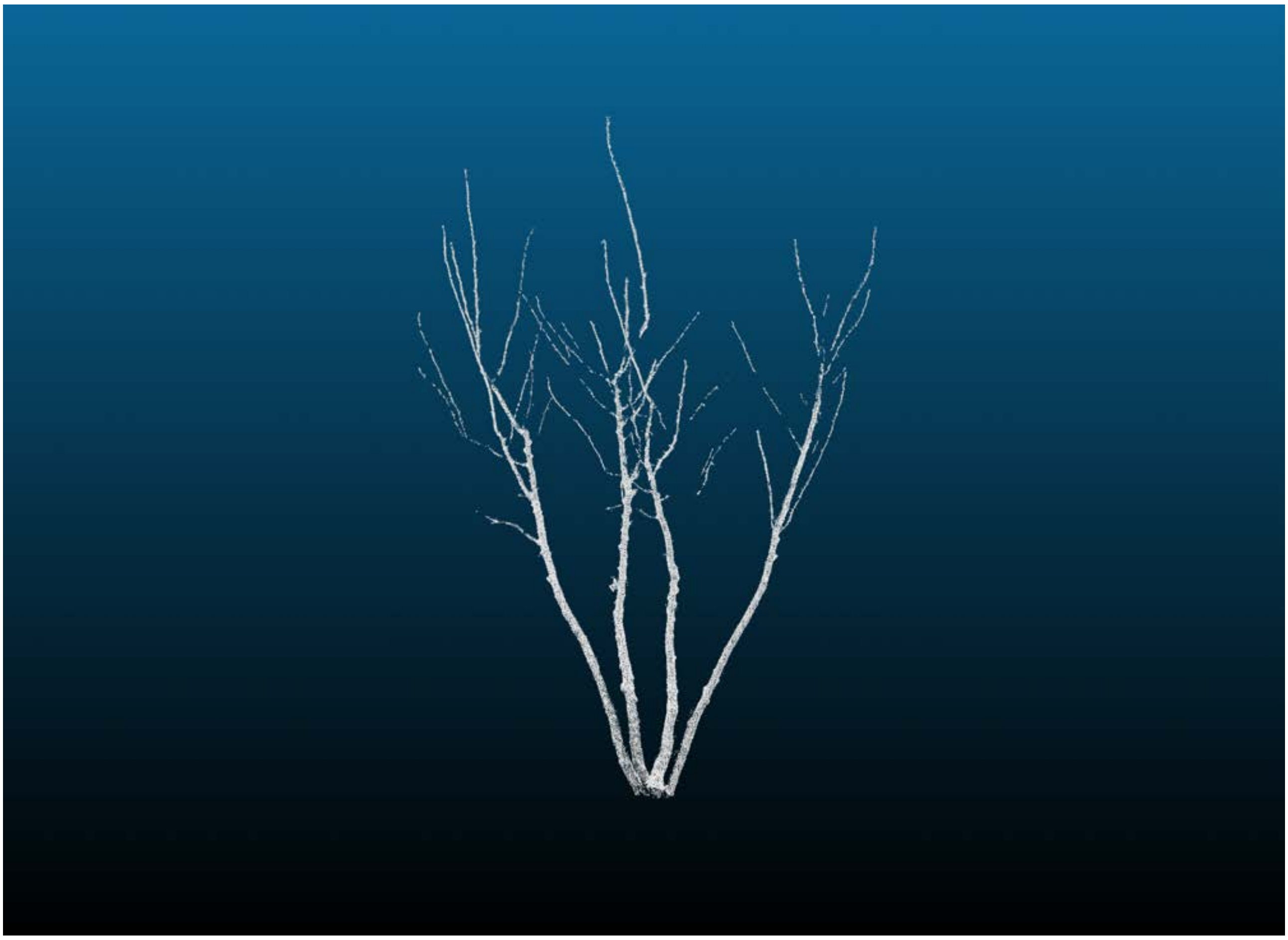

Figure 82 - 3D point cloud of A7 plant after pruning.

Plant B5

Figure 83 to Figure 87 concerns plant B5 of the orchard. The amount of pruned wood selected by the algorithm is equal to 0.170 kg.

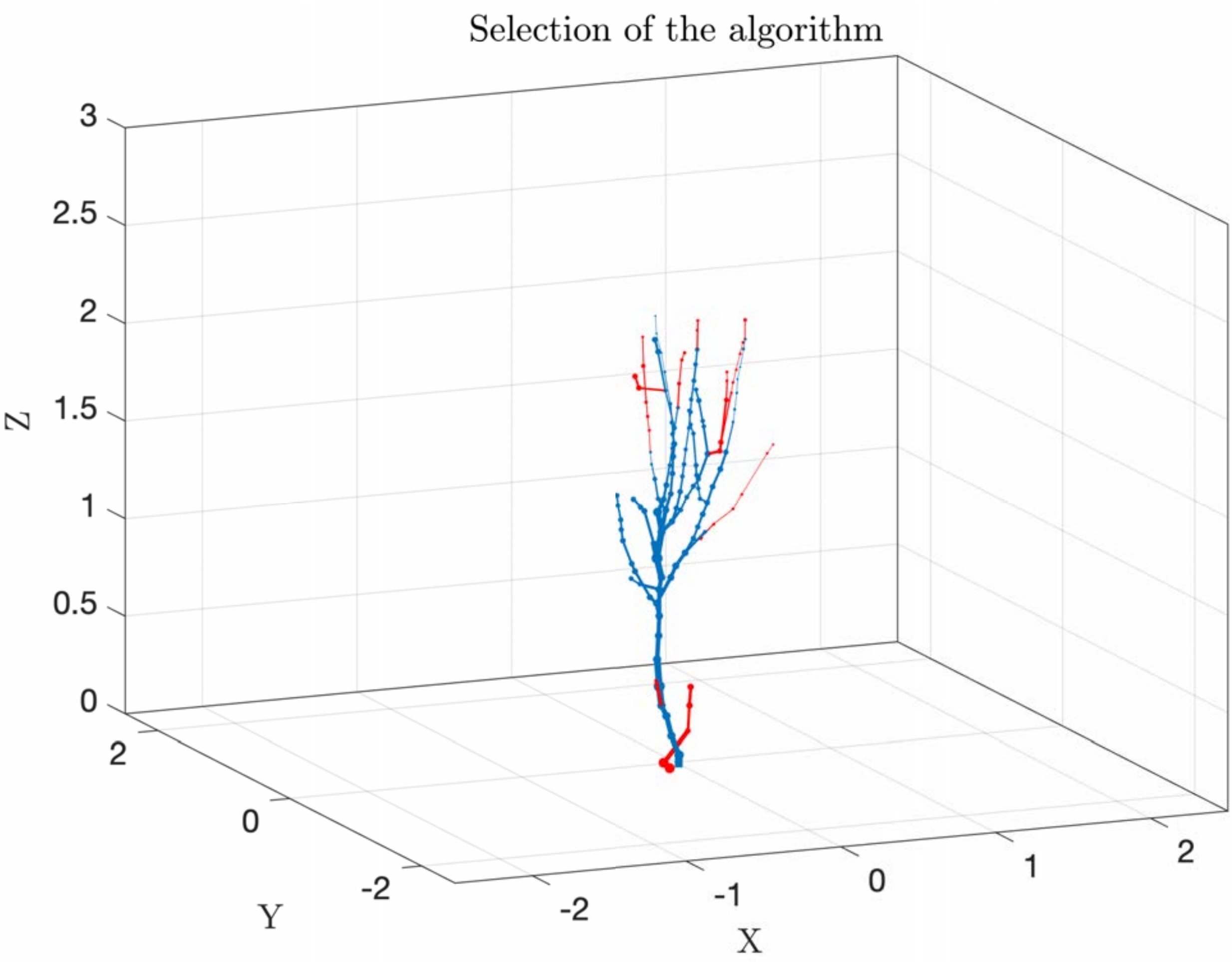

Figure 83 - Plant B5 where the algorithm has highlighted the branches to prune.

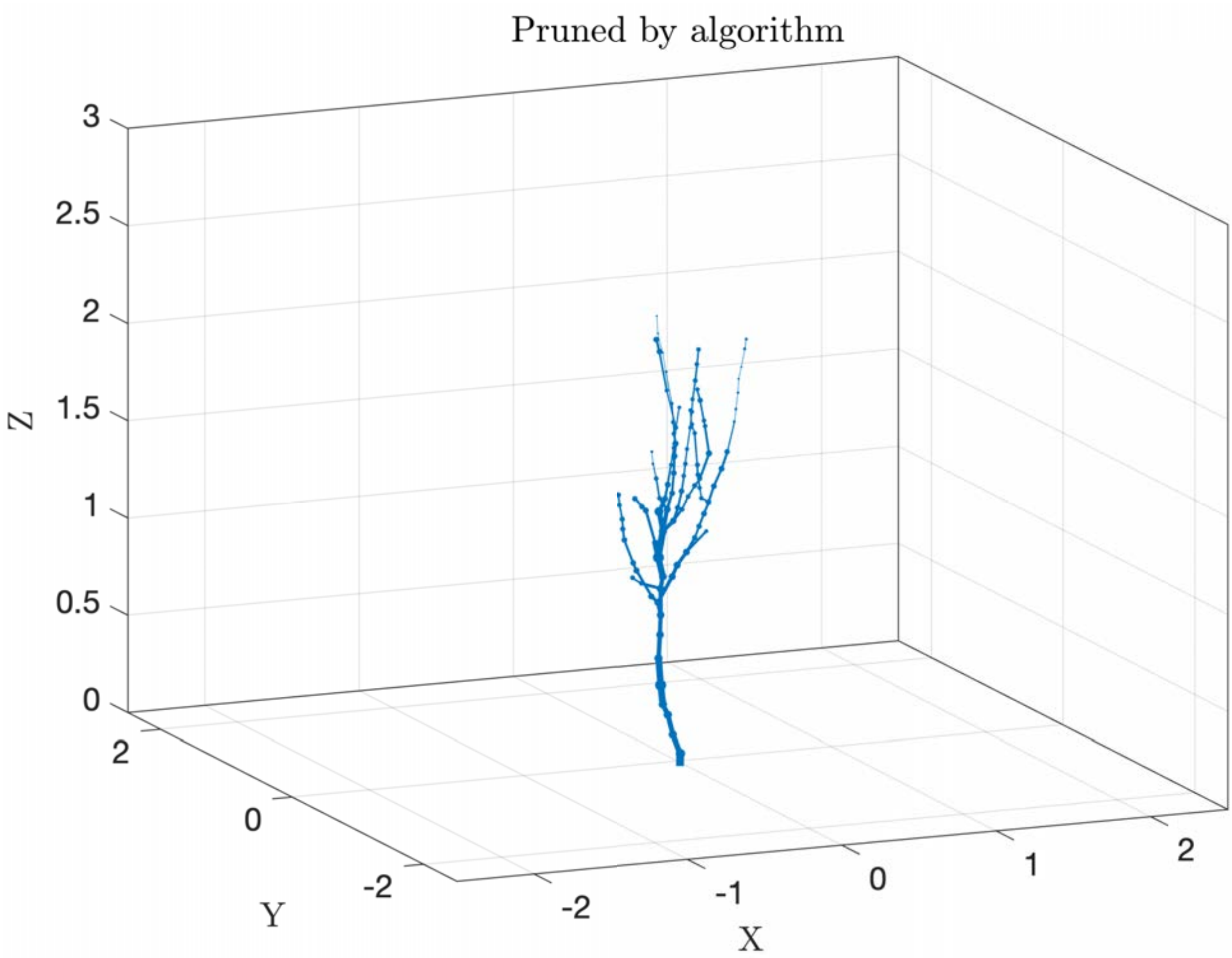

Figure 84 - Plant B5 pruned following the suggestions of the algorithm.

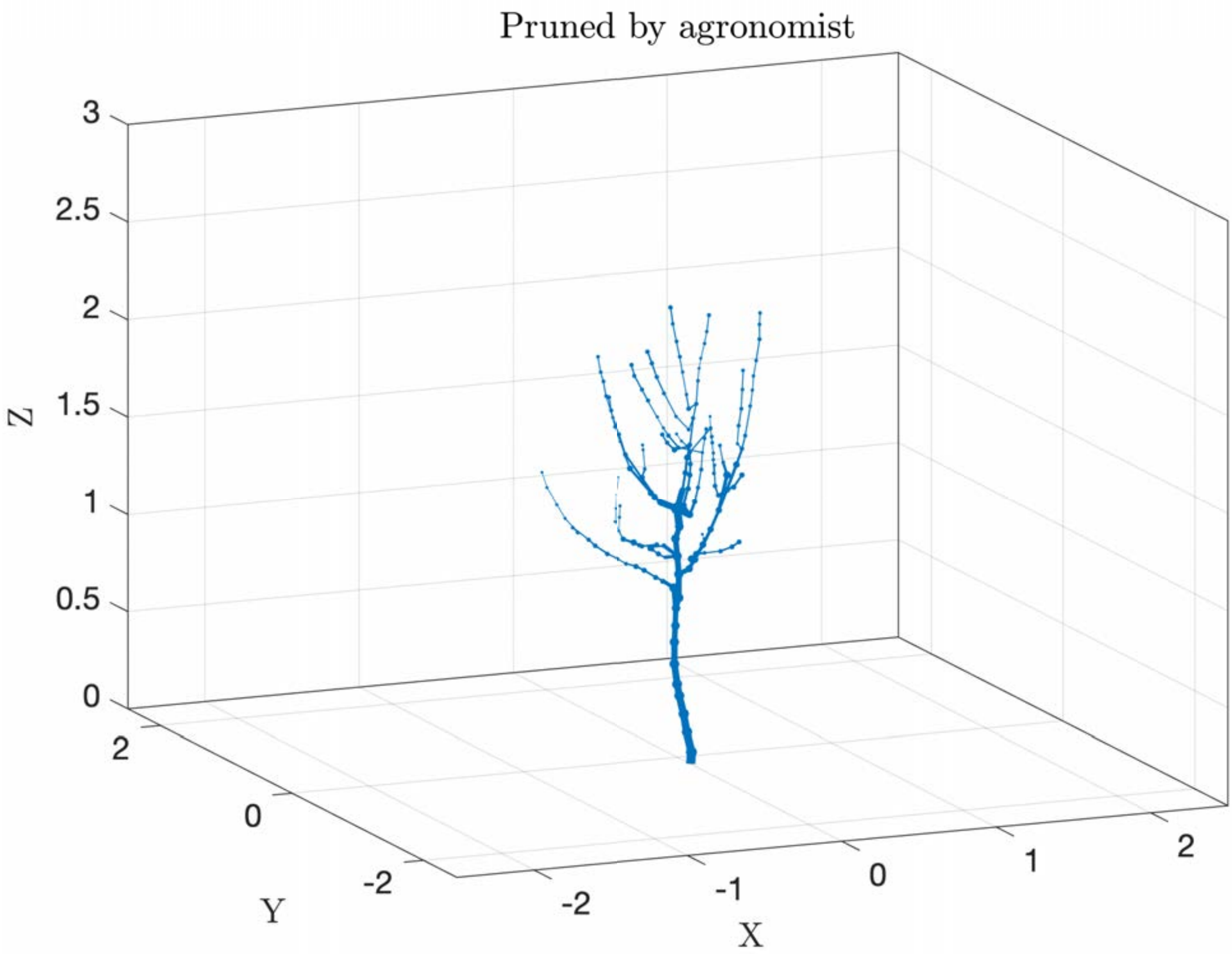

Figure 85 - Plant B5 pruned by an agronomical expert.

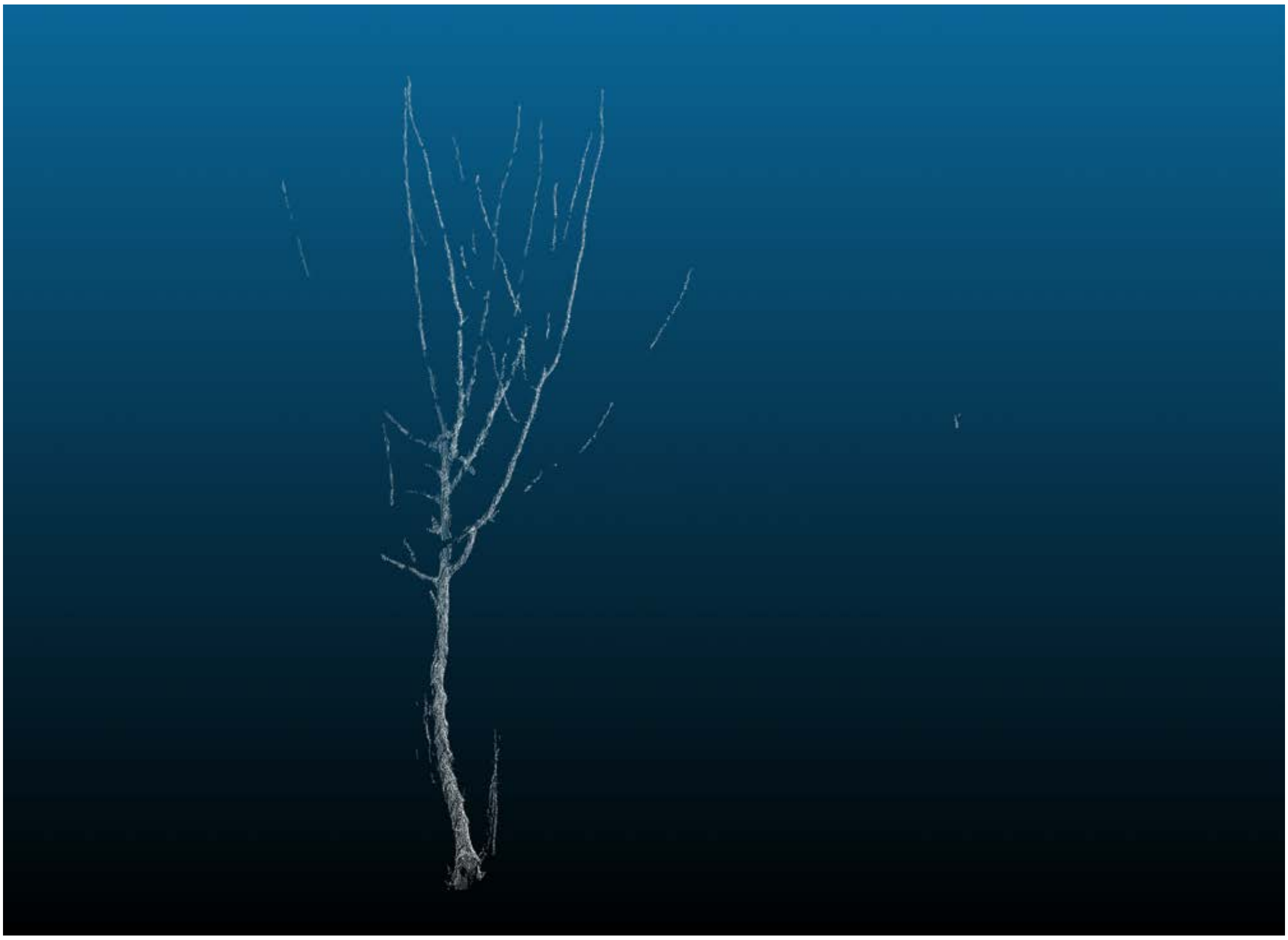

Figure 86 - 3D point cloud of B5 plant before pruning.

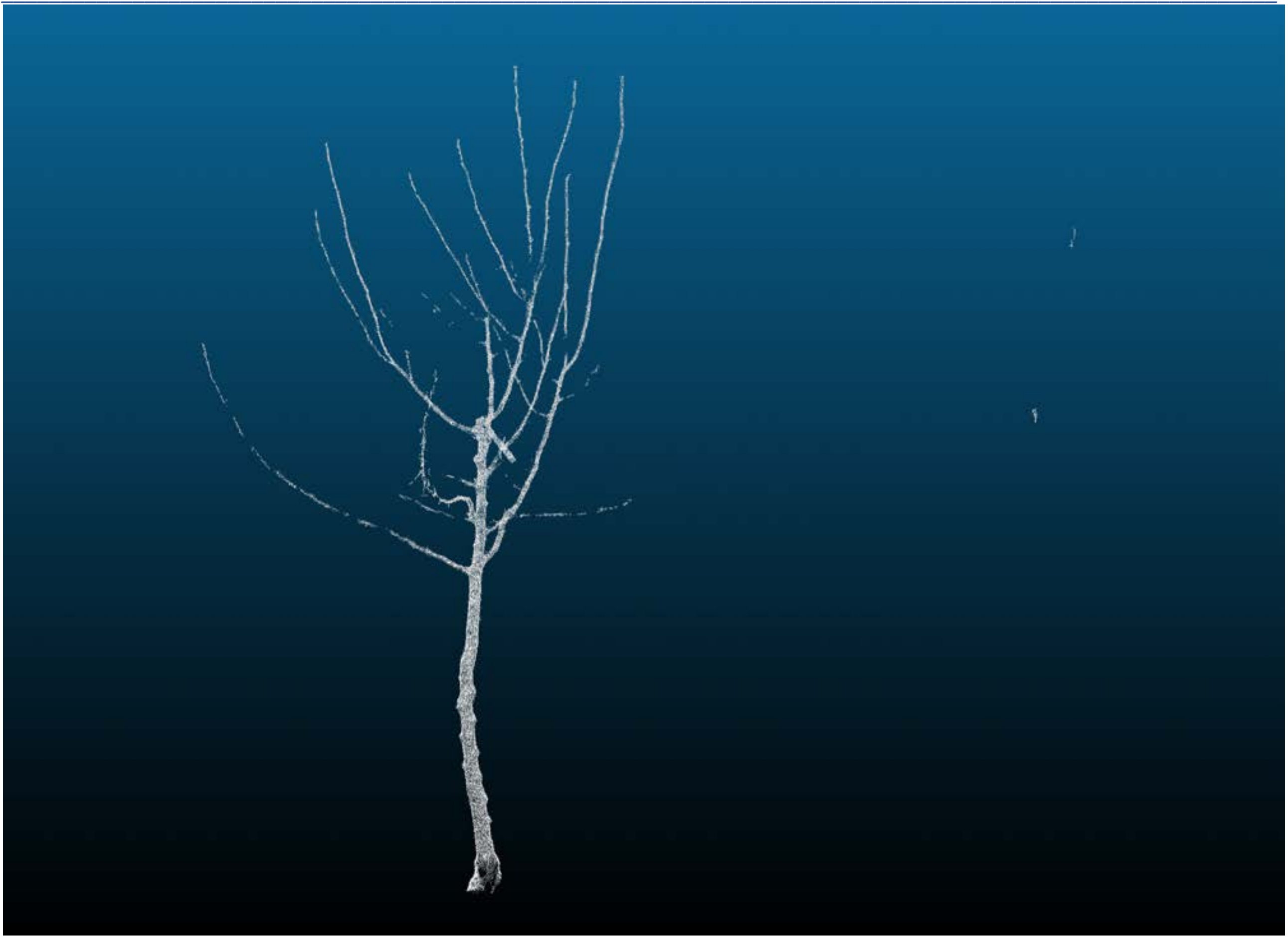

Figure 87 - 3D point cloud of B5 plant after pruning.

Plant B7

Figure 88 to Figure 92 concerns plant B7 of the orchard. The amount of pruned wood selected by the algorithm is equal to 0.600 kg.

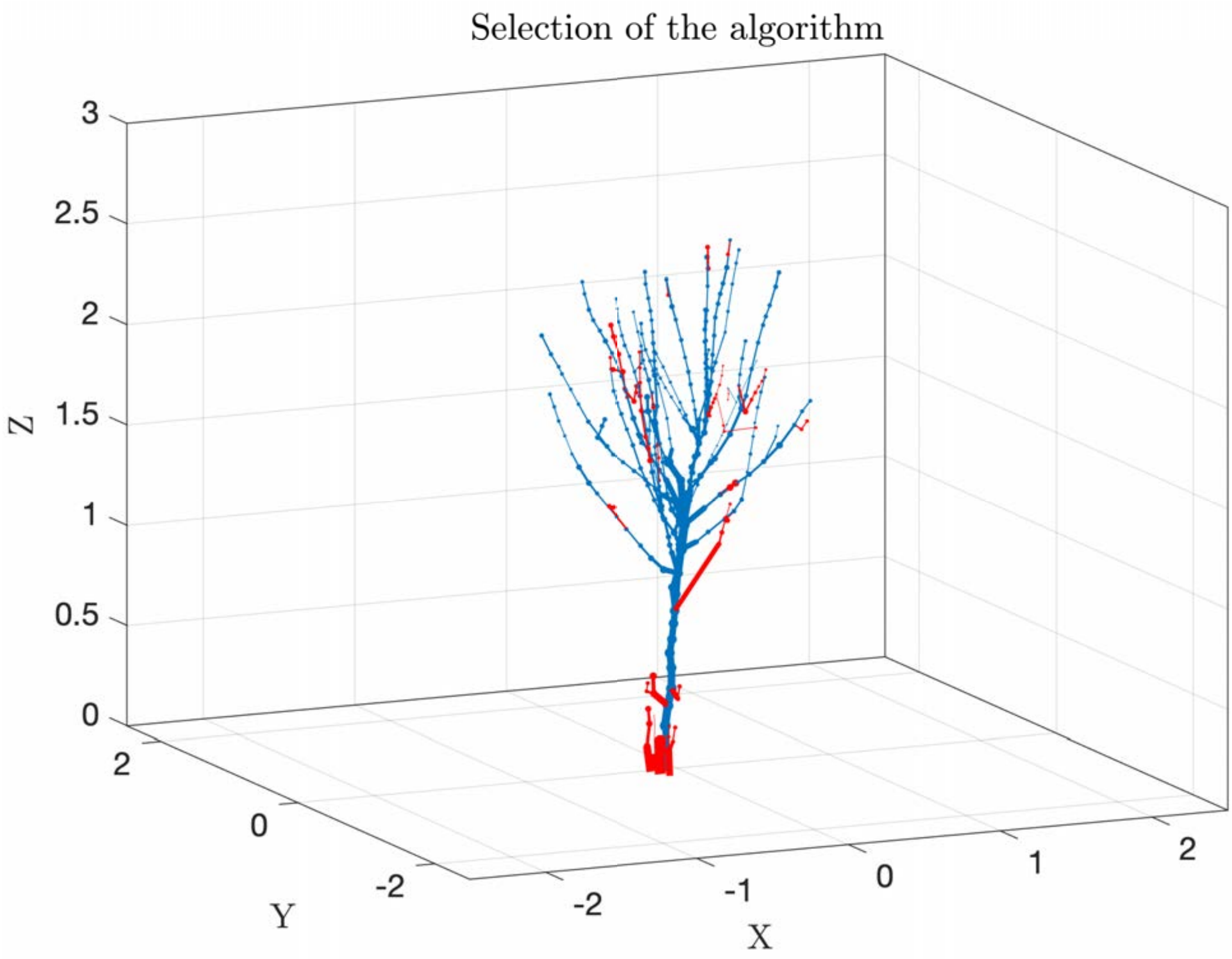

Figure 88 - Plant B7 where the algorithm has highlighted the branches to prune.

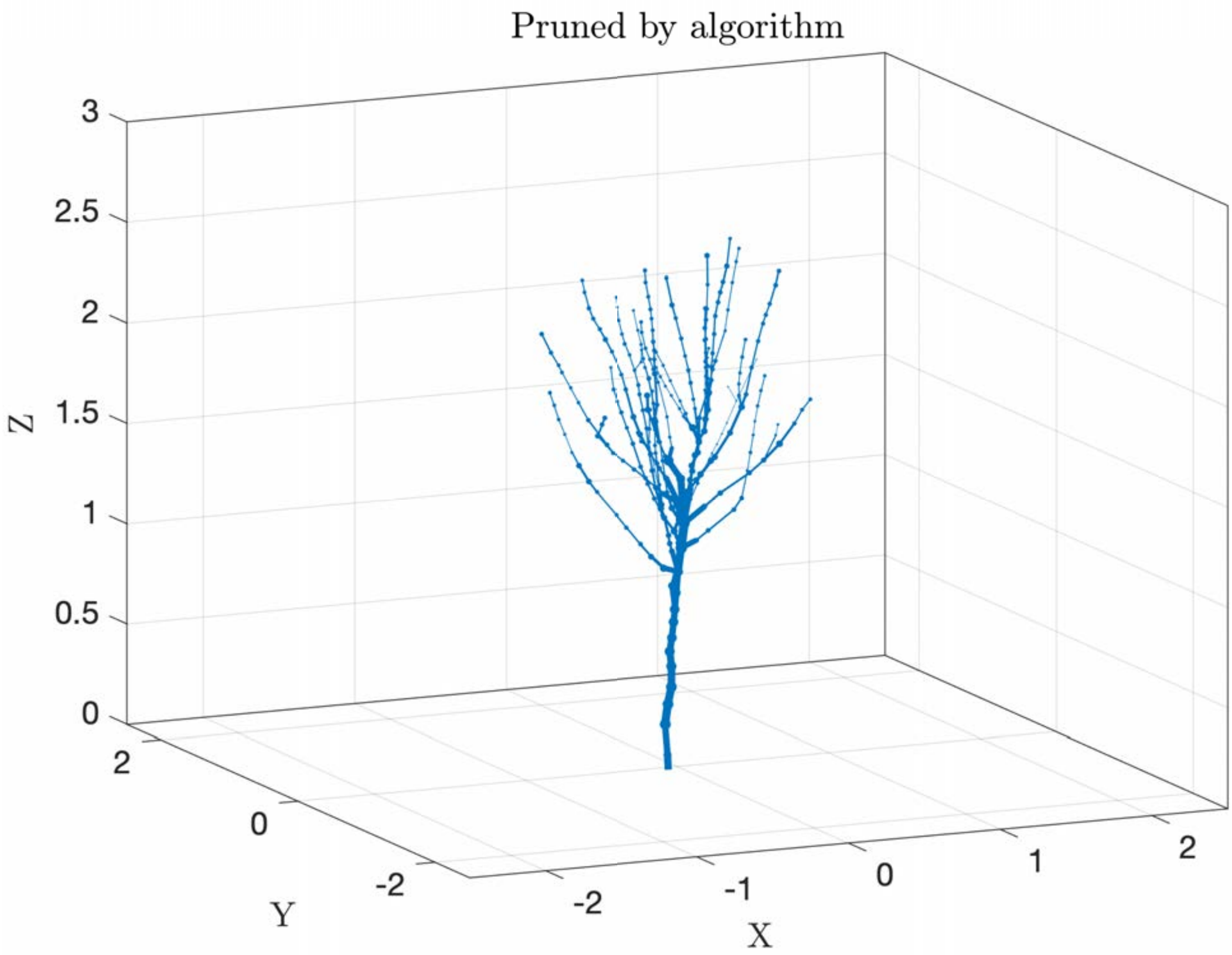

Figure 89 - Plant B7 pruned following the suggestions of the algorithm.

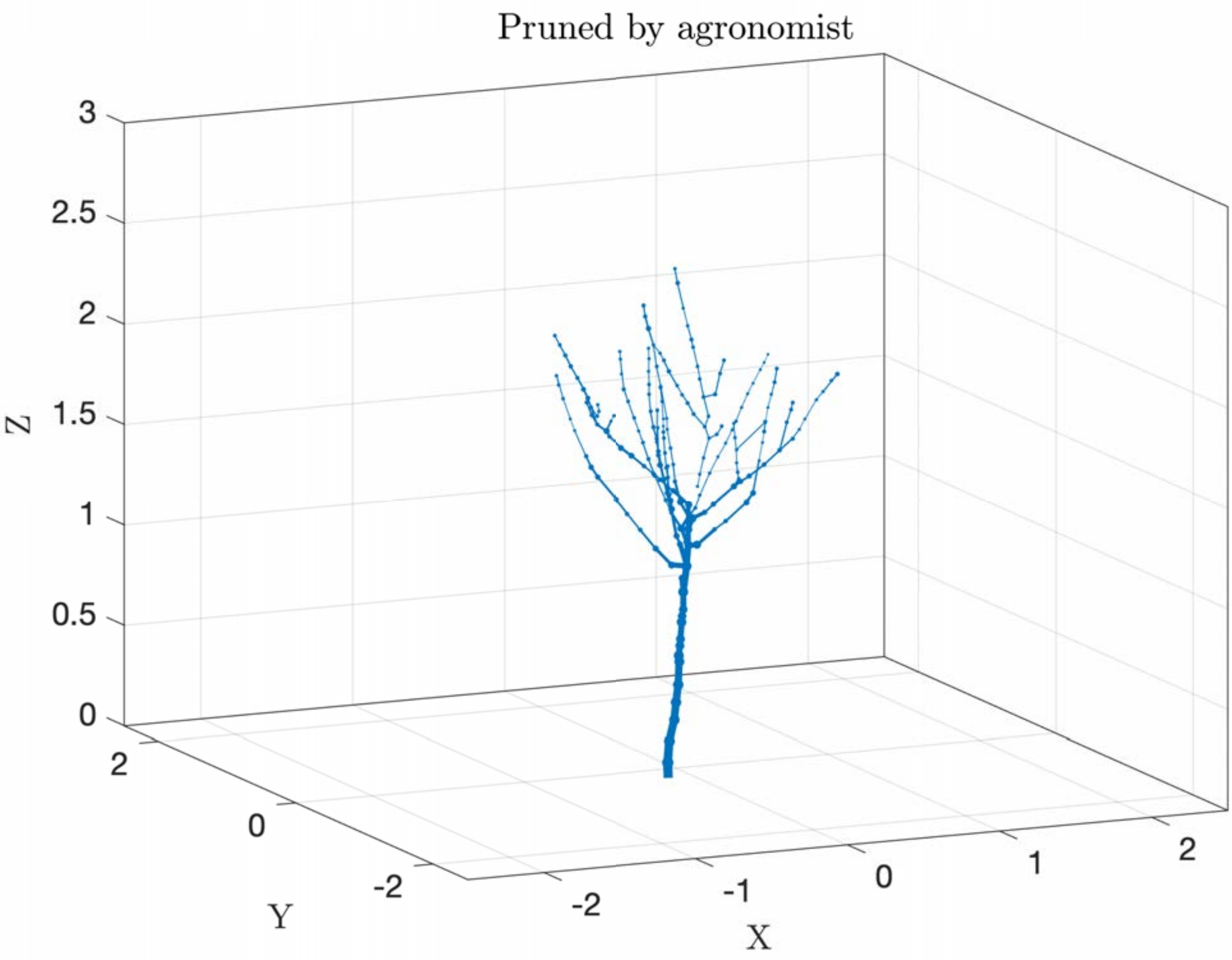

Figure 90 - Plant B7 pruned by an agronomical expert.

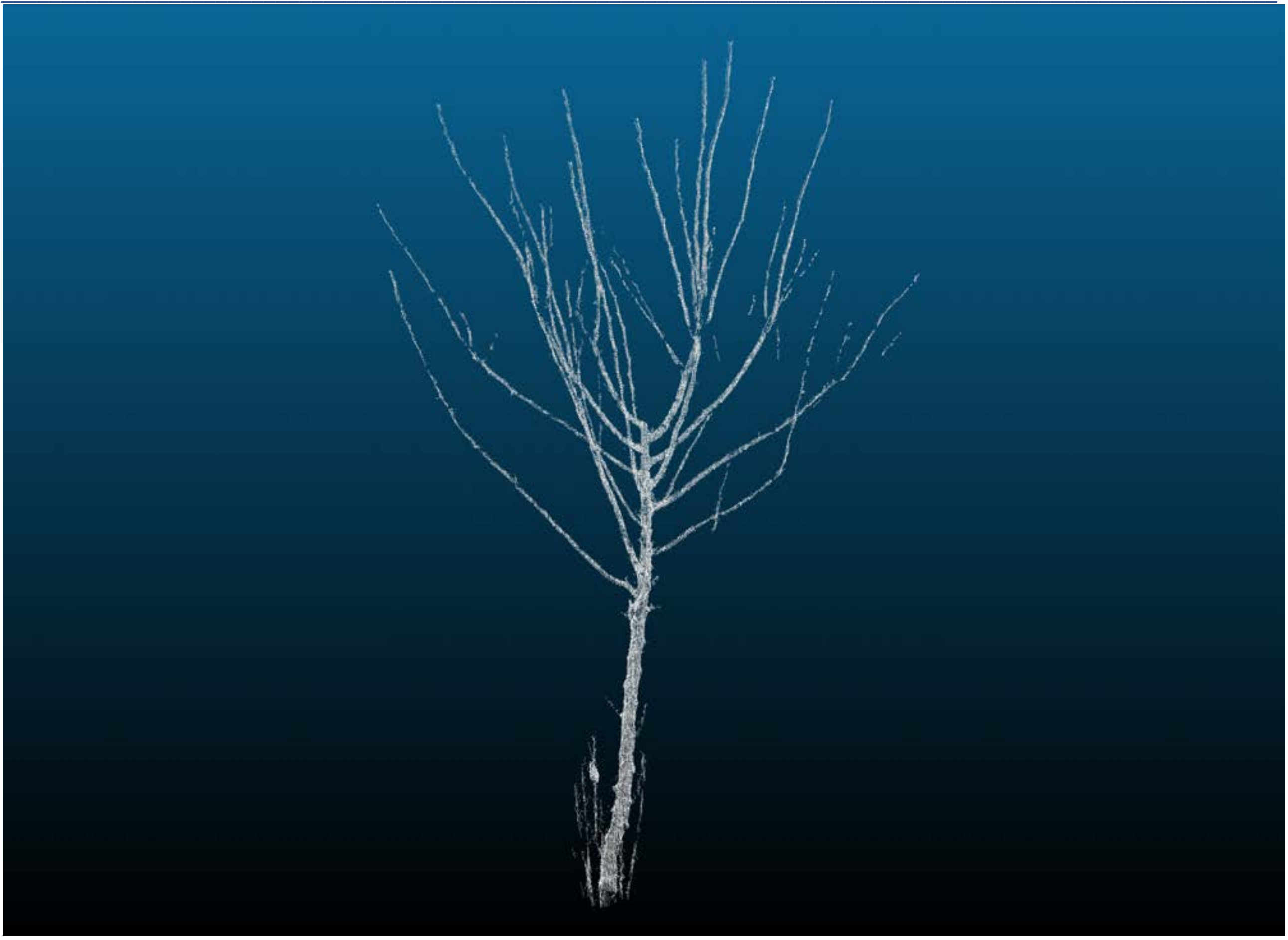

Figure 91 - 3D point cloud of B7 plant before pruning.

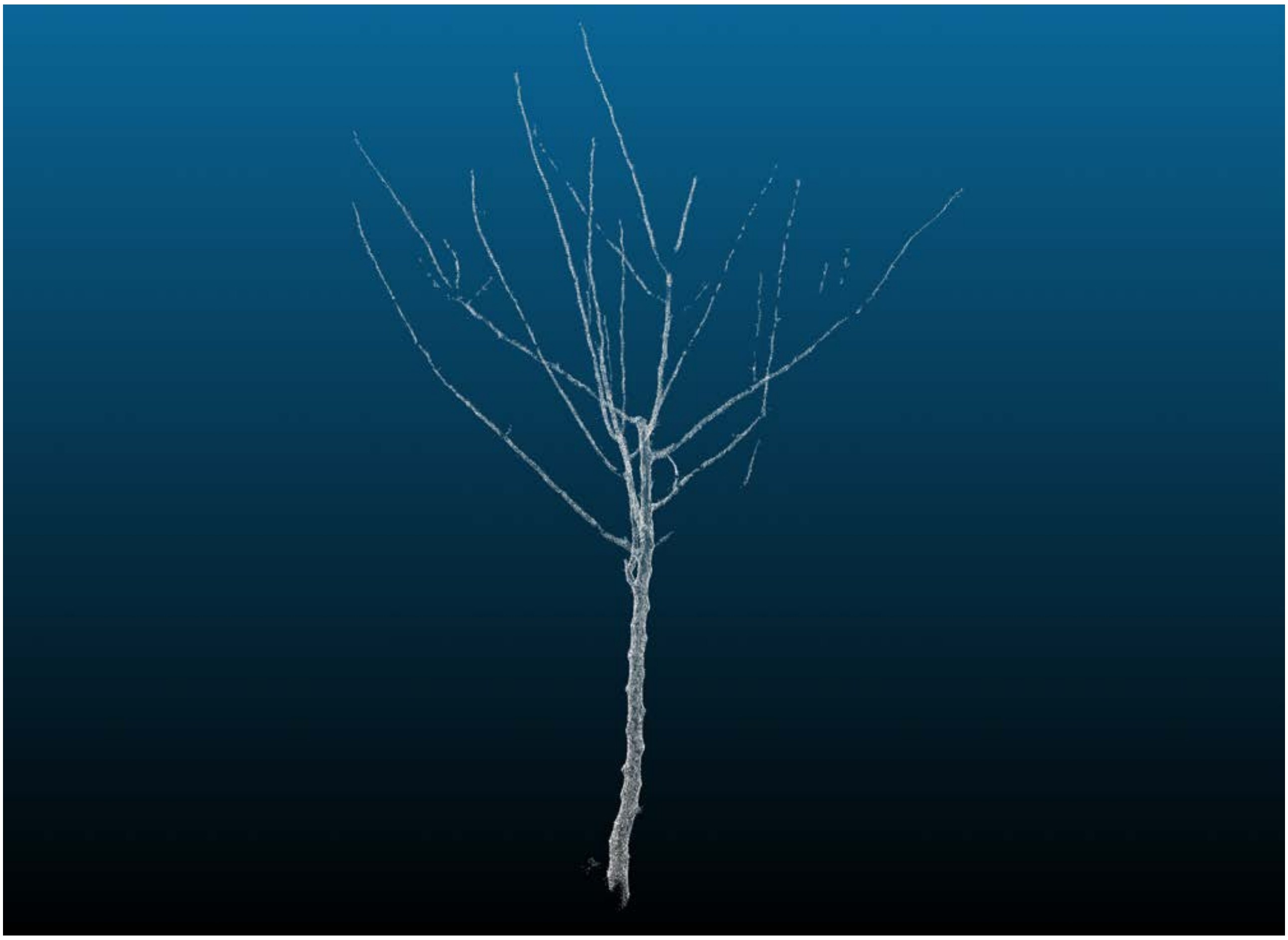

Figure 92 - 3D point cloud of B7 plant after pruning.

Plant C7

Figure 93 to Figure 97 concerns plant C7 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.748 kg.

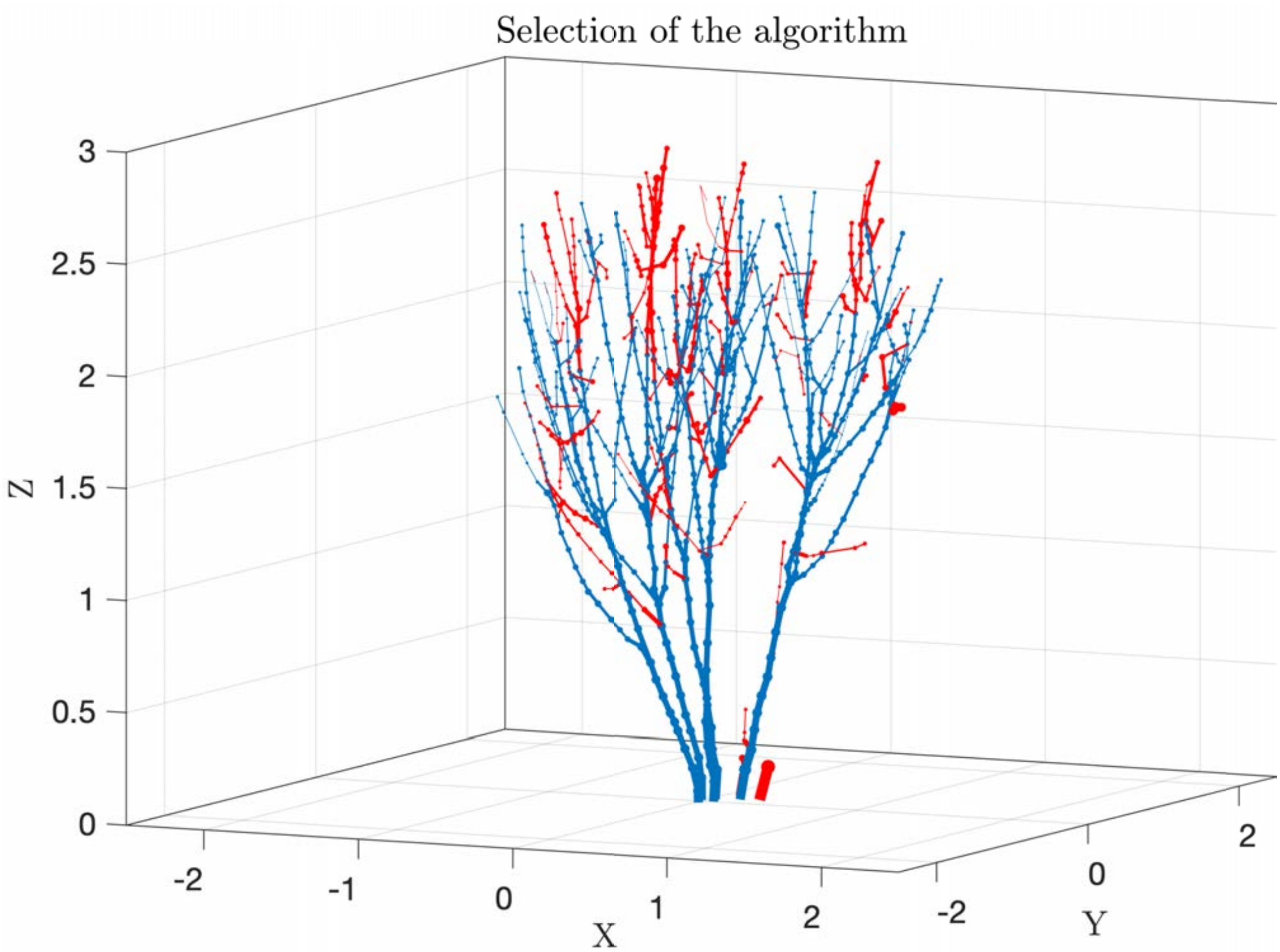

Figure 93 - Plant C7 where the algorithm has highlighted the branches to prune.

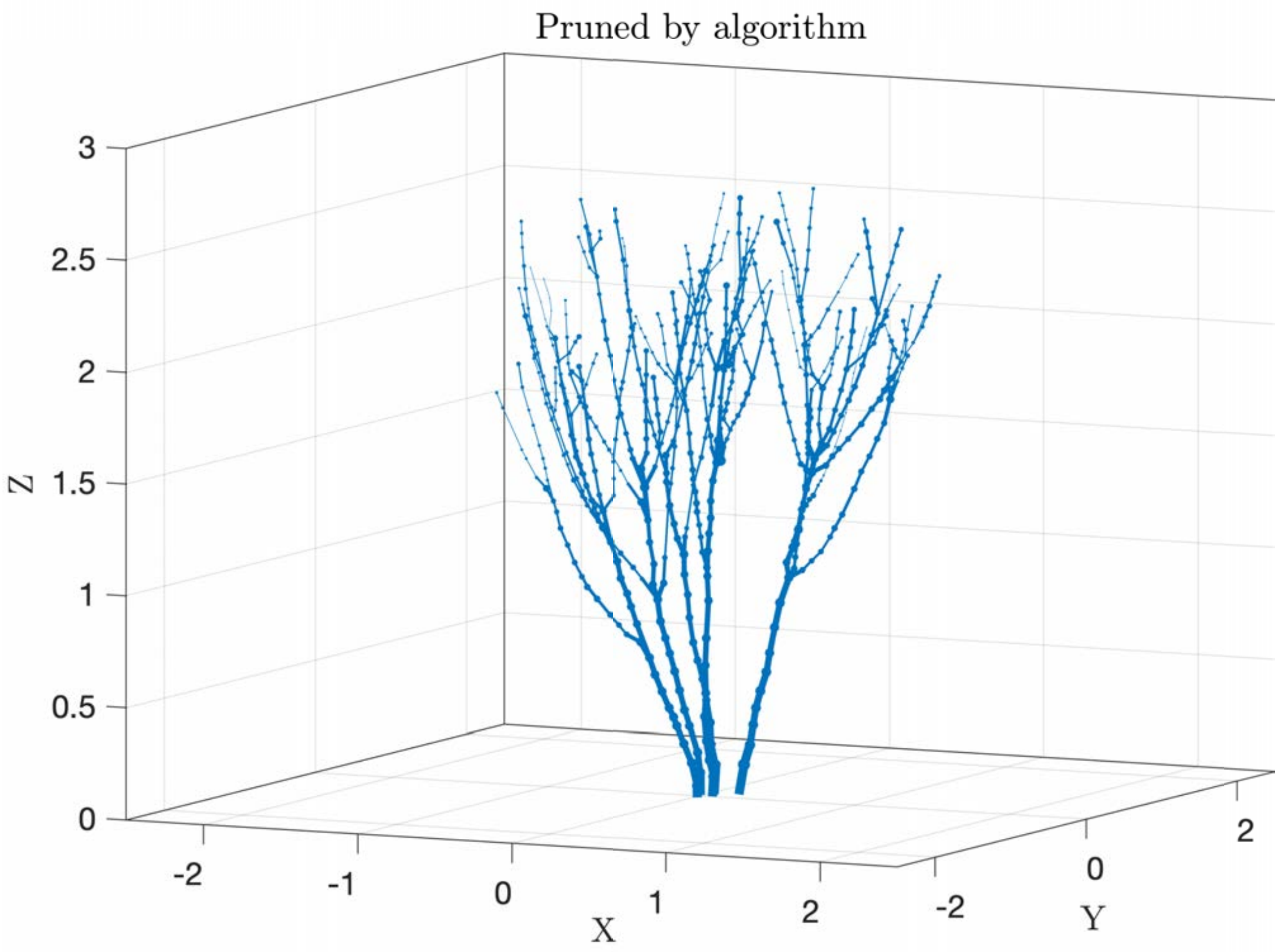

Figure 94 - Plant C7 pruned following the suggestions of the algorithm.

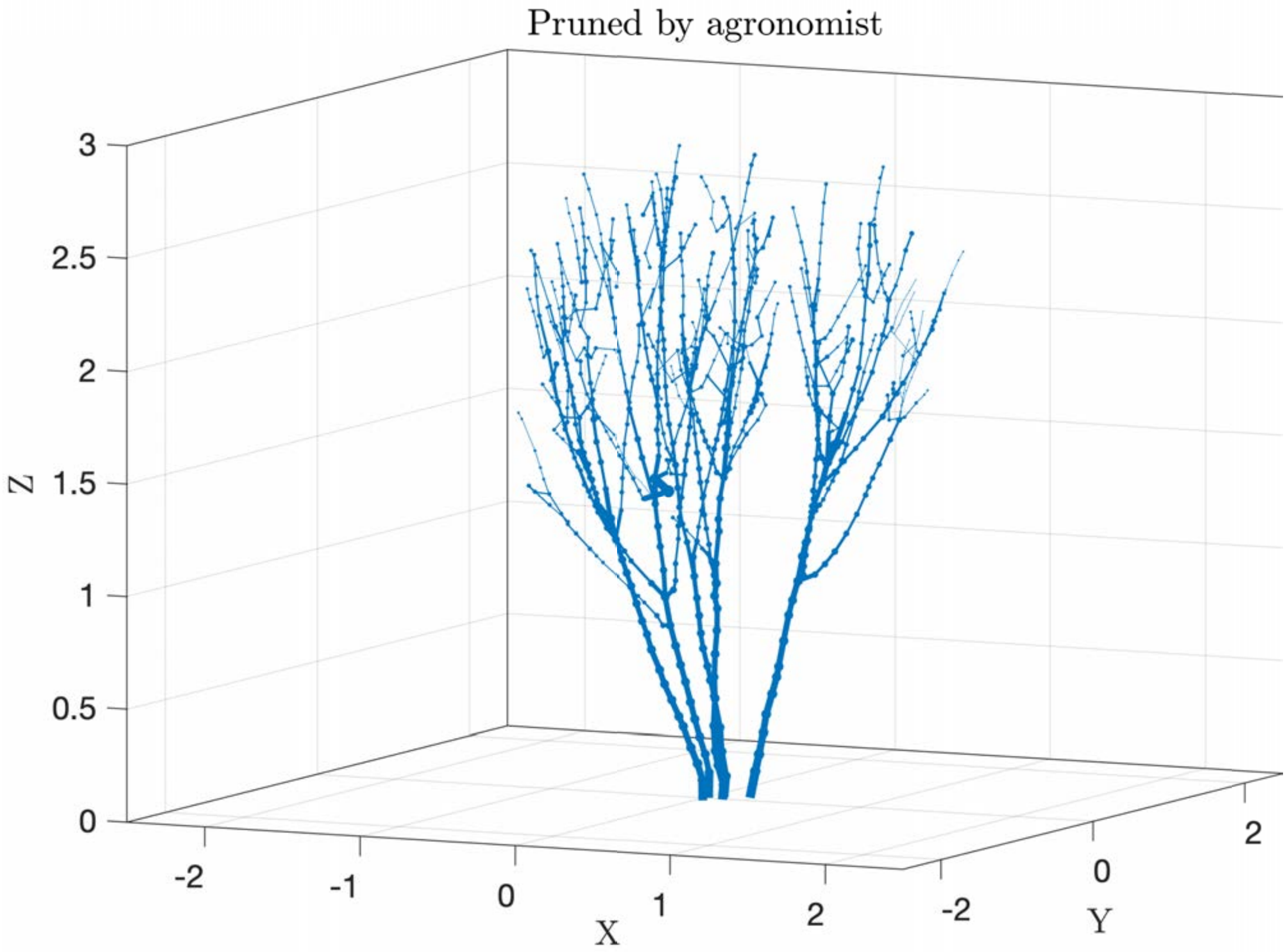

Figure 95 - Plant C7 pruned by an agronomical expert.

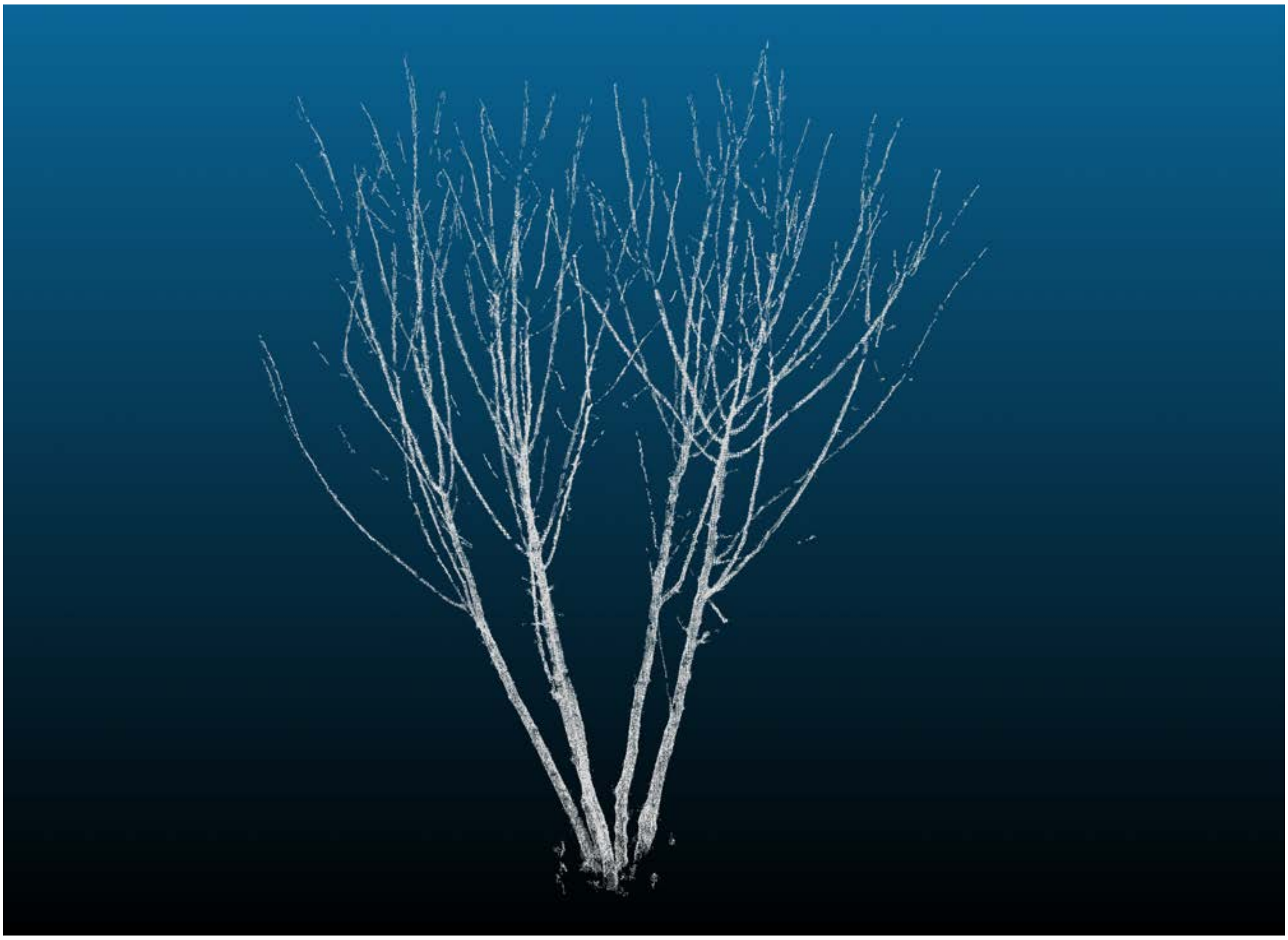

Figure 96 - 3D point cloud of C7 plant before pruning.

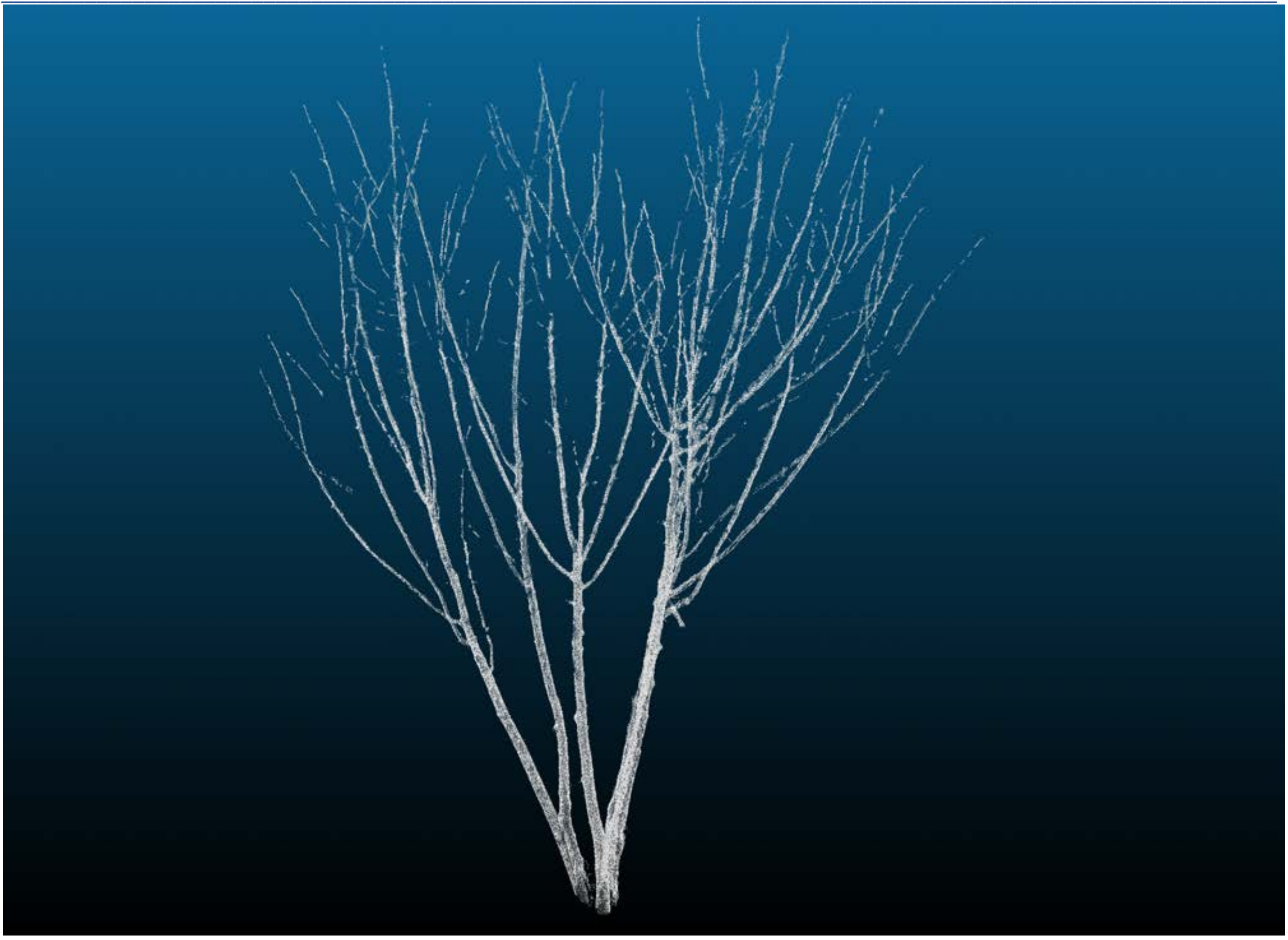

Figure 97 - 3D point cloud of C7 plant after pruning.

Plant C9

Figure 98 to Figure 102 concerns plant C9 of the orchard. The amount of pruned wood selected by the algorithm is equal to 1.272 kg.

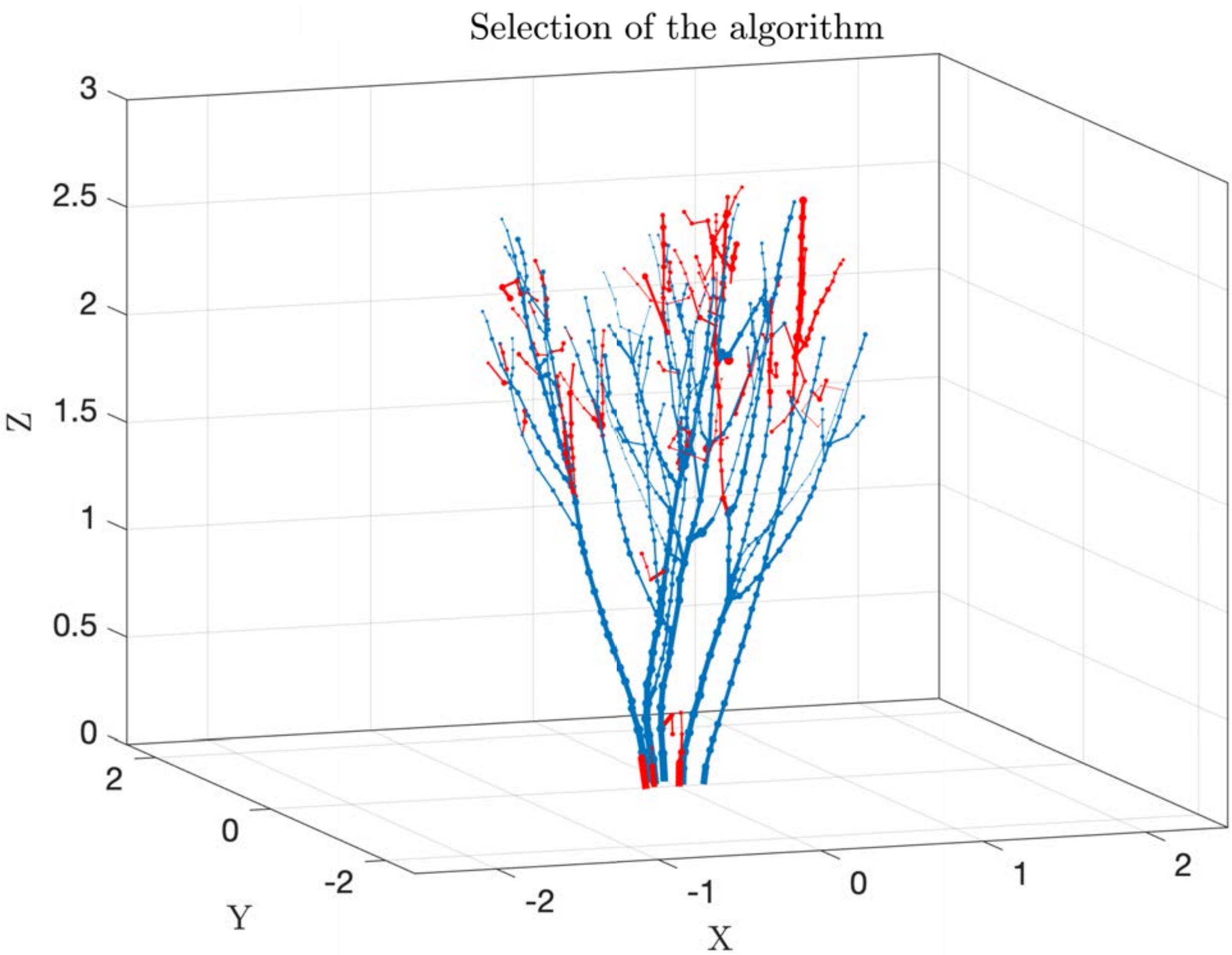

Figure 98 - Plant C9 where the algorithm has highlighted the branches to prune.

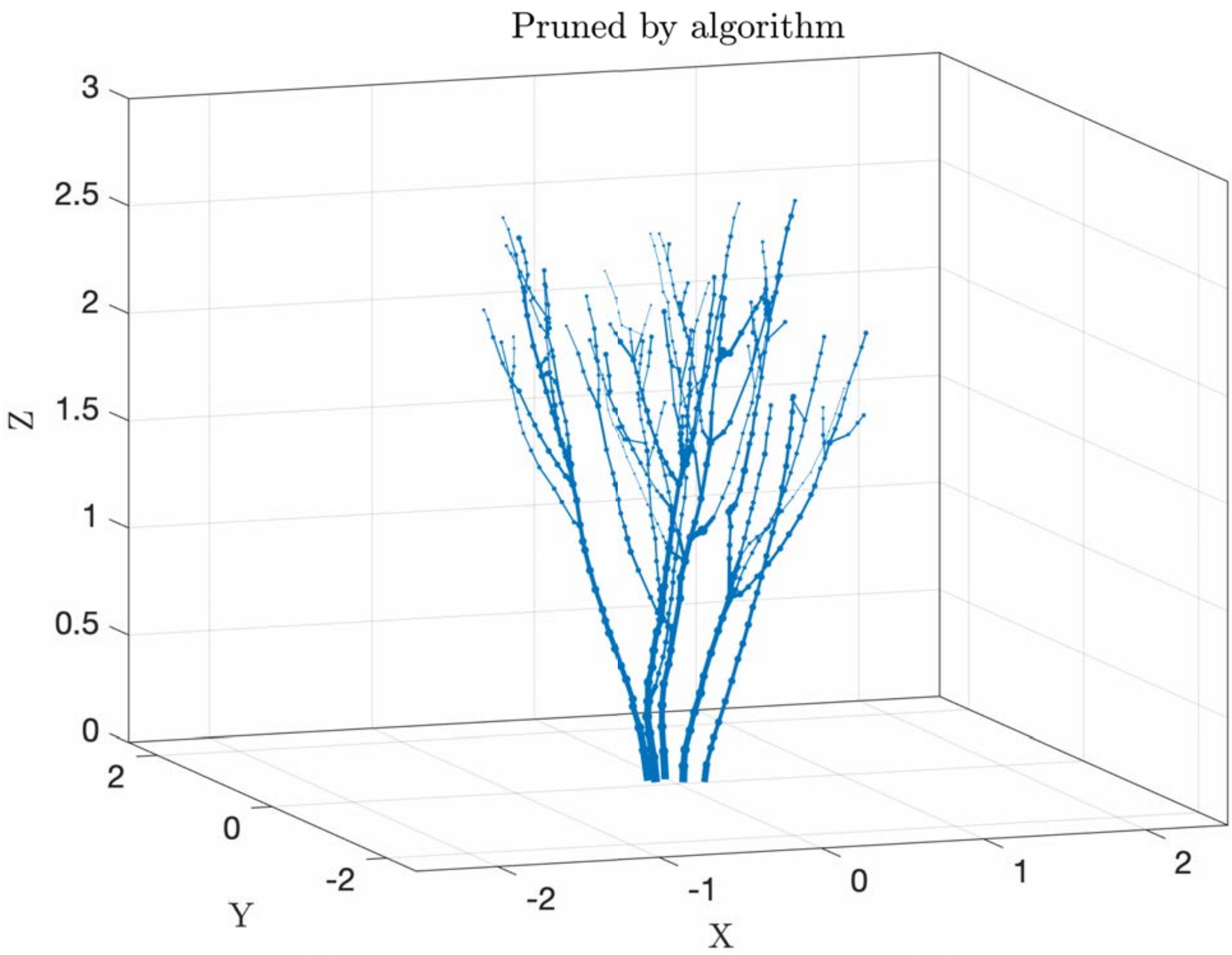

Figure 99 - Plant C9 pruned following the suggestions of the algorithm.

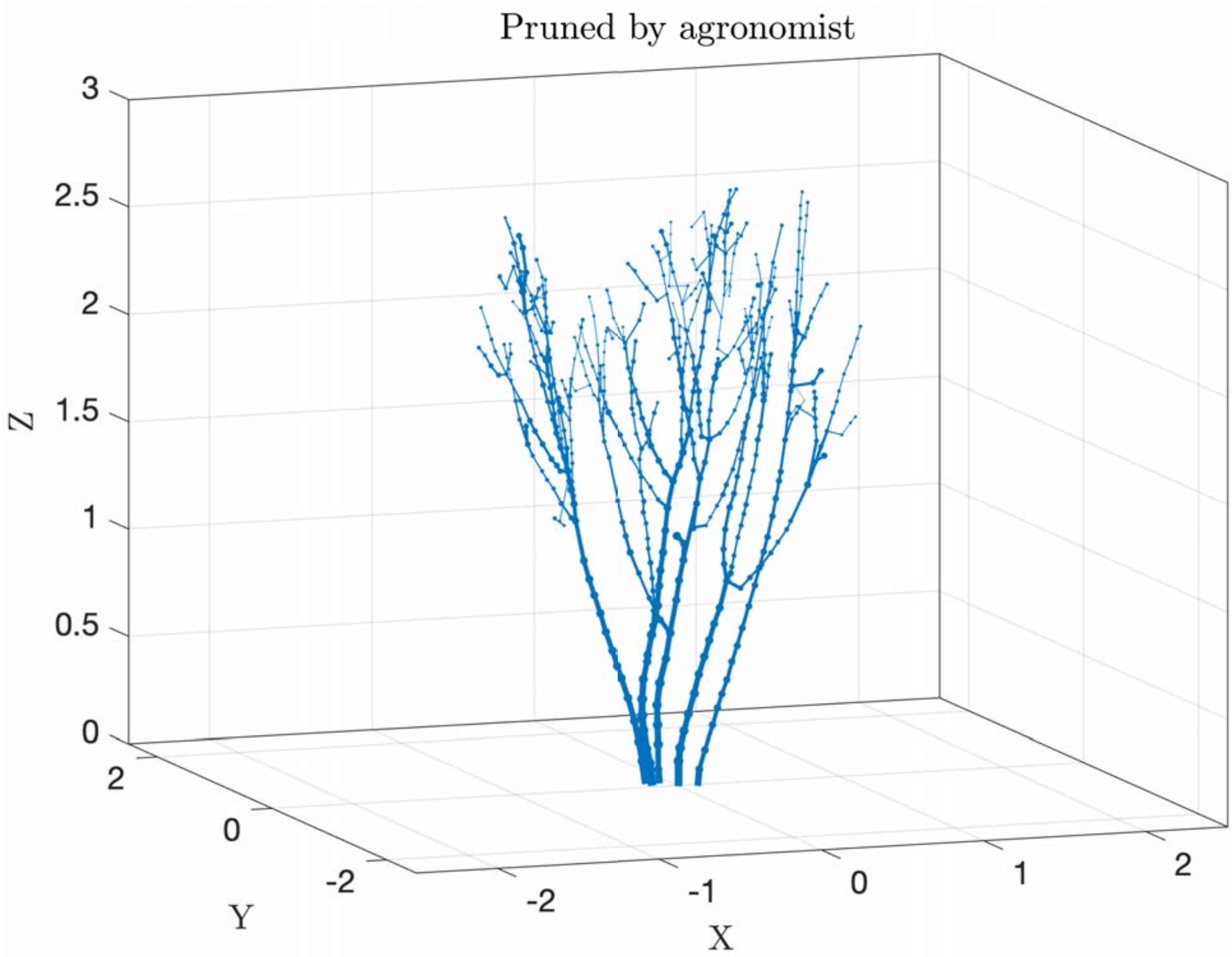

Figure 100 - Plant C9 pruned by an agronomical expert.

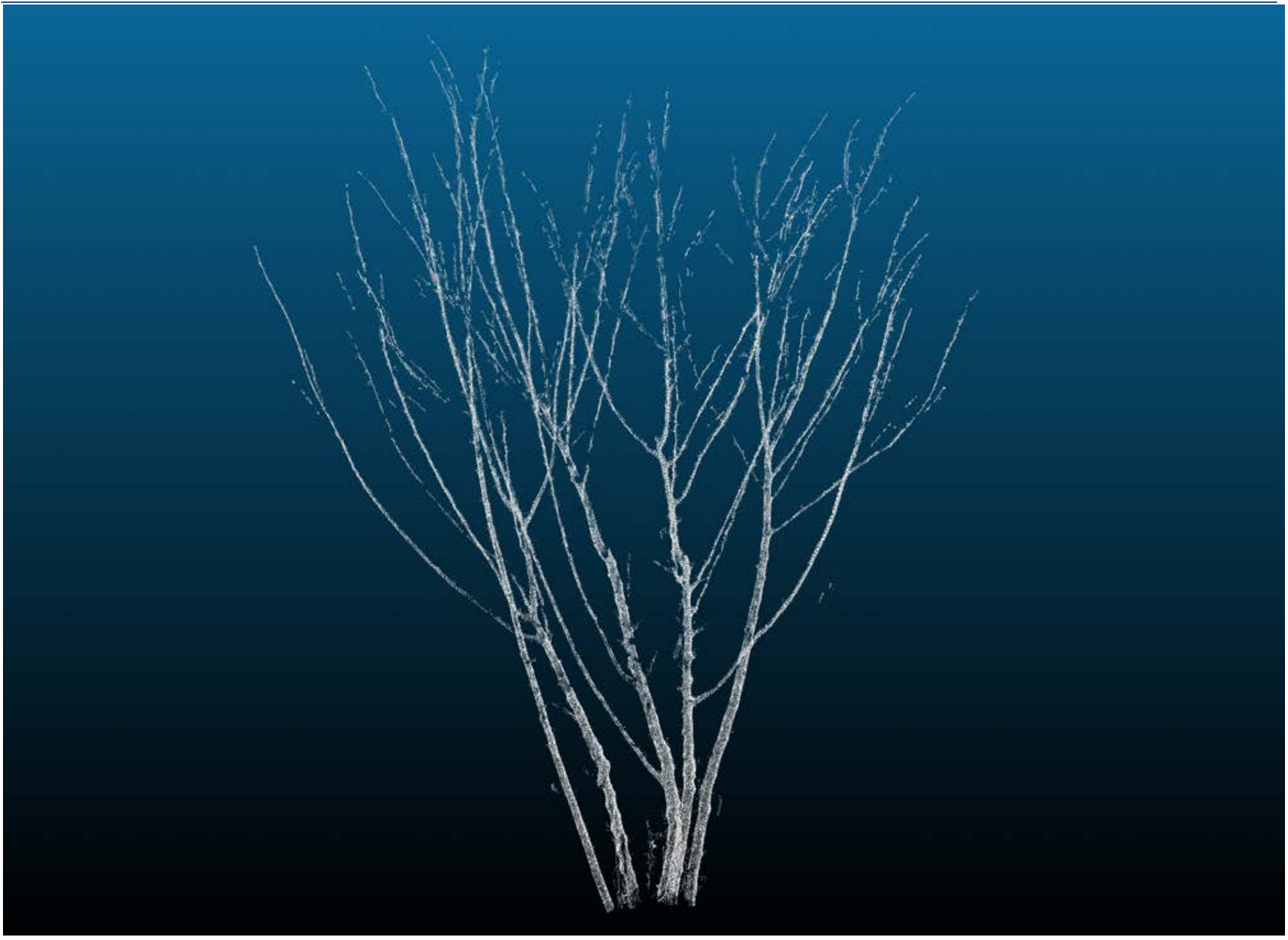

Figure 101 - 3D point cloud of C9 plant before pruning.

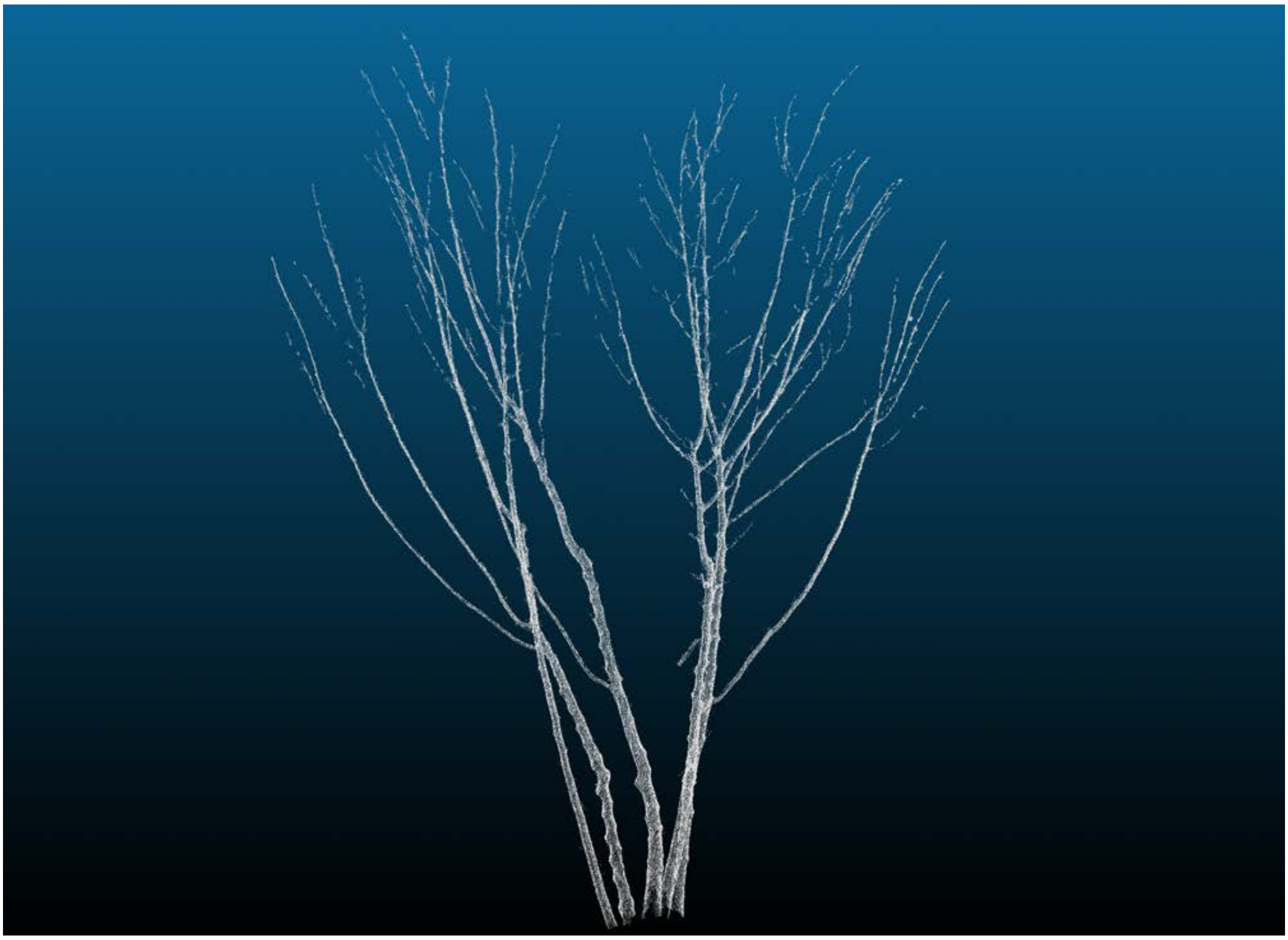

Figure 102 - 3D point cloud of C9 plant after pruning.