agriculture

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Autonomous Mower Management Systems Efficiency Improvement: Analysis of Greenspace Features and Planning Suggestions

Mino Sportelli *, Luisa Martelloni, Aura Orlandi, Michel Pirchio, Marco Fontanelli, Christian Frasconi, Michele Raffaelli, Andrea Peruzzi, Salvatore Brunello Consorti and Paolo Vernieri

Department of Agriculture, Food and Environment, University of Pisa, 56124 Pisa, Italy; lmartelloni@agr.unipi.it (L.M.); auraorlandi1988@gmail.com (A.O.); michel.pirchio@for.unipi.it (M.P.); marco.fontanelli@unipi.it (M.F.); christian.frasconi@unipi.it (C.F.); michele.raffaelli@unipi.it (M.R.); andrea.peruzzi@unipi.it (A.P.); brucon@libero.it (S.B.C.); paolo.vernieri@unipi.it (P.V.)

* Correspondence: mino.sportelli@phd.unipi.it

Received: 4 April 2019; Accepted: 28 May 2019; Published: 3 June 2019

Abstract: Autonomous mowers are battery-powered machines designed to mow turfgrass autonomously and continuously improving turfgrass quality and helping the person who takes care of the turf to save time and energy. However, autonomous mowers work in a way that sometimes does not match with the greenspace's design. The aim of this study was to analyze greenspace features that can be a hindrance for autonomous mowers in order to provide greenspaces design suggestions and management solutions when using an autonomous mowing system. Seven greenspaces managed by autonomous mowers ranging from 200–9000 m^2 were selected and studied. Interviews with the owners and on-site inspections were carried out to understand if manual interventions were required and to identify local plant communities. The results of the interviews showed that manual finishing work such as mowing grass along curbs and walls was needed in all the cases. Some cases needed manual interventions since autonomous mowers got stuck on because of shallow tree roots. Among the seven areas studied, the largest was chosen to be thoroughly analyzed in order to suggest two alternative design and management solutions and to carry out an economical comparison with the current state. When the inspection of this area was carried out, three autonomous mowers were used. Analyzing different management solutions showed that using only two autonomous mowers with specific technological devices was more advantageous. The costs of the current management solution using three autonomous mowers exceeded the costs of the suggested scenarios respectively of 2118.79 € and of 1451.15 €. Moreover, redesigning greenspaces with curbs slightly lower than grass and choosing trees with tap-root systems will help to avoid manual interventions. In this way, the efficiency of autonomous mowers will be enhanced, helping to obtain all the benefits derived from using autonomous mowers.

Keywords: landscape design; robotic management garden; boundary wire; evergreen trees; energy saving

1. Introduction

At a time when more and more people around the world live within cities, urban green areas have become increasingly important. These areas provide several benefits to the urban environment, such as carbon sequestration, dust stabilization, and reduction of heat island effects [1,2] on psychological and physiological human health [1,3]. The maintenance of greenspaces consists of a variety of operations.

Among these, turfgrass mowing is the most expensive, energy-requiring, and time-consuming operation [4,5]. Mowing turfgrass increases its aesthetic and functional quality, making it usable for the people as well [6].

Low mowing frequency lawns are steadily being requested by customers [7]. This trend indicates that people want to take advantage of a properly managed turfgrass without spending time and energy. In recent times, automation technologies have been adopted to provide and improve services in many sectors including agriculture and landscaping. Autonomous machines, such as autonomous mowers, are being increasingly used in vineyards [8], vegetable gardens [9] and especially in the field of turfgrass and landscape, where they show their full potential [10–14]. These machines are battery-powered and mow turfgrass alternating h of work and h of battery charging. Autonomous mowers can operate every day and being silent they can work at night saving a great amount of time. Mowing continuously reduces the size of the clippings and the problems associated with clippings left in place and their disposal [15]. Autonomous mowers do not produce polluting gasses or dust and prevent operators from coming in contact with allergens [16] and injuries [17]. Pirchio et al. [18] and Grossi et al. [19] observed that a turf managed with autonomous mowers showed a higher quality compared to a turf mown once a week with ordinary rotary mowers. Therefore, there is evidence showing that autonomous mowers represent a valuable tool for sustainable turfgrass management [19].

Currently available autonomous mowers can manage areas from 200 m^2 up to 30,000 m^2 [10–14], usually defined by a boundary wire. Commonly, autonomous mowers move within the perimeter of the boundary wire following random trajectories. Once they sense the electro-magnetic field generated by the boundary wire or hit obstacles, they stop and change direction. This way of functioning limits the work potential of these machines. In fact, to ensure the coverage of the whole area, it is necessary to allow the mower to work for longer periods of time. This increases the energy consumption and the wear of the equipment [20]. Furthermore, the shapes and configurations of greenspaces can be complex and a random motion may lead to a non-homogenous cut in such irregular shaped areas [20].

There are several technologies that allow better performance in these contexts such as differential GPS for systematic trajectories [14] or "random assisted" patterns [12] and research continues on this issue, but these solutions are often expensive or difficult to apply. The efficiency of these machines could also be enhanced using an intelligent approach to design green areas. A study by Liu et al. [4] shows how a proper arrangement of plant communities can reduce the cost of greenspaces maintenance. Thus, it is possible to plan and fulfil greenspaces suitable for autonomous mowing, reducing manual interventions and obstacles. For example, designing wide and regular shaped areas or ensuring the minimum passage for the autonomous mower between two areas are precautions that will improve their smooth functioning. However, in the literature there is no research focused on the proper installation of an autonomous mower in order to maximize its efficiency. In this study, the features of common greenspaces that can be a hindrance for autonomous mowers were analyzed. Among the various cases of greenspaces managed by autonomous mowers analyzed in this study, one case has been deeply studied in order to propose different management solutions analyzing the costs and developing design criteria to better fulfil greenspaces managed by autonomous mowers. The objective of this paper is to provide suggestions on the possible design of greenspaces and management solutions when using an autonomous mowing system.

2. Materials and Methods

2.1. Autonomous Mower Working Features

Autonomous mowers are machines designed to mow turfgrass without requiring an operator and work inside an area delimited by a shallow-buried boundary wire which generates an electro-magnetic fence [19]. The boundary wire must be laid around objects and plants that the autonomous mower must not run into. Sensors are able to sense when it approaches the boundary wire before stopping and changing direction. When the wire is not positioned around obstacles, the robot hits the obstacle at low speed, and then reverses and selects a new direction.

The charging station is positioned on the boundary and the autonomous mower starts to search for it when the charge level of the battery becomes too low [16]. The working area where the charging station is positioned is called main area or primary area, depending on the manufacturer. In addition to the battery charging function, the charging station sends control signals along the boundary wire and sends out signals that the autonomous mower can sense up to a distance of 6/7 m, so it finds the charging station. The charging station is connected to an electrical supply. The transformer is connected to the wall socket by an integrated power cord and to the charging station by a low voltage cable [12].

When the autonomous mower searches for the charging station it uses different search methods depending on the manufacturer, the model and the various settings. However, the autonomous mowers used in this study can search the charging station in three different ways: (a) randomly; (b) following the boundary wire; (c) following the guide wire. The method of returning to the charging station randomly provides that the autonomous mower operates randomly until it gets close to the charging station. This method involves that search times can be somewhat long. The method of returning to the charging station by following the boundary wire is suitable for an installation with an open lawn space, wide passages (wider than about 3 m) and no or few small islands. This charging station search method may lead to the formation of some tracks on the lawn alongside the boundary wire. The search time will also be longer if there are narrow passages or several islands in the garden. Conversely, the method of returning to the charging station by following the guide wire is suitable for an installation with many or large islands, narrow passages or steep slopes. The benefit of this search method is the shorter time needed to find the charging station. When this method is chosen, the autonomous mowers uses the guide loop to reach the charging station. The signal in the guide loop always goes to the left at the connection from the guide wire to the boundary wire.

Independently if the autonomous mower uses the boundary wire or the guide wire to move from or to the charging station, the area beside the wires used by the mower to come back to the charging station is called the corridor. The corridor width defines the distance from the autonomous mower path to the wire. Corridor width is a relative distance and is stated on a variable scale depending on the model. When it is set to the minimum distance, the autonomous mower will run over the wire. The higher the set corridor width value, the less risk there is of forming tracks. Autonomous mowers adapt to the corridor according to the shape of the working area when it follows along the guide wire. The autonomous mower always runs on the left of the guide wire as seen facing the charging station [12].

2.2. Cases of Study

Seven greenspaces located in Tuscany were selected as case studies. The criteria for the selection of the greenspaces was the autonomous mowers management system. These areas differed from each other for dimensions, landscape features and typology. Due to a safety issue, in Italy it is still hard to bring autonomous mower technology into public greenspaces, therefore, only two typologies of greenspaces were studied: private gardens and industrial green areas.

A questionnaire survey was carried out to the homeowners to investigate: (i) work area; (ii) garden features (slopes, narrow passages); (iii) number and model of autonomous mowers installed; (iv) the autonomous mowers work settings (h of work, areas managed); and (v) manual interventions or problems encountered.

On-site inspections where made to identify plant communities, garden features and eventual problems not detected with the questionnaires. Data analysis focused on finding the common criticisms in the different management scenarios, thus suggesting the proper management solution to avoid them in future installations.

Among the various cases analyzed, one case (study case number 5) presented most of the criticisms analyzed in this trial. Moreover, its large extension and great number of autonomous mowers made it suitable and representative in order to be redesigned. This greenspace is a private garden located in San Giuliano Terme (Pisa, Italy) (43°73′N, 10°43′E). Two design and management solutions were proposed for this case and the cost analysis was carried out.

2.3. Autonomous Mowers Involved in the Study

In order to better study the criticisms of case 5, the details of the autonomous mowers used in this greenspace have been reported. In this case study three Husqvarna® (Husqvarna, Stockholm, Sweden) autonomous mowers were used or suggested as a design implementation: Automower® 420, 430X, and 450X (Figure 3). The main technical features of these autonomous mowers are reported in Table 1 [12]. The choice of the proper autonomous mower was mainly based on the maximum area that it is able to mow, and the maximum lengths of the boundary wire and guide loop permitted. The boundary wire delimits the area in which the autonomous mower moves randomly. The guide wire is patented Husqvarna® and helps the autonomous mower find its way back to the charging station or to guide it through hard-to reach areas of the garden. The guide wire together with the part of the boundary wire loop makes the guide loop that comprises the return to the charging station [12].

Table 1. Technical features of the Husqvarna autonomous mowers involved in this study.

Features	Automower® 420	Automower® 430X	Automower® 450X
Working capacity	2200 m^2 ± 20%	3200 m^2 ± 20%	5000 m^2 ± 20%
Mean energy consumption at maximum use	19 kWh/month in a 2200 m^2 working area	20 kWh/month in a 3200 m^2 working area	24 kWh/month in a 5000 m^2 working area
Battery	Special Li-ion battery 18 V/3.2 Ah, Part no. 580 68 33-01	Special Li-ion battery 18 V/5.2 Ah, art no. 588 14 64-01	Special Li-ion battery 18 V/10.4 Ah, Part no. 588 14 64-01 (2 pack)
Average mowing time	105 min	135 min	260 min
Average charging time	55 min	65 min	75 min
Blade motor speed	2300 rpm	2300 rpm	2300 rpm
Power consumption during cutting	30 W ± 20%	30 W ± 20%	30 W ± 20%
Cutting width	24 cm	24 cm	24 cm
Maximum length of the boundary wire	800 m	800 m	800 m
Maximum length of the guide loop	400 m	400 m	400 m
Maximum number of remote areas	Three	Five	Five
Maximum number of guide wires	One	Two	Three
GPS assisted navigation	No	Yes	Yes

The Automower® 420 was developed for smaller lawns and does not have a GPS assisted navigation to move from the main area to the remote areas autonomously. Remote areas are generally distant areas and/or areas with narrow passages (narrower than about 3 m, but larger than 60 cm) [12]. In case of areas delimited by the boundary wire with a passage smaller than 60 cm, the autonomous mower must be moved manually from one area to the other. These areas are called secondary areas [12]. For these autonomous mowers, the distance from the charging station to one or more remote areas and the number of times it has to go from the charging station to the remote areas must be set. How often the autonomous mower must be steered to the remote area is selected as a proportion of the total number of times it leaves the charging station. At all other times, the autonomous mower starts to mow at the charging station [12]. The Automower® 430X and 450X use a built-in GPS to check which areas have been mowed and, thereby, which areas need to be mowed next. Using this assisted navigation, they can automatically get to parts of the working area that are hard to reach [12].

3. Results and Discussion

3.1. Interviews Results

The interviews showed that most of the problems encountered were planning errors which could easily be avoided during the planning phase. Table 2 shows the data gathered from each case of study. The data showed focuses on the criticisms found on the different greenspaces such as: (i) manual interventions; (ii) eventual owner interventions; and (iii) planning defects. In all cases finishing works were needed. These operations, most of the times, consisted of mowing grass along the curbs and walls. Five out of seven cases needed owner interventions because the mowers did not reach the charging stations and in four cases out of seven the autonomous mower needed to be manually moved from the main area to a secondary area. Generally, the autonomous mowers were not able to reach the charging station and got stuck on the tree's root systems. Five out of seven greenspaces had narrow passages, three out of seven had curbs, and four cases out of seven had slopes.

These findings were elaborated and integrated with on-site inspections in order to better understand the whole scenario and define the most common problems when managing a greenspace with autonomous mower systems.

3.2. *Analysis of Criticisms*

It is advisable to divide the total lawn area into as few small areas as possible. The number of these areas depends on the total surface of the garden and on the mowers. Moreover, fewer areas also mean a lower number of autonomous mowers involved and makes their maintenance easier, too. Simplifying shapes would decrease overlapping, thus raising autonomous mowers' random trajectories' efficiency. Many manufacturers suggest to size the working area about 20% smaller than the autonomous work capacity in order to better manage that area.

It is also necessary to check for slopes inside the working area and make sure that they are not steeper than what can be handled by the autonomous mowers. It is important to always ensure the minimum passage and avoid a narrow access between two areas.

The presence of hard-to-reach areas such as areas with a narrow access is common in gardens. Excessively tight passages may cause the autonomous mowers to struggle going through or even to get stuck. Locating flowerbeds in these places may simplify the managed area and prevent an operator from periodically moving the autonomous mower from one remote area to another.

Most of the gardens have containment curbs of paved areas taller than the turfgrass plane. If the curbs are higher than the grass, the boundary wire needs to be installed at a greater distance from the curbs. By leveling the heights of curbs and grass, the boundary wire can be installed closer to the curbs. In this way the autonomous mower can run a little over the path mowing along borders avoiding manual interventions. Along the walls in the garden, the same problem is repeated. A solution could be to provide curbs at the same height of the grass along the base of walls. In this way it is possible to avoid finishing work along the walls. Manual interventions increase management time and cost. In case several facilities such as passages or driveways lay across the area managed by the autonomous mower, creating joints between the interruptions and functional areas of the garden will simplify the work.

By installing the boundary wire around trees root systems, the autonomous mower will stop and change direction without getting stuck on the shallow roots. To avoid weeds growing in the small area surrounding the trees it may be suitable to mulch the area.

The aim of having a garden as automated as possible leads to the choice of non-deciduous species, as they are better suited to this type of management and they save time for manual removal of leaves left on the ground. Non-autonomous mowers allow operators to collect fallen leaves and clippings while mowing. This means that collecting fallen leaves is not an additional operation when mowing with manually-operated lawn mowers. Conversely, when turfgrass is managed with an autonomous mower, having deciduous trees will compromise the aesthetic aspect of the garden during fall. Additionally, trees with tap-root root systems are preferred to those characterized by root systems that raise from the ground. Moreover, it is important to detect and fill dips in the soil. Sometimes dips happen to be filled with water and this can damage the electric components of the autonomous mowers.

Table 2. Results of interviews.

Study Case	Typology	Area [m^2]	Number of Autonomous Mowers	Working Settings [h day^{-1}]	Secondary Areas	Manual Positioning	Slopes	Narrow Passages	Walls	Curbs	Wire around Objects	Finishing Works	Owner Interventions
1	Private	200	1	8	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
2	Private	850	1	8	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes
3	Private	1000	1	8	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
4	Industrial	3000	1	21	No	No	No	No	Yes	No	Yes	Yes	No
5	Private	9000	3	14	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
6	Industrial	2500	2	12	No	Yes	No	No	Yes	No	No	Yes	Yes
7	Private	1400	1	12	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

3.3. Description and Planning Improvements of the Selected Study Case

Study case number 5 was the most representative so it was selected to be redesigned. The total area of the studied case was about 9000 m^2, within which were included the main house, two smaller buildings, a swimming pool, three solar panels, and a cool season turfgrass (*Festuca arundinacea* Schreb. 80%, *Lolium perenne* L. 10%, *Poa pratensis* L. 10%) with an extension of 6940 m^2 (Figure 1).

Figure 1. Comparison between: (**a**) Actual state of case study number 5; and (**b**) photorealistic rendering of case study number 5.

The redesign of the study case consisted of improving the landscape features by correcting the planning defects according to the suggestions previously described in order to reduce criticisms. Since plant features may also be an issue, suitable species have been chosen and located in the right place to obtain the best performances from the autonomous mowers.

Four tree species were chosen for this project: Mediterranean cypresses (*Cupressus semprevirens* L.); camphor trees (*Cinnamomum camphora* (L.) J. Presl.); evergreen oaks (*Quercus ilex* L.), and olive trees (*Olea europea* L.). All of these species are evergreen trees and the cypress and olive trees were already present in the garden. The cypresses were positioned along the driveway, while the olive trees in the middle area and in the long area on the right side of the garden (Figure 1). Although olive trees are an evergreen species, their shallow root system does not match with the autonomous mower activity. The extension of the long area with the olive trees was lower than the maximum working capacity of a single autonomous mower, so, theoretically, one autonomous mower would be enough to manage this area. The manufacturer's manual suggests to lay the boundary wire around obstacles or trees with shallow roots. However, installing the boundary wire around such a large number of trees would significantly increase the total cost of the project. The length of the boundary wire necessary for this operation would exceed the maximum length allowed so the owner would be forced to use several autonomous mowers to manage the whole area.

An inexpensive alternative would be to fill the surrounding part of the trees with mulch or gravel in order to make the ground level higher and to avoid the machine getting stuck. Camphor trees were planted in the edge of the area between the olive trees and the house while the evergreen oaks were positioned behind the house and in the green area close to the entrance. The whole garden and parts of the working areas were surrounded by a mixed hedge. The mixed hedge was fulfilled using Mediterranean shrub species (*Arbutus unedo* L., *Cotoneaster franchetii* Bois, *Euonymus* L., *Laurus nobilis* L., *Viburnum tinus* L.). Flowerbeds were made in narrow areas with perennial flower species (*Agapanthus africanus* (L.) Hoffmanns, *Allium ambassador* L., *Lithodora rosmarinifolia* (Ten.) I. M.

Johnst.), or perennial aromatic plants (*Lavandula* spp., *Mentha sppc*, *Origanum vulgare* L., *Rosmarinus* spp., *Salvia officinalis* L.).

3.4. Autonomous Mowers Management Solutions Redesigning

Before this study, the total working area was 6940 m^2 (Figure 2a) and was managed by three autonomous mowers (two Husqvarna Automower® 430X and one Husqvarna Automower® 420). This solution did not maximize the efficiency of the autonomous mowers. The two Automower® 430X managed areas of 2880 m^2 and 3020 m^2, respectively. The Automower® 420 managed an area of 1040 m^2. The areas managed by the two Automower® 430X were larger than what was suggested by the manufacturer. Thus, the mowers may not cut the total area in an optimal way. The Automower® 420, instead, managed an area significantly smaller than what was suggested by the manufacturer. This can lead to a lower efficiency due to the excessive overlapping.

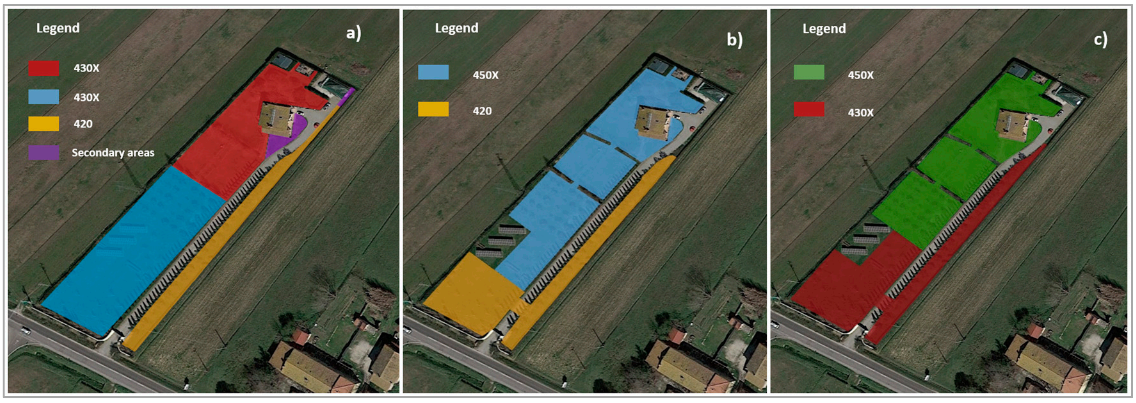

Figure 2. Areas cut by autonomous mowers: (**a**) Current state; (**b**) Scenario 1; and (**c**) Scenario 2.

Furthermore, having a greater number of machines involves a higher cost for their maintenance. Based on the evidence that the same area could be managed by only two mowers, two different management solutions were proposed (Figure 2b,c). The garden areas were redesigned paying attention to interfere as little as possible with the autonomous mower's work. Both solutions consider the surface divided in two smaller areas, each managed by a single machine. For easier management, the areas with the solar panels, the swimming pool and the driveway were excluded from the autonomous mower operational area. In the area with the solar panels, the turfgrass was replaced with gravel pavements, and the secondary areas previously managed with the Automower® 420 (Figure 2a) were replaced with flowerbeds. In order to allow the autonomous mowers to manage the secondary area in both the scenarios (Figure 2b,c), a four-meter-wide path was established through the driveway, between the main area and the secondary area. In the two scenarios, the total working area was smaller than the current area, measuring only 6450 m^2 (Figure 3). The guide wires were installed in order to cross every remote area and create a loop with the boundary wire (Figure 3).

Scenario 1 considers the use of an Automower® 420 and of an Automower® 450X. In this solution, the Automower® 450X managed an area of 4510 m^2 and Automower® 420 managed an area of 1940 m^2. Both areas exceed the suggested work area for such machines by about 500 m^2. Despite this, the constant work of the machines will ensure the total coverage of the area. The Automower® 420 and the Automower® 450X will cover the working area in 21 h and 6 min and 21 h and 42 min, respectively. Setting their work timers as the previous solution (14 h per day) they covered the whole area in about 1.5 days. The Automower® 420 does not have the option of a GPS assisted navigation, so the distances of the remote areas and how many times the Automower® 420 must reach them must be set manually. The distance of the remote area 1 was 50 m and the distance of the remote area 2 was 100 m (Figure 4). In Figure 4 it is possible to see the main area and the remote area managed by the Automower® 420, noticing the paths made on the driveway to bond the two areas. The guide wire ensures that the autonomous mower can reach the remote area. The area managed by the Automower® 450X is consistently wider than the other one. Concerning the areas near the house, it was possible to consider them remote areas by creating passages where the distance between the boundary wires was larger than 60 cm. In this way the autonomous mower was able to reach these areas autonomously. The autonomous mowers can reach the most distant areas from the charging station by using the GPS assisted navigation.

Figure 3. The two scenarios of management and the autonomous mowers involved in the study.

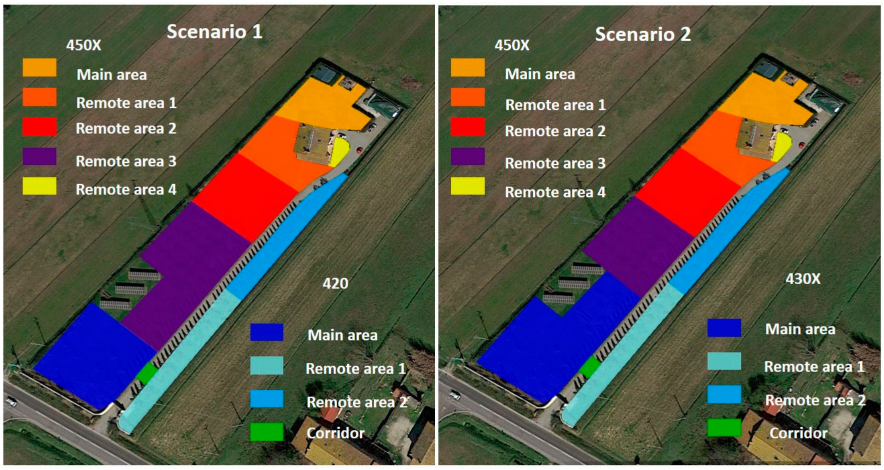

Figure 4. Remote areas of the two scenarios.

Scenario 2 is slightly more expensive than Scenario 1. The smaller of the two areas measures 2400 m^2 and is mowed by a Husqvarna Automower® 430X. The other one measures 4050 m^2 and is mowed by a Husqvarna Automower® 450X. As in Scenario 1, these extensions are in line with the manufacturer's guidelines, thus enhancing the mowers efficiency. In this scenario, the Automower® 430X will cover the whole area in 18 h and the Automower® 450X in 19.5 h. With the same work settings, the working area would be covered in 1.3 work days for the Automower® 430X and 1.4 work days for the Automower® 450X. The area managed by the Automower® 430X was composed by a main area in which the charging station is placed and by two remote areas (Figure 4). The area managed by the Automower 430X is crossed by the driveway so a path was created to allow the autonomous mower to move from the main area to the remote areas. Since the Automower® 430X has the option for the "random assisted" navigation, from a management perspective it would have been smarter to design another area, called Remote Area 3, due to the long and narrow shape of this area. In this situation it may be difficult for the autonomous mower to cover the whole area moving randomly.

3.5. Analysis of Costs

Tables 3–5 show the costs of the current management solution comparing them with the costs of the two scenarios.

Table 3. Total costs of current management solution.

Features	Unit of Measure	Quantity	Unit Price	Total Price
Husqvarna Automower 430X.	pcs	1	€3343.00	€3343.00
Boundary wire + installation	m	519.82	€1.58	€821.31
Guide wire1 + installation	m	100.56	€1.58	€158.88
Guide wire 2 + installation	m	54.15	€1.58	€85.55
Husqvarna Automower 430X.	pcs	1	€3343.00	€3343.00
Boundary wire + installation	m	284.11	€1.58	€448.89
Guide wire + installation	m	85.55	€1.58	€135.16
Husqvarna Automower 420.	pcs	1	€2721.00	€2721.00
Boundary wire + installation	m	388.56	€1.58	€613.92
Guide wire + installation	m	137.25	€1.58	€216.85
			Total:	€11,662.56

Table 4. Total cost of Scenario 1.

Features	Unit of Measure	Quantity	Unit Price	Total Price
Husqvarna Automower 450X.	pcs	1	€4514.00	€4514.00
Boundary wire + installation	m	644.53	€1.58	€1018.36
Guide wire 1 + installation	m	135.46	€1.58	€214.03
Guide wire 2 + installation	m	79.33	€1.58	€125.34
Husqvarna Automower 420.	pcs	1	€2721.00	€2721.00
Boundary wire + installation	m	452.15	€1.58	€714.40
Guide wire + installation	m	149.77	€1.58	€236.64
Husqvarna Automower 450X.	pcs	1	€4514.00	€4514.00
Boundary wire + installation	m	644.53	€1.58	€1018.36
Guide wire 1 + installation	m	135.46	€1.58	€214.03
			Total:	€9543.77

Table 5. Total cost of Scenario 2.

Features	Unit of Measure	Quantity	Unit Price	Total Price
Husqvarna Automower 450X.	pcs	1	€4514.00	€4514.00
Boundary wire + installation	m	573.46	€1.58	€906.07
Guide wire 1 + installation	m	135.46	€1.58	€214.03
Guide wire 2 + installation	m	79.33	€1.58	€125.34
Husqvarna Automower 430X.	pcs	1	€3343.00	€3343.00
Boundary wire + installation	m	510.84	€1.58	€807.13
Guide wire + installation	m	191.04	€1.58	€301.84
Husqvarna Automower 450X.	pcs	1	€4514.00	€4514.00
Boundary wire + installation	m	573.46	€1.58	€906.07
Guide wire 1 + installation	m	135.46	€1.58	€214.03
			Total:	€10,211.41

Both scenarios were less expensive than the current management solution. Scenario1 was less expensive for 2118.79 € and Scenario 2 was less expensive for 1451.15 €. Although the current management solution may seem more organized, it does not represent the best solution for these mowers. The greater cost of the current management solution is mainly due to the presence of an extra machine. Moreover, Scenario 2 is only 667.64 € more expensive than Scenario 1. This is mainly due to the higher price of the Automower® 430X compared to the Automower® 420. Indeed, the total cost of the wires and of the installation of Scenario 2 exceed the costs of Scenario 1 by 45.64 €.

Nevertheless, the performance of the Automower® 430X was much higher than the performance of the Automower® 420. First, the Automower 430X can manage a larger area than the Automower 420 (3200 m^2 versus 2200 m^2). Second, the GPS device allows it to autonomously move to the remote areas. This makes the management easier and more efficient. It is fair to highlight that the initial costs of both scenarios are consistently high. However, Grossi et al. [19] compared the costs of two different mowing systems finding that the cost per week of an autonomous mower is lower than the cost per week of an ordinary gasoline rotary mower (19.36 €/week vs. 32.22 €/week). However, these high initial costs will be recovered over time since autonomous mowers, compared to ordinary rotary mowers, require lower energy inputs, have a higher efficiency and do not need operators.

4. Conclusions

Autonomous mower management systems are a sustainable solution that ensures a high quality turfgrass and reduces the total costs of greenspace maintenance. However, the work of the autonomous mowers can be improved by a proper greenspace design and a proper installation. This study analyzed seven greenspaces to find the design errors that hinder autonomous mower management systems causing additional human labor. The findings showed that, in all cases, manual intervention to carry out finishing work along curbs and walls were needed, and most of the time the autonomous mowers got stuck on tree root systems. From the data acquired, it was possible to draw greenspace planning suggestions that properly suit autonomous mower activity.

First, the total area should be divided into the minimum number of smaller areas, possibly giving them a simple shape. Slopes should be taken into account to make sure that they are not steeper than what can be traversed by the autonomous mowers. Low spots in the working area should be detected and filled.

Secondly, narrow passages between two areas should be avoided. If not possible, it is necessary to ensure that the autonomous mowers have at least the minimum space to pass through narrow areas. Flowerbeds should be located in tight or hard-to-reach areas instead of placing them in the working area. Providing walkways with curbs at the same height of the grass and curbs along the base of the walls will help to avoid finishing work. Create corridors between the interruptions and the functional areas of the garden.

The third planning suggestion concerns using proper plant species: non-deciduous species ease autonomous mower management saving time for manual removal of leaves left on the ground. Choosing trees and bushes with a tap-root root system will prevent autonomous mowers form getting stuck.

Redesigning one of the study cases made it possible to apply these suggestions and to determine the economic benefits of the different solutions. Two different scenarios were proposed in order to apply the suggestions for a better management of the studied garden. Both the scenarios showed that managing the working area with the lowest possible number of autonomous mowers significantly reduced the initial costs. Scenario 2 was slightly more expensive than Scenario 1, however the higher cost was justified by a higher grade of technology of the autonomous mowers which guarantees better performances. This trial highlighted that planning greenspaces following the suggestions proposed can maximize the efficiency of the autonomous mowers. Further research should be carried out to understand how the optimal design of greenspaces managed by autonomous mowers may offer some environmental benefits.

Author Contributions: M.S., L.M., A.O., M.P., C.F., M.R., A.P., P.V., S.B.C. and M.F. conceived and designed the experiments, performed the experiments, analyzed the data, contributed analysis tools, and wrote the paper.

Funding: This research received no external funding.

Acknowledgments: We would sincerely like to thank Fercad s.p.a. (Altavilla Vicentina, Vicenza, Italy) and Rossi machine agricole (Ponte a Egola, Pisa, Italy) for technical assistance and supporting this research.

Conflicts of Interest: The authors declare no conflict of interest.

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