sustainability

MDPI

Article

Assessing the Economic Performance of Multipurpose Collaborative Robots toward Skillful and Sustainable Viticultural Practices

Emmanouil Tziolas [1], Eleftherios Karapatzak [1], Ioannis Kalathas [1], Aikaterini Karampatea [2], Antonios Grigoropoulos [1], Aadil Bajoub [3], Theodore Pachidis [1] and Vassilis G. Kaburlasos [1,*]

[1] Human-Machines Interaction (HUMAIN) Lab, Department of Computer Science, International Hellenic University (IHU), 65404 Kavala, Greece
[2] Department of Agricultural Biotechnology and Oenology, International Hellenic University (IHU), 66100 Drama, Greece
[3] Laboratory of Food and Food By-Products Chemistry and Processing Technology (AcopTech), National School of Agriculture, Meknes 50000, Morocco
* Correspondence: vgkabs@teiemt.gr; Tel.: +30-2510-462-320

Abstract: The increased cost of labor in modern viticulture stemming from the nature of operations that require physical strength and precision, coupled with labor shortages, poses a significant constraint in facilitating and scheduling seasonal activities. Therefore, autonomous collaborative robots present a potential solution for achieving sustainable development objectives and decreasing operational expenditures in agricultural operations. The current paper presents an economic assessment of collaborative robots (or cobots for short) in comparison to conventional labor for four different cultivars in Greece in a lifecycle costing methodological framework. The selected cultivars are Asyrtiko, Cabernet Sauvignon, Merlot and Tempranillo, which are cultivated by two private wineries in the area of interest. All the relevant expenses of their annual production were distributed to agricultural operations, and eight scenarios were developed to compare conventional and cobot practices. The results indicate the great potential of cobots regarding specific viticultural operations such as weed control, pruning, herbiciding and topping. The adoption of cobots in these operations has the potential to contribute to sustainable agriculture by reducing labor costs and addressing labor shortages, while also increasing the efficiency and precision of these tasks. Nevertheless, the defoliation and tying operations appeared to be inefficient in most cases in comparison to conventional labor practices. Overall, the annual equivalent costs could be reduced by up to 11.53% using cobots, even though the projected lifetime of the cobots plays a significant role in the cost-effectiveness of autonomous robotic labor in viticulture. In conclusion, cobots could be instrumental in the Greek viticulture, integrating innovation and high-quality products toward sustainable agricultural development.

Keywords: capital service cost; collaborative robots; cobots; discounted cost; farm management; lifecycle costing; viticulture

check for updates

Citation: Tziolas, E.; Karapatzak, E.; Kalathas, I.; Karampatea, A.; Grigoropoulos, A.; Bajoub, A.; Pachidis, T.; Kaburlasos, V.G. Assessing the Economic Performance of Multipurpose Collaborative Robots toward Skillful and Sustainable Viticultural Practices. *Sustainability* **2023**, *15*, 3866. https://doi.org/10.3390/su15043866

Academic Editors: Maria Batsioula, Apostolos Malamakis, Spiliotis Xenofon and George Banias

Received: 9 January 2023
Revised: 9 February 2023
Accepted: 10 February 2023
Published: 20 February 2023

1. Introduction

The Mediterranean ecosystem includes several wine regions due to favorable climatic parameters for viticulture [1]. Table grapes, raisins, wines and spirits enhance the economic importance of viticulture in the Mediterranean basin, as over 75% of the total area under vines in the EU is located in that region [2]. The diversity of commodities from viticulture is further capitalized on by Chaikind [3], underlining the importance of wine not only as an investment good but also as a contributor to modern economic theory. Furthermore, the entertainment and tourism industry can be heavily related to the magnitude of local wine industries [4]. Therefore, viticulture plays a significant role in several sectors of the economy, enhancing its importance via manifold entrepreneurial ventures. Regarding both wine production and consumption, the EU today is facing declining interest due to COVID-19 pandemic changes in lifestyles, preferences between younger and older generations and other uses of grapes (e.g., vinegar, production of other beverages, etc.) [5]. However, long-term projections regarding the EU wine sector are optimistic, increasing the export value of the zone by 0.5% every year until 2031. In addition, agricultural land covered by vineyards is not expected to expand and the increasing trend of exports will be covered by quality products such as organic, protected designation of origin (PDO), and protected geographical indication (PGI) wines, as well as new varieties that have been adapted to climate changes [5].

Sustainable management of agricultural systems requires a holistic and multidisciplinary approach to efficiently use water, energy resources and inputs [6]. The required multifaceted management strategies call for environmentally friendly practices, reduced usage of agrochemicals and rational water management in order to balance the economic and environmental requirements. In particular, the climate targets of the European Green Deal integrate ambitious goals which are in dire need of a multithreaded approach to agricultural policy and a rational approach to farmers' attitudes [7]. This attitude is the key to managing the transition to a sustainable future, although the economic motivation is a major actor in farmers' decision-making. In this context, the farm-to-fork strategy, which is at the heart of the EU Green Deal, focuses on strengthening the efforts to tackle climate change to protect the environment and to preserve biodiversity while ensuring a sustainable livelihood in terms of income [8]. The pricing of wine is a significant factor for both consumers and producers; however, variations in profitability among farm holdings in the European region primarily stem from the designation and geographical origin [9]. In addition, agricultural management that integrates innovative precision viticulture techniques could highlight the differences in relation to environmental impact [10], although innovative initiatives entail economic impacts as well.

Management costs for the entire lifecycle of grape production differ significantly among vineyards due to different cultivation practices (e.g., harvesting operations, capital service cost and overheads) and planting and training techniques. More specifically, considerable cost differences could be related to skilled labor or the maintenance of dry-stone walls, as reported in Giano dell' Umbria, Perugia, and Lamole, Firenze, respectively [11]. Of course, the expenses related to irrigation, energy consumption and agrochemicals are of the utmost importance in vineyard management, especially in a commodity market currently stressed by the war in Northeastern Europe after the long-term effects of the pandemic. Nevertheless, agronomic measures (e.g., optimized regulated deficit irrigation) could improve efficiency and yield quality, taking into account the limiting conditions and climate change implications [12]. In this context, a credible methodological framework should be followed to provide a holistic economic assessment of agricultural practices in viticulture.

Lifecycle Costing (LCC) is a methodological approach that distributes the costs analytically to specific processes and products in order to identify the best practices and hotspots related to farm management. An evaluation of economic performance in southern Italy utilizing an LCC approach revealed that the conventional espalier system was the most economically feasible option compared to combinations of organic, conventional and gobelet systems [13]. Through the integration of the LCC and VIKOR multicriteria method, Falcone et al. [14] determined key economic challenges in the planting phase and operating costs, particularly with regard to labor costs. Internal and external environmental costs were calculated for table grape cultivation in Italy, highlighting the trade-offs in wastewater reuse via an integrated Lifecycle methodological framework [15]. In this sense, the importance of the Lifecycle Assessment (LCA) framework is discussed in terms of quantifying external impacts and converting them into monetary units by a study carried out by Wageningen Economic Research [16]. The existence of tradeoffs between environmental and economic performance is thoroughly depicted by Roselli et al. [17] regarding early, delayed and normal harvesting production models regarding the Italian table grape sector.

A key element of the abovementioned studies is the identification of hotspots in wine-grape production systems via an LCC approach, which is linked to specific labor operations (both machine and human).

Targeted automation in viticulture can increase the share of winemaking in the economy with strategic codevelopmental benefits not only for agriculture but also for the secondary and tertiary sectors as a service provider. Nevertheless, sustainability assessments mainly focus on the environmental component, neglecting social and economic impacts [18]. Within this framework, the management practices that are heavily affected by economic factors (due to subsidiary measures or plain profit) should develop an equilibrium among the environmental, economic and social aspects. Precision viticulture integrates management strategies, which typically involve the application of uniform-based field measurements [19]. However, precision agriculture practices may produce dubious results for specific agricultural tasks (such as harvesting, pruning, sprinkling, etc.), especially when critical manual skills based on experiential knowledge are required. The motivations for automating skillful viticultural tasks include quality consistency, a lack of skilled labor during seasonal demand, the mitigation of environmental pollution, and a reduction in expenditures for spraying pests. The literature regarding automation in field crop production via integrating autonomous operations is rather limited [20]. Autonomous robotic operations are mainly focused on weeding operations [21–23], while McCorkle et al. [24] illustrated the potential economic benefits of autonomous robotic labor in comparison to human labor for selected vineyards in Texas, USA.

Therefore, the aim of the current study is a holistic economic assessment following an LCC approach of four vineyard production plans based on different cultivars located in the region of Eastern Macedonia-Thrace, Greece. In particular, this study focuses on the agricultural operations performed conventionally and by cobots in order to compare their performance and highlight the potential trade-offs while also covering a literature gap regarding the implementation of LCC in autonomous viticultural operations. In this study, the lifespan of cobots is considered as well, since their resilience to adverse weather conditions and potential failures are yet to be fully elucidated and remain subject to investigation. This study is innovative in its examination of viticultural operations carried out by cobots, as well as in its use of an LCC approach to account for the potential costs of relevant cobot practices over a three-year period, expressed in annual equivalent cost. The layout of this work is as follows: Section 2 includes the four subsections presenting the case study area, the economic assessment methodology, the inventory analysis and a brief description of the cobots. Section 3 presents the results regarding the economic assessment of the cobots in viticulture. Section 4 discusses the contribution of the present study and compares the results to similar studies. Finally, Section 5 summarizes the main ideas behind cobots in viticulture and highlights potential future research.

2. Materials and Methods

2.1. Study Area

The agricultural land under consideration is located in the region of Eastern Macedonia and Thrace and covers 2227 hectares, which corresponds to 3.5% of the total agricultural land under vines in Greece. Nevertheless, the region of Eastern Macedonia and Thrace saw the third largest increase, at +5.4%, in agricultural land devoted to vine cultivation between 2015 and 2020 among all the regions of Greece. Therefore, the region integrates a raising trend for viticulture, whereas the main wine grape variety is the Sauvignon Blanc (16.8% of the region's vineyards) [25].

The first winery of the study, i.e., Ktima Pavlides (KP), is a quality-orientated wine-producing estate that includes 60 ha of vineyards producing white, rosé and red wines of recognized quality that best express the characteristics of their respective terroir. KP is currently producing at least seven PGI-labeled wines that are matured and marketed both nationally and internationally. The second winery, i.e., Nico Lazaridi (NL), is also a quality-orientated wine-producing estate that includes at least 80 ha of vineyards, producing a plethora of labels under four different protected geographical indications (PGI) marketed both nationally and internationally. Since both studied wineries are quality-oriented, the crop load on the vines is strictly regulated in all studied cultivars/cases at ≤10 tn/ha via the management of vegetative/reproductive balance with consecutive pruning and crop-load reduction applications following the development of the vines across a vintage. In addition, a regulated deficit irrigation (RDI) process is implemented in both wineries via drip irrigation coupled with integrated pest management (IPM). In Table 1, the basic vineyard management practices that are implemented within the above framework are presented at both KP and NL in a chronological order throughout each vintage.

Table 1. Vineyard management practices calendar following the phenological development of vines for the two studied wineries.

Indicative Time of Season (Month)	Vines' Phenological Stage (Respective Modified BBCH Scale No)	Management Practice	Details
January	Dormancy (00, 01)	Winter pruning	Following the employed bilateral cordon (Guyot) system
February	Dormancy (eco dormancy) (02)	Soil fertilization once every 3 years/integration in soil of pruning residues	
March	Pre-emergence (03, 05)	Vine trellising and training operations	Setting the vines onto the trellis system
April	Bud emergence/vegetative growth (07–30)	Budding/between-row weeding	≈50% of emerged buds removed
May	Vegetative growth/reproductive development/flowering (31–50)	Plant protection applications/Vine trellising and training operations/start of defoliation	Fungicide sprays/biological control of pests via mating disruption pheromones
June	Flower fertilization, fruit set (55–70)	Plant protection applications/Vine trellising and training operations/defoliation/vine topping	Leaves from the grape clusters' emergence zone are removed
July	Grape growth stages/start of veraison (70–80)	Plant protection applications/vine topping/crop load reduction	Topping stops unnecessary height growth of vines/crop load on the emerged clusters is reduced in balance with defoliation
August	Completion of veraison (80–90)	Grape harvest	From the middle of the month onwards
September	Grape and vine maturity (80–90)	Grape harvest	
October	Start of leaf discoloration (90–93)	Vine resting period/soil N enrichment when necessary	
November	Start of leaf shedding (93)	Between-row tillage operations	
December	Vines enter dormancy	Start of partial pruning as a pre-treatment to the forthcoming winter pruning	

As stated above, the current case study focuses on two separate wineries located at a relatively close distance to the viticultural area of Drama, where several PGI-labeled wines are produced. Two cultivars/cases have been selected from the vineyards of each winery (Table 2), whereas the selected wineries/estates implement conventional vineyard management techniques. The terroir of the wineries' area can be described as terraced hills within a valley at around a 200 m elevation under Mediterranean climatic conditions with continental features. The topsoil type across all studied vineyards ranges from sandy loam to loamy clay, generally of medium composition.

Table 2. Details of location, cultivars and vineyard set-up of the two studied wineries.

Winery	Coordinates (HGRS87/EGSA87) (Lat, Lon)	Elevation	Cultivars/Rootstocks	Planting Distance/Vines ha^{-1}
Ktima Pavlides winery (KP)	41.200400 N, 23.953084 E	200 m	Tempranillo/110 Richter Asyrtiko/1103 Paulsen	2.2 × 1.2 3780
Nico Lazaridi winery (NL)	41.127832 N, 24.275972 E	190 m	Cabernet Sauvignon/SO4 Merlot/SO4	2.5 × 1.2 3330

2.2. Collaborative Robots in Agriculture

The production of high-quality agricultural products requires critical manual skills based on experience. The current study is based on a project named "Technology for Skillful Viniculture (SVtech)", for which the goal is the development of an integrated (in the sense of multiskill integration) innovative system for the optimal co-operation of a team of wheeled robots equipped with sensing electronics to perform manifold viticultural operations. Furthermore, the wheeled robots are equipped with arms on which appropriate tools may be attached and handled by robotic hands and/or grippers. The (ground) team of robots navigates using a map drawn based on images supplied by a drone. The objective is the massive automation of manual viticultural tasks with the long-term goal of minimizing the human presence in the vineyard during the production process. The collaborative robot (or cobots for short) technology is based upon the interaction and co-ordination of robots and humans during production [26]. Cobots are wheeled robots equipped with sensing electronics, as well as arms, to which robotic arms and/or grippers are attached for handling the appropriate tools. The (ground) team of robots is provided with navigation maps by a drone to automate the massively manual viticultural tasks [27] in the context of the fourth industrial revolution of agricultural production, namely, "Agriculture 4.0" [28], as well as in the context of "Agriculture 5.0" [26], which pursues the co-operative integration of humans with robots/machines.

Operations of interest in viticulture are classified into the following four basic categories: (i) cutting, including pruning, weeding, defoliation, harvesting and topping; (ii) spraying; (iii) tying; and (iv) decision making, e.g., for pattern recognition and production forecasting. The system includes a drone and four properly equipped wheeled robots. The drone captures the geographic data (see digital images of the vineyard) in order for the high-computing base station to calculate the optimal path for the wheeled robots through the vineyard [29]. Each skilled robot (master) has at least one robotic arm equipped with a robotic hand attached to it, as well as various electronic sensing devices, including cameras, while each slave robot has up to one robotic arm equipped with a gripper attached to it. A skilled robot (master) performs skillful viticultural tasks, either alone or co-operatively with another skilled robot in the selected viticultural tasks, e.g., in tying, whereas a slave robot transports the materials produced by the work of a skilled robot, e.g., it transports grapes (during harvest), leaves (during defoliation), etc. In addition, a skilled robot (master) can direct the robot carrier (slave) if needed. Further information about the skilled (RB-EKEN) and assistant (RB-VOGUI) robots can be found in Robotnik Automation [30]. Some technical specifications for the two selected robots are shown in Figure 1.

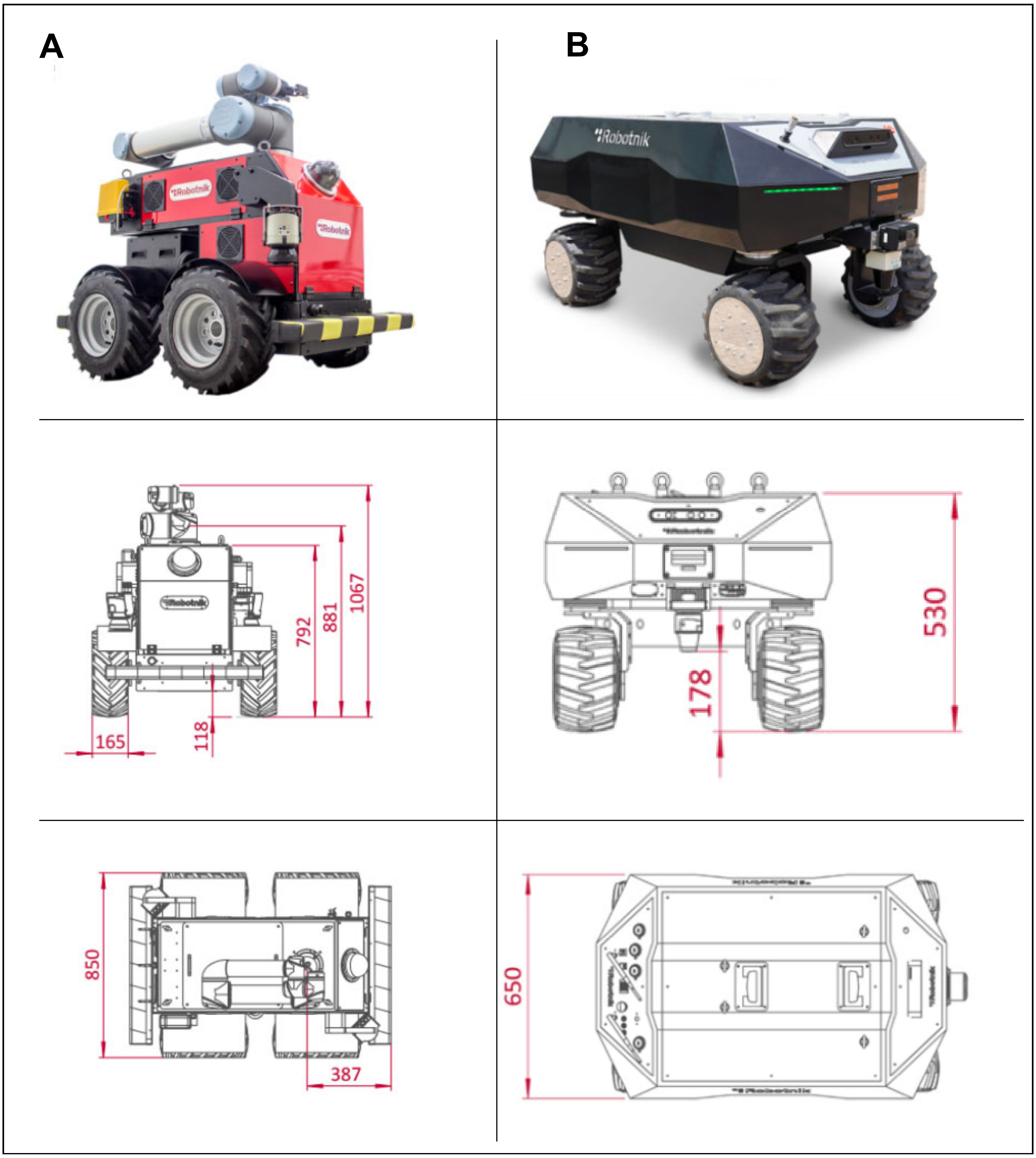

Figure 1. Technical specifications in mm of the (**A**) RB-EKEN and (**B**) EB-VOGUI robots [30].

The robots communicate via the base station, which is also the control center. The cobot technology is based on the interaction and coordination between robots (Figure 2) and humans acting in the production. The robots have built-in LiFePo4 technology batteries inside their shell to meet their operational needs. The actions that reduce the battery lifetime are movement on the field and the use of sensors and computing systems, as well as powering of the telecommunication systems with the base station. The study integrates two types of robots, and the purchase cost was EUR 80,000 and EUR 150,000 for the RG-VOGUI and the RB-EKEN, respectively. An accurate estimation of the robots' lifetime and functionality is a difficult task; therefore, the base lifetime of the two selected robots was set at 15 years, following the estimations of farm machinery costs [31].

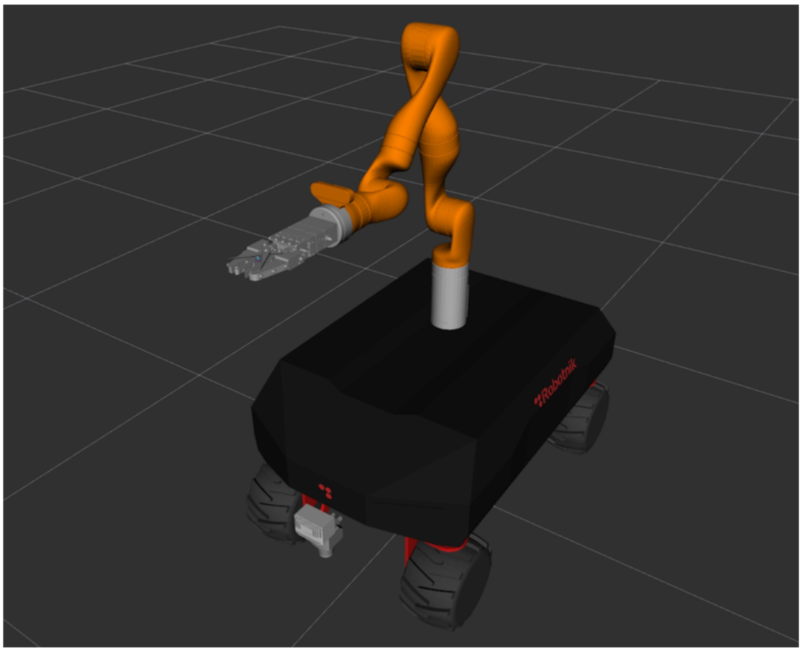

Figure 2. Schematic depiction of skilled robot with one robotic arm.

2.3. Economic Assessment Methodology

The economic impact of agricultural production is a crucial component of sustainable European policy, as 39.1% of the total land area in the European Union is utilized for agriculture [32]. LCC is a methodological framework that allocates the total cost of a product or an activity and distributes it equally over its lifecycle [33]. In addition, LCC is considered a more clear and simple method when compared to LCA, which is based on databases. Financial data are tangible and can be extracted easily at any time by various methods of qualitative and quantitative research. Unlike emission-related data that require ideal conditions and expensive equipment to measure, economic data are more easily accessible and can be targeted to selected areas. The International Organization for Standardization (ISO) provides two different perspectives regarding LCC [34]:

- LCC considers the cash flows or costs, i.e., all the relevant costs (externalities and income, if included in the system boundaries) arising from the acquisition phase to the final disposal of a product or procedure;
- LCC compares alternatives or projects future costs for a single project, portfolio or component over a specified period of analysis.

The development of LCC begins around the mid-1960s with the work of MJ Epstein, measuring corporate environmental performance [33]. It is clear that LCC predates LCA with separate and distinct conceptual foundations and methodological approaches [35]. Since 1990, numerous research studies have been conducted with the objective of developing the LCC methodological framework for the construction industry and/or incorporating an environmental perspective. The tripartite of environmental, economic and social sustainability was enhanced over the past decade, developing an integrated lifecycle Sustainability Assessment (LCSA). Apart from the economic impact assessment of buildings [36], LLC was extended to business models and their supply chains [37]. Furthermore, LCC has been introduced to farm management and to bioenergy production [38,39]. Currently, LCC is one of the most important methodological approaches for assessing economic impacts in a variety of areas related to food waste management [40], the management of integrated product systems [41] and wastewater reuse [42].

The economic life of vineyards extends over 15 years, whilst farming costs are different due to irregular agricultural operations and weather conditions over time. The true representative annual estimates (considering all cash flow variations, investment costs and revenue during the lifecycle of agricultural crops) can be calculated following an LCC approach [39,43]. Especially for the economic assessment of table and wine grape production, LCC is considered an appropriate and credible methodological framework, especially in the Mediterranean basin [13–15,17,44–46]. The LCC approach hinges on the allocation of fixed and variable costs to the whole lifetime of cultivation and several project evaluation indices that can be estimated if needed. Net Present Value (*NPV*) is calculated as the difference between the discounted present value of revenue (cash inflows) and the discounted present value of costs (cash outflows) over a time period, as follows:

$$NPV = \sum_{t=0}^{n} \frac{DI_t - DO_t}{(1+i)^t} \tag{1}$$

where DI_t denotes the discounted annual inflows, DO_t is the discounted annual outflows, i is the discount rate and t is the number of time periods. Although *NPV* identifies the most profitable option among all the alternatives, the current project focuses on the identification of the cost and efficiency of the cobots in vineyards. In this context, the discounted costs (*DCs*) are calculated following a similar mathematical formula that considers only the outflows [13]:

$$DC = \sum_{t=0}^{n} \frac{DO_t}{(1+i)^t} \tag{2}$$

Therefore, the cost calculation of vineyards under varying labor operation management techniques can be analyzed, emphasizing the differences between the on-field activities and the inputs. The discounting rate was set at 4%, since other studies use this value for similar investments, following the condition of the market as well as the risk to the wineries [17,47]. The cost-related information for the selected vineyards was thoroughly documented and inputted into the Activity-Based Costing software (ABC©) v.2.1.2.0 [48], a package for analyzing the costs of investment projects in agriculture. ABC© has been widely used in manifold agricultural projects [39,49,50], integrating a similar scope to Activity-Based LCC and illustrating comprehensiveness and effectiveness [51]. In viticulture, Activity-Based LCC consists of several agricultural operations and the assignment of all the relevant costs (inputs, land rent, wages, etc.) to the respective activity as follows:

$$TC_i = \sum Cop_i + \sum Cland_i + \sum Cover_i \tag{3}$$

where TC_i is the total costs for each cultivar i, *Cop* represents the aggregate costs for the respective agricultural operations (namely: fertilization, irrigation, pruning, weed control, herbiciding, topping, tying, defoliation and harvesting), *Cland* is the cost of land ownership and *Cover* includes all the relevant overheads (e.g., replacement of irrigation hoses). The agricultural operations listed above are formulated by an assortment of relevant inputs, which are described by the following equation:

$$Cop_i = \sum M_i + \sum RM_i + \sum L_i + \sum EN_i \tag{4}$$

where *EN* represents the costs of energy consumption, *L* is the cost of human labor, *RM* accounts for the raw materials and *M* is the capital service cost of machinery usage for the cultivar i. Capital service costs for farm equipment can play a significant role in the formulation of the total annual equivalent costs, especially for a project such as SVtech, in which cobots substitute conventional labor. Capital service cost integrates the equivalent costs of maintenance, insurance and purchase costs throughout the lifetime of each piece of machinery equipment. Apart from the above-mentioned, capital service cost includes the average annual interest cost for the asset j (AIC_j), which is calculated as follows:

$$AIC_j = \frac{PC_j + SC_j}{2} \times ir \tag{5}$$

where PC is the purchase cost of the equipment j, SC is the salvage cost and ir is the interest rate. Profit or loss for the total investments is calculated as follows:

$$PL_i = SA_i + SU_i - TC_i \tag{6}$$

where PL_i is the profit or loss for each vine growing system i, SA_i represents the revenue from the sales of the products and SU_i depicts the subsidies received for complying with the Common Agricultural Policy (CAP) framework regarding Direct Payments for farmers. Finally, in order to measure and compare productivity, a broad agricultural productivity metric is chosen that accounts for the contributions of inputs to the production of each scenario [52]. Total factor productivity (*TFP*) can be expressed scientifically as the quotient of the aggregate output generated and the aggregate input utilized in systems with multiple inputs and outputs [53]. Outputs (*O*) and inputs (*I*) are typically aggregated in monetary terms [54], and the *TFP* mathematical formula is expressed as follows by the acceleration of total agricultural output relative to inputs for a specific time period (t):

$$TFP_i = \frac{O_0^t}{I_0^t} \tag{7}$$

2.4. System Boundaries and Inventory Analysis

The present study restricts the analysis to a three-year lifecycle of the selected vineyards during their full production stage by including all the relevant agricultural activities, namely, fertilization, harvesting, spraying/herbiciding, tipping, etc. The idea behind the three-year threshold is documented in order to highlight the critical stage of the consecutive production stage, in which the robotic labor is performed via manifold tasks, developing the studied system boundaries (Figure 3). Nevertheless, this approach has limitations, and the main issues are related to the absence of the relevant planting, training and disposal stages in the analysis. Data regarding the establishment cost are important, especially for vineyards, though the objective of this study is a comparison between conventional and cobot labor within a holistic framework. Moreover, the cost of acquiring a cobot service system is currently not accessible to the majority of wineries as this type of service is not yet commercially available, making it impossible to determine its cost.

The survey focuses on all the scenario combinations of a) four grapevine cultivars, namely, Asyrtiko (A), Cabernet Sauvignon (C), Merlot (M) and Tempranillo (T) and one training system, namely, Guyot, as well as the b) conventional (C) and cobot (CB) factors among the robots on the field: "Asyrtiko Conventional" (AC), "Asyrtiko cobot" (ACB), "Cabernet Sauvignon Conventional" (CC), "Cabernet Sauvignon cobot" (CCB), "Merlot Conventional" (MC), "Merlot cobot" (MCB), "Tempranillo Conventional" (TC) and "Tempranillo cobot" (TCB). Table 3 shows an inventory of the main parameters for each scenario as well as the main differences among them in terms of technical parameters.

A questionnaire was compiled for data acquisition following Mourad et al. [55] alongside the formulation of an economic inventory, integrating necessary aspects for the ABC software [39], such as capital service cost of machinery, wages, etc. The questionnaire was filled out by the agronomists of the wineries, who provided data for the specific vineyards integrated into the SVtech project, regarding a land area of up to 3 ha. Adhering to the LCC methodological framework, economic data was collected with a focus on the operations performed over the selected life cycle of the vineyards. To minimize uncertainty, the production years of 2019, 2020 and 2021 were selected for analysis, despite the fact that these years occurred during the height of the COVID-19 pandemic. According to the agronomists of the two selected wineries, the pandemic did not have any significant impact on their production phases. The analysis sheds light on the capacity of cobots to enhance the economic viability of the Greek wine-growing industry through their demonstrated resilience. The collected economic data concerned specific aspects such as yield output (kg/ha), land rent (EUR/ha), inputs (EUR/kg), wages (EUR/h), machinery usage (EUR/h), overheads (EUR/ha), electrical energy (EUR/kWh), and diesel and petrol (EUR/L). Electricity prices were acquired from the Eurostat statistics reports [56], with an average price of EUR 0.3042 per kWh, whereas the prices of the petroleum products were acquired from the European Commission [57], calculating an average of 50 Weekly Oil Bulletins in 2022. The average price for automotive gas oil (diesel oil) was set at EUR 1.8703 per liter, and for eco-super (petrol), it was set at EUR 2.0554 per liter.

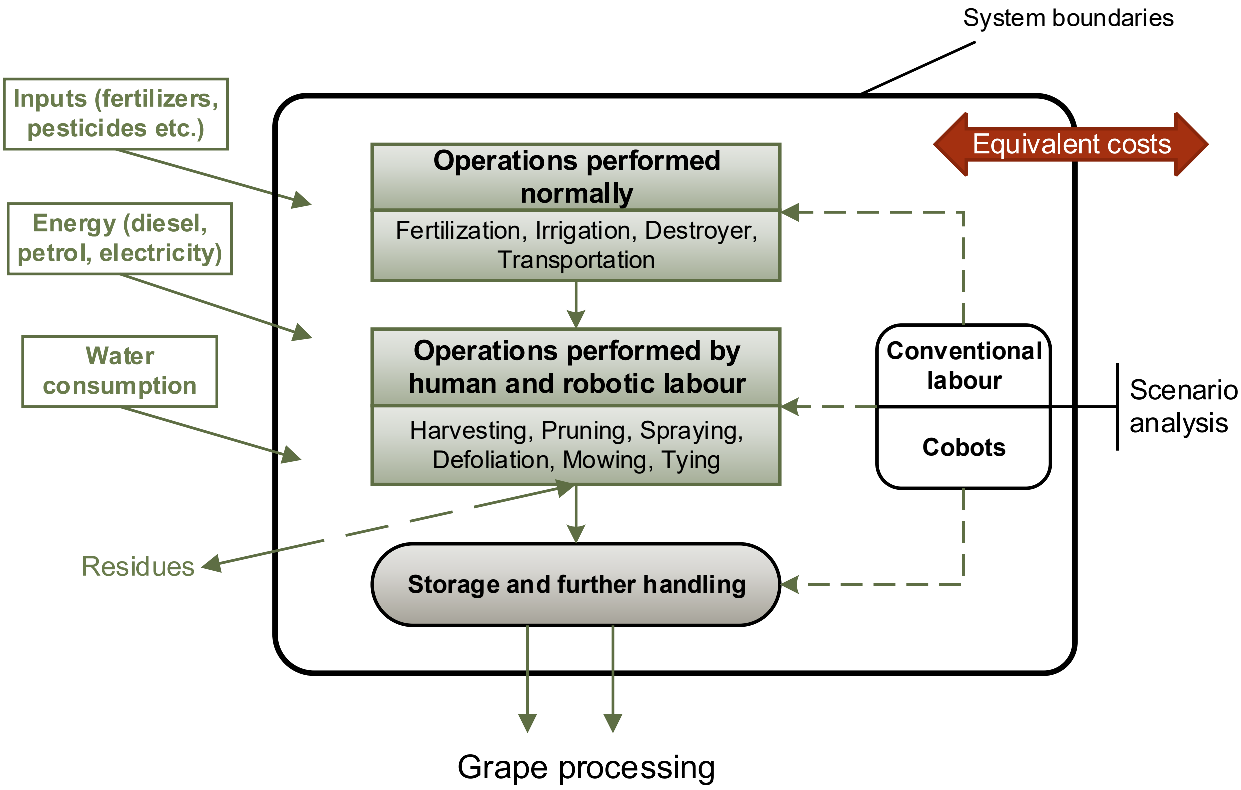

Figure 3. System boundaries flow chart.

Table 3. Economic inventory analysis.

Parameter	Unit	AC	ACB	CC	CCB	MC	MCB	TC	TCB
General details									
Irrigation water	m^3/ha	820		302		317		792	
Number of vines	vines/ha	3780		3300		3300		3780	
Land rent	EUR/ha	200		150		150		200	
Inputs									
Fertilizer 10-10-10	kg/ha	30	30					30	30
Fertilizer 12-12-17-2	kg/ha			125	125	87.5	87.5		
Fertilizer 30-0-15	kg/ha	100	100						
Olive residues	kg/ha			1100	1100				
Poultry manure	kg/ha			244	244	940	940		
Fungicides and Herbicides	kg/ha	25	25	15.44	15.44	11.5	11.5	25	25
Energy									
Electricity	kWh/ha	1450	1506.82	580	626.78	600	644.32	1300	1349.46
Diesel	l/ha	255	121	111.8	68.95	142	55.5	255	121
Petrol	l/ha	40		20		20		40	
Labor									
Human labor	h/ha	447.5	97.5	308.66	88.49	401.25	182	450	106
Tractor	h/ha	32.5	15.5	23.7	11.03	32.75	7.5	30	14
Other machinery	h/ha	65.5	33.12	71.2	25.23	83.75	22.97	62	27.65
cobots	h/ha		309.6		291.3		288.99		299.13
cobots' accessories	h/ha		272.48		263.89		263.35		269.33

3. Results

The economic performance of four grape cultivars was evaluated using an LCC analysis, computing all production costs that are relevant and comparing the conventional approach to cobot scenarios. The results regarding acreage, annual yield and total costs for three production years and for several categories per scenario are summarized in Table 4. In particular, the eight formulated scenarios were compared regarding the basic parameters of the four cultivars, such as acreage and annual yield, are presented. The results demonstrate that conventional scenarios exhibit high labor costs, while cobot scenarios entail high machinery costs, which was anticipated. More specifically, human labor costs exceeds 50% of the total cost for the CC and MC scenarios, whereas in the corresponding cobot scenarios, the human labor costs are reduced to less than 30% of the total cost. Nonetheless, the capital service cost of the machinery is increased in all scenarios involving the cobots, but the overall cost of cobot scenarios is consistently below the equivalent cost of conventional scenarios. Moreover, the energy costs are lower in all the cobot scenarios when compared to the respective conventional scenarios due to the fact that the tractors (using fossil fuels) are substituted by the more energy-efficient cobots.

Table 4. Economic results for the selected acreages in total.

Scenarios	Acreage (ha)	Annual Yield (tn/ha)	Human Labor (EUR)	Machinery (EUR)	Energy (EUR)	Total Cost (EUR)
AC	2.90	9.63	5426.63	1431.59	2900.70	16,211.41
ACB			1243.38	4937.42	1999.55	14,632.85
CC	2.20	5.32	3794.05	493.00	938.63	7535.40
CCB			1212.93	3122.59	722.17	7367.40
MC	2.40	5.05	5702.66	720.53	1174.08	9952.75
MCB			2718.22	3324.98	740.23	9138.91
TC	1.90	8.02	3562.50	865.07	1813.76	9803.83
TCB			872.10	3011.99	1226.49	8673.08

Presumably, the differences in Table 4 regarding the total costs are mainly due to the allocation of economic resources to the alternative cost categories. The economic analysis of the selected scenarios to the six main input categories, namely, energy, labor, land, machinery, overheads and raw materials, provides an enhanced perspective on the cost allocation of each scenario. Figure 4 shows the impact of each input category on the respective scenario in annual equivalent costs, while the land, overheads and raw materials categories obtain similar values for paired scenarios. The pattern is repeated in all cobot scenarios, highlighting a significant reduction in human labor costs, whereas the energy costs are decreased to a lesser degree. Furthermore, the expenses related to the operating costs of the machinery play a significant role in the cobot scenarios, although the total cost per hectare is lower in all the cobot scenarios in comparison to the conventional ones, especially for the TCB and ACB (−11.53% and −9.74%, respectively). Nonetheless, the potential cost savings from the implementation of cobots in viticultural operations are significant for both MCB and CCB scenarios, resulting in a decrease of 8.18% and 2.23% in total costs, respectively, compared to their conventional counterparts.

As explained above, the major differences among the scenarios depend on the number of human labor hours, the capital service cost of the machinery, and energy consumption. Having said that, the allocation of the costs to the respective viticultural operations could result in useful conclusions regarding the sustainability of cobots in agriculture. The ABC© software segments the expenses into operations for the whole lifecycle of the project and transmutes them into the annual equivalent costs. The cost operation analysis integrates important aspects and neglects land rent and overheads, focusing on viticultural practices, which are the core of the current study.

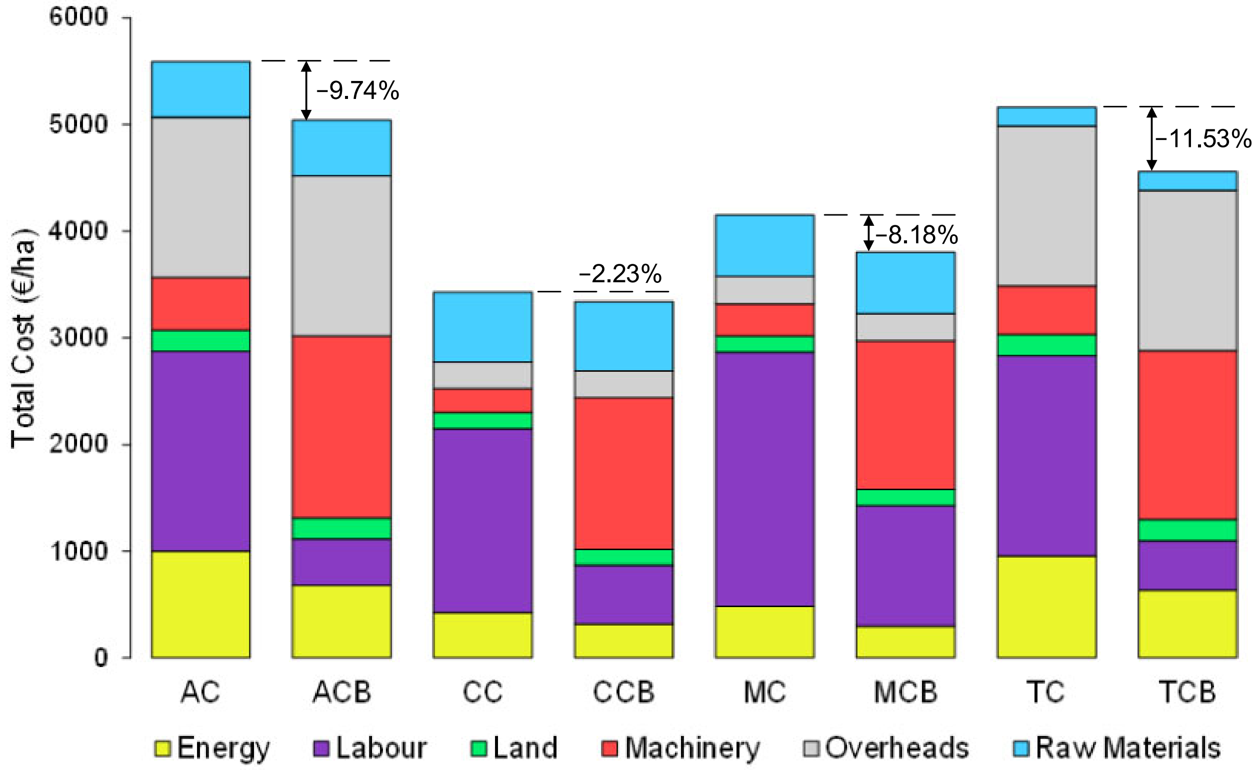

Figure 4. Economic analysis barplot of the scenarios in EUR per hectare per year.

In this context, Figure 5 depicts the operation analysis bar plot in EUR/ha, as exported by the ABC software and illustrated by RStudio 2022.07.1 + 554 [58], for the Asyrtiko scenarios. Obviously, tying, pruning, irrigation and fertilization are the most cost-demanding activities for AC, while defoliation exceeds the operation cost in comparison to the conventional scenario for ACB. Nevertheless, weed control, tying, pruning and herbiciding are the activities that could be performed by cobots, lowering the expenses to a significant degree. In particular, savings from the relevant operations for ACB are weed control at 194.22 EUR/ha, tying at 75.17 EUR/ha, pruning at 71.74 EUR/ha and herbiciding at 35.90 EUR/ha. For the Cabernet Sauvignon scenarios (Figure 6), weed control, pruning and herbiciding are the major aspects for the cost reductions between the CB and CCB scenarios, achieving −242.96 EUR/ha, −93.74 EUR/ha and −80.74 EUR/ha, respectively. However, all the other operations performed by cobots (topping, tying and harvesting) present increased expenses in comparison to the CC scenario.

The agricultural practices regarding the Merlot cultivar include an extra operation (weed control/spraying) in weed control, which involves an added on-field spraying operation with selected herbicides. The current practice could be performed by cobots generating a cost reduction of 45.53 EUR/ha, as shown in Figure 7. Nevertheless, the tying, harvesting and defoliation operations are considered uneconomical for the MCB scenarios in contrast to MC. The subsequent bar graph (Figure 8) accentuates the feasible cost reduction associated with the Tempranillo cultivar, showcasing the most substantial economic deviation as depicted in Figure 4. Indeed, all the relevant operations performed by cobots (TCB) achieve lower costs in comparison to the conventional operations (TC), except for the defoliation.

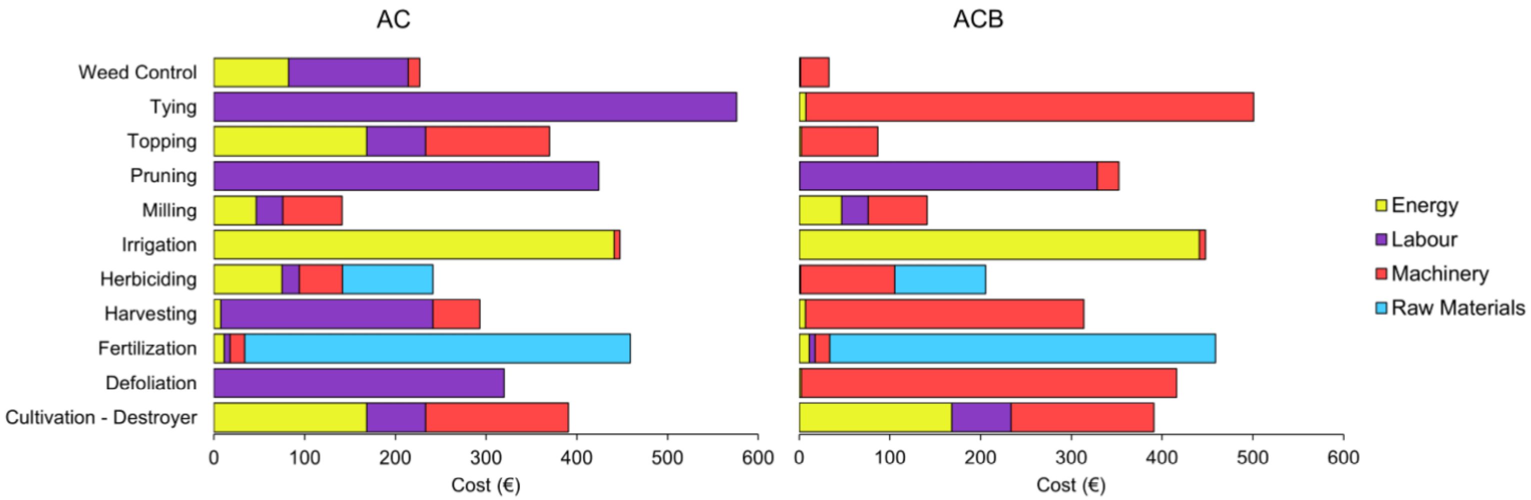

Figure 5. Operation analysis barplot for the Asyrtiko scenarios in EUR/ha.

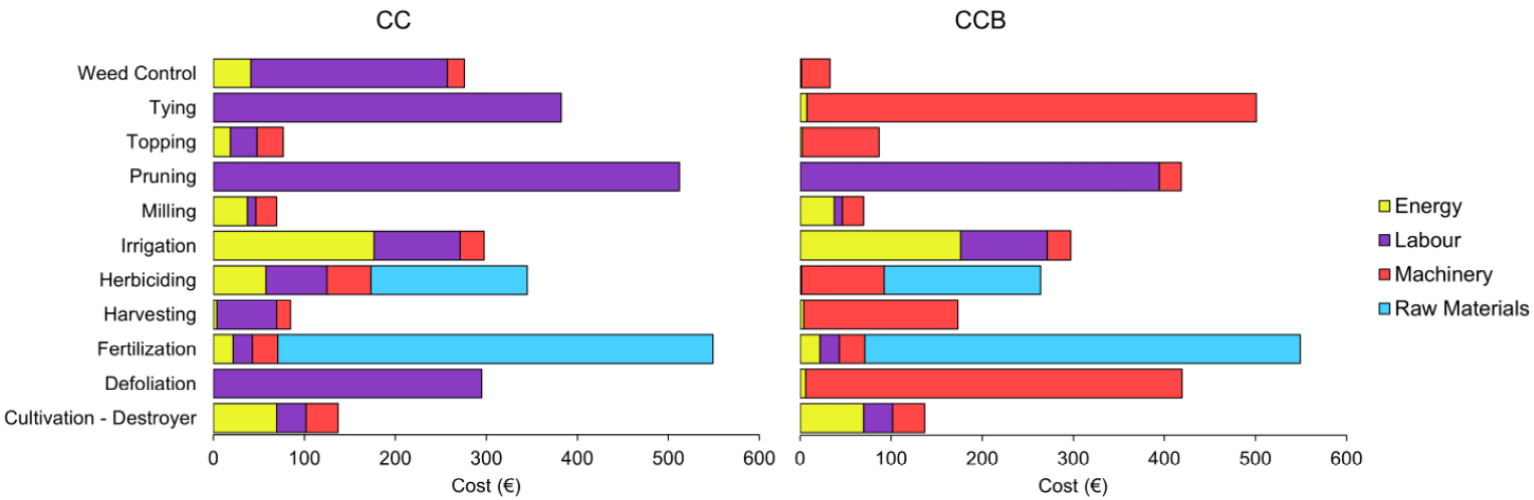

Figure 6. Operation analysis barplot for the Cabernet Sauvignon scenarios in EUR/ha.

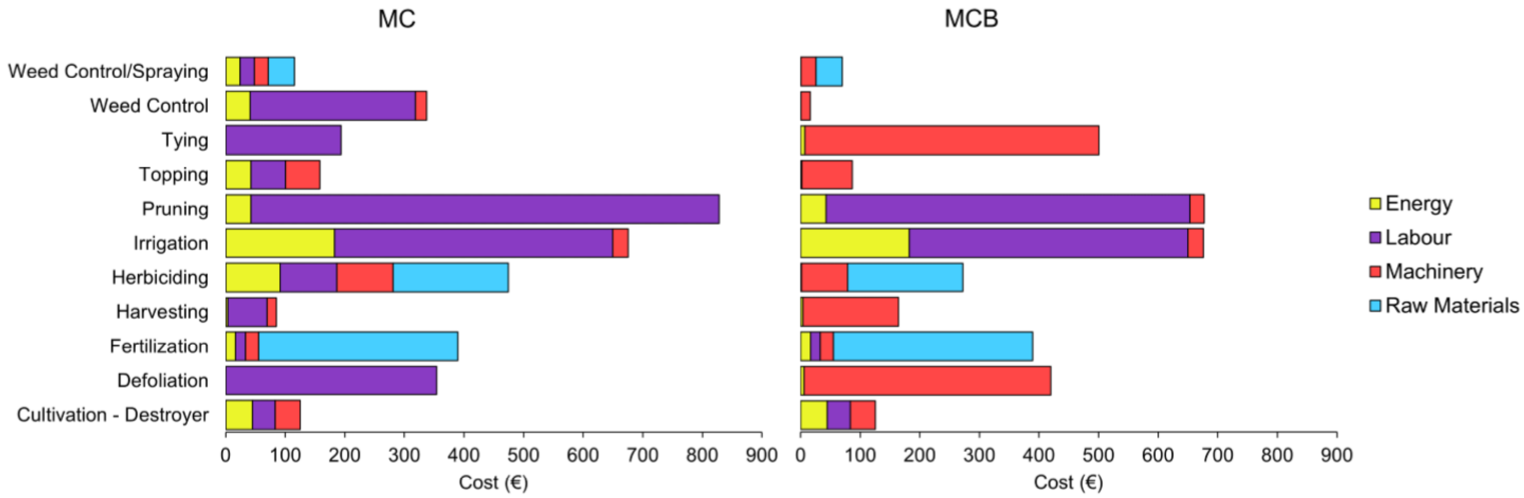

Figure 7. Operation analysis barplot for the Merlot scenarios in EUR/ha.

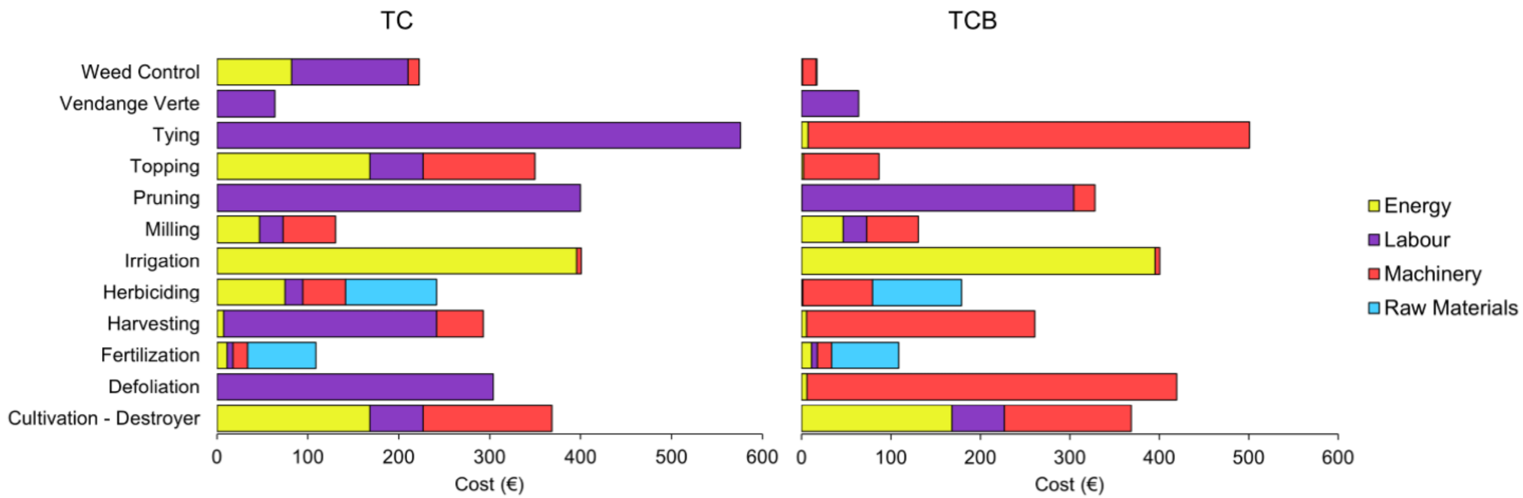

Figure 8. Operation analysis bar plot for the Tempranillo scenarios in EUR/ha.

As illustrated by the operation analysis bar plots, the capital service cost of the machinery and the human labor costs are the main economic factors of annual viticultural production for the selected cultivars. In the present study, the lifespan of cobots is of considerable importance; however, the robustness to environmental conditions and the likelihood of malfunctions are still uncertain and warrant further investigation. Therefore, the framework of the discounted costs during the three years of the production phase was compared, integrating different lifecycles for the cobots, as explained below with reference to Table 5.

Table 5. Difference between the values of the discounted costs considering the lifecycle of the cobots.

Lifecycle of Cobots	Asyrtiko (AC-ACB)		Cabernet Sauvignon (CC-CCB)		Merlot (MC-MCB)		Tempranillo (TC-TCB)	
	Discounted Cost (EUR/ha)	Deviation (%)	Discounted Cost (EUR/ha)	Deviation (%)	Discounted Cost (EUR/ha)	Deviation (%)	Discounted Cost (EUR/ha)	Deviation (%)
5 years	−3531.25	−22.76%	−4281.02	−45.04%	−3495.45	−30.37%	−3052.02	−21.31%
15 years (base)	1510.57	9.74%	211.91	2.23%	941.03	8.18%	1651.54	11.53%
25 years	2478.82	15.98%	1072.88	11.29%	1792.60	15.58%	2554.97	17.84%
35 years	2870.69	18.50%	1421.62	14.96%	2137.65	18.57%	2920.87	20.40%

When assuming a short lifetime for the cobots (5 years), conventional practices are considered superior choices since the margin for discounted costs is negative for all respective cobot scenarios. Despite this, the integration of cobots in viticulture has the potential to significantly reduce the expenses of farm management, provided that the cobots have a lifespan exceeding 15 years. In a three-year framework, the least economic impact is illustrated in the Cabernet Sauvignon scenarios, in which the CCB scenario saves 211.91 EUR/ha in comparison to the CC scenario. The most favorable scenario for integrating cobots in viticultural production involves considering a lifespan of 35 years for the cobots when dealing with the Tempranillo cultivar. The discounted cost discrepancy between TC and TCB is 2920.87 EUR/ha, demonstrating a deviation of 20.40%. Nonetheless, the lifetime of the cobots is a significant factor when regarding the sustainability of a project substituting conventional labor in viticulture.

In order to measure and compare productivity among the selected scenarios, the *TFP* indicator was implemented. In Table 6, a summary of findings on *TFP* and the respective deviations between the corresponding scenarios are presented regarding the selected production period. *TFP* growth rose for all the scenarios, and the main reason for this is the implementation of on-farm automation, information and data management from cobots. Cobots minimize the time required for farmers to operate the farm, thus achieving higher scores for *TFP*.

Table 6. Total factor productivity (*TFP*) indicator and deviations among scenarios.

Scenario	*TFP*	Deviation (%)
AC	1.55	10.78%
ACB	1.72	
CC	1.39	2.28%
CCB	1.42	
MC	1.10	8.91%
MCB	1.19	
TC	1.56	13.04%
TCB	1.76	

The reduction in cost resulting from labor savings had a notable effect on the AC and TC scenarios, as demonstrated by the deviation of *TFP*, which exceeded 10% (10.78% and 13.04%, respectively). However, the Merlot scenarios (MC and MCB) displayed the lowest

TFP, indicating an imbalanced ratio between inputs and outputs. This low measure of productivity was attributed to a significant decrease in total production due to hail in 2021. As a result, this specific cultivar was removed in 2022.

4. Discussion

In Greece, the total agricultural land used for wine grape cultivation slightly increased by 1.7% from 2015 to 2020, whereas the area dedicated to raisin vineyards decreased by 3.1% during the same time period. Regarding the total area and categories of grape vines, 22.1% of viticulture is dedicated to PDO wines, 63.1% to PGI wines, 11.4% to other wine types, and 3.5% to vines for grapes and wine consumption [25]. Obviously, viticulture is a major actor in the Greek production plan, aligning with the EU policies for quality over quantity products. The introduction of autonomous robots has demonstrated promising potential [59], and Greek viticulture is moving in this direction. The assimilation of knowledge and innovative technologies should formulate the cornerstone of autonomous multipurpose robotic operations in viticulture [60]; therefore, the economic performance of an innovative system as such is a novelty presented by the current study.

The economic analysis indicates that the TCB and ACB scenarios resulted in the lowest total cost per hectare when analyzed in a framework of LCC, followed by the MCB and CCB scenarios. However, the significant aspects of cobot integration into viticultural production pertained to operations such as weed control, pruning, herbiciding and topping. Autonomous weeding practices are operations considered to be cost-effective alternatives to conventional practices, as reported by other studies [21,22]. McCorkle et al. [24] reported potential positive economic returns for pruning and topping operations in vineyards, which align with the corresponding operations in the present study. Nevertheless, the defoliation and tying operations have generated higher costs in comparison to conventional practices that are carried out manually. The identification of objects (usually leaves) and tying the shoots of a vine are time-consuming operations for cobots, increasing the robot's operation time as well as the capital service cost.

As stated by Pradel et al. [61], robotic solutions in viticulture should be tested from different perspectives, and the lifetime of the technology is one of them. Assuming that cobots have a lifecycle of 15 years, the tying and defoliation operations are not cost-effective in most of the investigated cases. Nevertheless, if the lifecycle of cobots is prolonged to 25 or 35 years, the results have indicated that total costs could be reduced by a significant margin. The progress in technology and the development of autonomous cobot labor in viticulture showcase the interplay between learning and physical depreciation over the long term. The concept "learning by doing" refers to an increase in productive efficiency that results from the acquisition of experience through the production of goods or services [62]. The concept of "learning by doing" was formally modeled for the first time by Arrow [63] in a pursuit of a theory of economic growth that did not rely on the assumption of exogenous changes in productivity as the primary driving force. The increasing knowledge and experience regarding agricultural operations of cobots can be quantified by cumulative investment, referred to as accumulated software capital. As a result, the cost of replacing a new cobot is reduced due to this inherited legacy as accumulated software capital. The viewpoint of accumulated software capital has the potential to decrease production costs even further, warranting the possibility of further research over time.

This study is mainly focused on the full production phase of viticulture, neglecting the disposal, training and planting phases, which correspond to significant expenses as well [17]. The integration of cobots throughout the entire lifecycle of vineyards could be the next step of economic assessment, as the available literature in this area is limited. There are few economic studies regarding robotics in agriculture, and experience related to cobots in agriculture is limited [20]; hence, the primary objective of this study was focused solely on the production phase.

5. Conclusions

This study analyzed the economic performance of various agricultural activities performed by cobots, and to the best of our knowledge, such an examination has not been previously conducted in the literature. The study has revealed that the integration of cobots in viticulture can decrease the overall cost of yearly production while underlining the significance of the lifespan of crop robots and the possibility of failures. In addition, the integration of cobots in viticulture has the potential to increase productivity, as the reduction in labor costs can boost growth in *TFP* [54]. Furthermore, the transition from traditional labor techniques to cobots may generate systemic impacts on operations analysis, reducing the costs of operations, such as weed control, pruning, herbiciding and topping, while decreasing the cost-effectiveness of operations such as defoliation and tying. The quality of robotic work should meet the higher standards of viticultural production since the majority of the produced grapes are meant for PDI and PGI wine production. Nevertheless, marketing activities regarding the promotion of Greek wine by the industry and the Greek Ministry of Rural Development and Food remain vague and are without an export-oriented management plan, making it difficult into integrate innovative technologies to viticultural production.

Value-added activities are limited, and branding is not the strong point of the Greek wine industry abroad, although the development of an autonomous service performing agricultural operations could give the boost that is needed. In addition to the establishment of a financially supported international promotion and distribution channel by the Greek ministry, the combination of wine tourism with holiday destinations could greatly enhance the competitiveness of the Greek wine industry at the macroeconomic level [64]. Cobots in agriculture could lower production costs and increase the competitiveness of the whole Greek wine-making industry toward seizing opportunities on an international level and enhance the dynamic of wine exports [65].

Future studies could integrate the market price fluctuations of different wines in a mathematical programming decision-making model under conventional and cobot operation constraints, in order to identify the optimal production plan for each winery. Ultimately, production efficiency can be estimated through the application of a data envelopment analysis (DEA) with the aim to distinguish and rank decision-making units based on their efficiency.

Author Contributions: Conceptualization, E.T. and V.G.K.; data curation, E.T., E.K., I.K. and A.K.; formal analysis, E.T., E.K. and I.K.; investigation, E.T., E.K., A.K. and A.G.; methodology, E.T., T.P. and V.G.K.; supervision, E.T., A.B. and V.G.K.; validation, E.T. and I.K.; writing—original draft, E.T., E.K., I.K., A.B. and V.G.K.; writing—review and editing, E.T., A.B., T.P. and V.G.K. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge support for this work by the project "Technology for Skillful Viniculture (SVtech)" (MIS 5046047), which is implemented under the Action "Reinforcement of the Research and Innovation Infrastructure", funded by the Operational Program "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020), and co-financed by Greece and the European Union (European Regional Development Fund).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request after the end of the project.

Acknowledgments: The authors would like to thank Ioannis Chronis from Ktima-Pavlidis winery and Nikolaos Tsipouridis from Nico Lazaridi winery for providing us with data regarding all the relevant expenses, including wages, inputs, energy, machinery maintenance and capital service cost.

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

References

1. Jones, G.V.; Reid, R.; Vilks, A. Climate, grapes, and wine: Structure and suitability in a variable and changing climate. In *ography of Wine: Regions, Terroir and Techniques*; Springer: Amsterdam, The Netherlands, 2012; ISBN 9789400704640.
2. Eurostat Wine-Grower Holdings by Production. Total Area under Vines (in/Not yet in Production). Available online: https://ec.europa.eu/eurostat/databrowser/view/vit_t1/default/table?lang=en (accessed on 28 July 2022).
3. Chaikind, S. The Role of Viticulture and Enology in the Development of Economic Thought: How Wine Contributed to Modern Economic Theory. *J. Wine Econ.* **2012**, *7*, 213–225. [CrossRef]
4. Franken, J.; Gómez, M.; Ross, R.B. Social Capital and Entrepreneurship in Emerging Wine Regions. *J. Wine Econ.* **2018**, *13*, 419–428. [CrossRef]
5. European Commission. *EU Agricultural Outlook for Markets, Income and Environment, 2021–2031*; European Commission, DG Agriculture and Rural Development: Brussels, Belgium, 2021.
6. De Luca, A.I.; Molari, G.; Seddaiu, G.; Toscano, A.; Bombino, G.; Ledda, L.; Milani, M.; Vittuari, M. Multidisciplinary and Innovative Methodologies for Sustainable Management in Agricultural Systems. *Environ. Eng. Manag. J.* **2015**, *14*, 1571–1581. [CrossRef]
7. Wrzaszcz, W.; Prandecki, K. Agriculture and the European Green Deal. *Probl. Agric. Econ.* **2020**, *365*, 156–179. [CrossRef]
8. EU Farm to Fork Strategy. DG SANTE/Unit 'Food Information and Composition, Food Waste'. 2020. Available online: https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (accessed on 8 February 2022).
9. Delord, B.; Montaigne, É.; Coelho, A. Vine planting rights, farm size and economic performance: Do economies of scale matter in the French viticulture sector? *Wine Econ. Policy* **2015**, *4*, 22–34. [CrossRef]
10. Balafoutis, A.T.; Koundouras, S.; Anastasiou, E.; Fountas, S.; Arvanitis, K. Life Cycle Assessment of Two Vineyards after the Application of Precision Viticulture Techniques: A Case Study. *Sustainability* **2017**, *9*, 1997. [CrossRef]
11. Torquati, B.; Giacchè, G.; Venanzi, S. Economic analysis of the traditional cultural vineyard landscapes in Italy. *J. Rural. Stud.* **2015**, *39*, 122–132. [CrossRef]
12. Romero Azorín, P.; García García, J. The Productive, Economic, and Social Efficiency of Vineyards Using Combined Drought-Tolerant Rootstocks and Efficient Low Water Volume Deficit Irrigation Techniques under Mediterranean Semiarid Conditions. *Sustainability* **2020**, *12*, 1930. [CrossRef]
13. Strano, A.; De Luca, A.I.; Falcone, G.; Iofrida, N.; Stillitano, T.; Gulisano, G. Economic and environmental sustainability assessment of wine grape production scenarios in Southern Italy. *Agric. Sci.* **2013**, *4*, 12–20. [CrossRef]
14. Falcone, G.; De Luca, A.I.; Stillitano, T.; Strano, A.; Romeo, G.; Gulisano, G. Assessment of Environmental and Economic Impacts of Vine-Growing Combining Life Cycle Assessment, Life Cycle Costing and Multicriterial Analysis. *Sustainability* **2016**, *8*, 793. [CrossRef]
15. Canaj, K.; Mehmeti, A.; Berbel, J. The Economics of Fruit and Vegetable Production Irrigated with Reclaimed Water Incorporating the Hidden Costs of Life Cycle Environmental Impacts. *Resources* **2021**, *10*, 90. [CrossRef]
16. Ponsioen, T.; Nuhoff-Isakhanyan, G.; Vellinga, T.; Baltussen, W.; Boone, K.; Woltjer, G. *Monetisation of Sustainability Impacts of Food Production and Consumption*; Wageningen Economic Research: Wageningen, The Netherlands, 2020.
17. Roselli, L.; Casieri, A.; de Gennaro, B.C.; Sardaro, R.; Russo, G. Environmental and Economic Sustainability of Table Grape Production in Italy. *Sustainability* **2020**, *12*, 3670. [CrossRef]
18. Santiago-Brown, I.; Metcalfe, A.; Jerram, C.; Collins, C. Sustainability Assessment in Wine-Grape Growing in the New World: Economic, Environmental, and Social Indicators for Agricultural Businesses. *Sustainability* **2015**, *7*, 8178–8204. [CrossRef]
19. Bramley, R.G.V. Precision viticulture: Managing vineyard variability for improved quality outcomes. In *Managing Wine Quality: Viticulture and Wine Quality*; Elsevier: Amsterdam, The Netherlands, 2010; ISBN 9781845694845.
20. Lowenberg-DeBoer, J.; Huang, I.Y.; Grigoriadis, V.; Blackmore, S. Economics of robots and automation in field crop production. *Precis. Agric.* **2020**, *21*, 278–299. [CrossRef]
21. Gaus, C.-C.; Urso, L.-M.; Minßen, T.-F.; De Witte, T. Economics of mechanical weeding by a swarm of small field robots. In Proceedings of the 57th Annual Conference of the GEWISOLA (German Association of Agricultural Economists) and the 27th Annual Conference of the ÖGA (Austrian Society of Economics) "Bridging the Gap between Resource Efficiency and Society's Expectations in the Agricultural and Food Economy", Munich, Germany, 13–15 September 2017.
22. Saidani, M.; Pan, Z.; Kim, H.; Wattonville, J.; Greenlee, A.; Shannon, T.; Yannou, B.; Leroy, Y.; Cluzel, F. Comparative life cycle assessment and costing of an autonomous lawn mowing system with human-operated alternatives: Implication for sustainable design improvements. *Int. J. Sustain. Eng.* **2021**, *14*, 704–724. [CrossRef]
23. Pedersen, S.M.; Fountas, S.; Blackmore, S. Agricultural robots—Applications and economic perspectives. In *Service Robot Applications*; InTech: London, UK, 2008; p. 16.
24. McCorkle, D.A.; Dudensing, R.M.; Hanselka, D.; Hellman, E.W. Economics of robotic technology in texas wine grape production. In Proceedings of the Southern Agricultural Economics Association Annual Meeting, San Antonio, TX, USA, 6–9 February 2016.
25. Hellenic Statistical Authority Press Release. 2020 Vineyard Survey 2022; p. 8. Available online: https://www.statistics.gr/en/statistics?p_p_id=documents_WAR_publicationsportlet_INSTANCE_qDQ8fBKKo4lN&p_p_lifecycle=2&p_p_state=normal&p_p_mode=view&p_p_cacheability=cacheLevelPage&p_p_col_id=column-2&p_p_col_count=4&p_p_col_pos=1&_documents_WAR_publica (accessed on 8 February 2023).

26. Lytridis, C.; Kaburlasos, V.G.; Pachidis, T.; Manios, M.; Vrochidou, E.; Kalampokas, T.; Chatzistamatis, S. An Overview of Cooperative Robotics in Agriculture. *Agronomy* **2021**, *11*, 1818. [CrossRef]
27. Hendrickson, D.A.; Lerno, L.A.; Hjelmeland, A.K.; Ebeler, S.E.; Heymann, H.; Hopfer, H.; Block, K.L.; Brenneman, C.A.; Oberholster, A. Impact of Mechanical Harvesting and Optical Berry Sorting on Grape and Wine Composition. *Am. J. Enol. Vitic.* **2016**, *67*, 385–397. [CrossRef]
28. Bonneau, V.; Copigneaux, B.; Probst, L.; Pedersen, B. Industry 4.0 in Agriculture: Focus OnIoT Aspects. 2017. Available online: https://ati.ec.europa.eu/sites/default/files/2020-07/Industry%204.0%20in%20Agriculture%20-%20Focus%20on%20IoT%20aspects%20%28v1%29.pdf (accessed on 8 February 2023).
29. Delmerico, J.; Mueggler, E.; Nitsch, J.; Scaramuzza, D. Active Autonomous Aerial Exploration for Ground Robot Path Planning. *IEEE Robot. Autom. Lett.* **2017**, *2*, 664–671. [CrossRef]
30. Robotnik Autonomous Mobile Robot (AMR). Suitable for Indoor and Outdoor Logistics Applications Due to Its Versatility and High Mobility Autonomous and Collaborative Mobile Manipulator Designed for Industry. Available online: https://robotnik.eu/products/mobile-robots/#robots (accessed on 1 September 2022).
31. Ag Decision Maker Estimating Farm Machinery Costs, File A3-29. Available online: https://www.extension.iastate.edu/agdm/crops/pdf/a3-29.pdf (accessed on 24 December 2022).
32. Eurostat Land Use Statistics, Main Land Use by Land Use Type, EU. 2018. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics#Land_use (accessed on 6 August 2022).
33. Gluch, P.; Baumann, H. The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. *Build. Environ.* **2004**, *39*, 571–580. [CrossRef]
34. *ISO 15686-5:2017(E)*; Buildings and Constructed Assets—Service Life Planning. ISO: Geneva, Switzerland, 2017.
35. Swarr, T.E.; Hunkeler, D.; Klöpffer, W.; Pesonen, H.-L.; Ciroth, A.; Brent, A.C.; Pagan, R. Environmental life-cycle costing: A code of practice. *Int. J. Life Cycle Assess.* **2011**, *16*, 389–391. [CrossRef]
36. Morrissey, J.; Horne, R. Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy Build.* **2011**, *43*, 915–924. [CrossRef]
37. Lindahl, M.; Sundin, E.; Sakao, T. Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases. *J. Clean. Prod.* **2014**, *64*, 288–296. [CrossRef]
38. Resurreccion, E.P.; Colosi, L.M.; White, M.A.; Clarens, A.F. Comparison of algae cultivation methods for bioenergy production using a combined life cycle assessment and life cycle costing approach. *Bioresour. Technol.* **2012**, *126*, 298–306. [CrossRef] [PubMed]
39. Soldatos, P. Economic Aspects of Bioenergy Production from Perennial Grasses in Marginal Lands of South Europe. *Bioenergy Res.* **2015**, *8*, 1562–1573. [CrossRef]
40. Edwards, J.; Burn, S.; Crossin, E.; Othman, M. Life cycle costing of municipal food waste management systems: The effect of environmental externalities and transfer costs using local government case studies. *Resour. Conserv. Recycl.* **2018**, *138*, 118–129. [CrossRef]
41. Corti, D.; Fontana, A.; De Santis, M.; Norden, C.; Ahlers, R. Life cycle assessment and life cycle costing for PSS. In *Models, Methods and Tools for Product Service Design: The Manutelligence Project*; Cattaneo, L., Terzi, S., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 83–100; ISBN 978-3-319-95849-1.
42. Tarpani, R.R.Z.; Azapagic, A. Life cycle costs of advanced treatment techniques for wastewater reuse and resource recovery from sewage sludge. *J. Clean. Prod.* **2018**, *204*, 832–847. [CrossRef]
43. Hoogmartens, R.; Van Passel, S.; Van Acker, K.; Dubois, M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environ. Impact Assess. Rev.* **2014**, *48*, 27–33. [CrossRef]
44. Falcone, G.; Strano, A.; Stillitano, T.; De Luca, A.I.; Iofrida, N.; Gulisano, G. Integrated Sustainability Appraisal of Wine-growing Management Systems through LCA and LCC Methodologies. *Chem. Eng. Trans.* **2015**, *44*, 223–228. [CrossRef]
45. Canaj, K.; Morrone, D.; Roma, R.; Boari, F.; Cantore, V.; Todorovic, M. Reclaimed Water for Vineyard Irrigation in a Mediterranean Context: Life Cycle Environmental Impacts, Life Cycle Costs, and Eco-Efficiency. *Water* **2021**, *13*, 2242. [CrossRef]
46. Strano, A.; Stillitano, T.; De Luca, A.I.; Falcone, G.; Gulisano, G. Profitability Analysis of Small-Scale Beekeeping Firms by Using Life Cycle Costing (LCC) Methodology. *Am. J. Agric. Biol. Sci.* **2015**, *10*, 116–127. [CrossRef]
47. Hartman, J.C.; Schafrick, I.C. The Relevant Internal Rate of Return. *Eng. Econ.* **2004**, *49*, 139–158. [CrossRef]
48. ABC. ABC Software Documentations. Available online: http://abcsoftware.org/software.aspx (accessed on 30 December 2022).
49. Tziolas, E.; Bournaris, T. Economic and Environmental Assessment of Agro-Energy Districts in Northern Greece: A Life Cycle Assessment Approach. *BioEnergy Res.* **2019**, *12*, 1145–1162. [CrossRef]
50. Tziolas, E.; Ispikoudis, S.; Mantzanas, K.; Koutsoulis, D.; Pantera, A. Economic and Environmental Assessment of Olive Agroforestry Practices in Northern Greece. *Agriculture* **2022**, *12*, 851. [CrossRef]
51. Emblemsvag, J. Activity-based life-cycle costing. *Manag. Audit. J.* **2001**, *16*, 17–27. [CrossRef]
52. Fuglie, K. Accounting for Growth in Global Agriculture. *Bio-Based Appl. Econ.* **2015**, *4*, 201–234. [CrossRef]
53. Coelli, T.J.; Prasada Rao, D.S.; O'Donnell, C.J.; Battese, G.E. *An Introduction to Efficiency and Productivity Analysis*; Springer: New York, NY, USA, 2005; ISBN 0387242651.
54. Coomes, O.T.; Barham, B.L.; MacDonald, G.K.; Ramankutty, N.; Chavas, J.P. Leveraging Total Factor Productivity Growth for Sustainable and Resilient Farming. *Nat. Sustain.* **2019**, *2*, 22–28. [CrossRef]

55. Mourad, A.L.; Coltro, L.; Oliveira, P.A.P.L.V.; Kletecke, R.M.; Baddini, J.P.O.A. A simple methodology for elaborating the life cycle inventory of agricultural products. *Int. J. Life Cycle Assess.* **2007**, *12*, 408–413. [CrossRef]
56. Eurostat Electricity Price Statistics—Electricity Prices for Non-Household Consumers. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers (accessed on 22 December 2022).
57. European Commission Weekly Oil Bulletin—Price Developments—By Year (1994–2005) (for All EU Countries). Available online: https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en (accessed on 22 December 2022).
58. RStudio Team RStudio: Integrated Development Environment for R 2020. Available online: https://www.r-project.org/conferences/useR-2011/abstracts/180111-allairejj.pdf (accessed on 8 February 2023).
59. Kapetanović, N.; Goričanec, J.; Vatavuk, I.; Hrabar, I.; Stuhne, D.; Vasiljević, G.; Kovačić, Z.; Mišković, N.; Antolović, N.; Anić, M.; et al. Heterogeneous Autonomous Robotic System in Viticulture and Mariculture: Vehicles Development and Systems Integration. *Sensors* **2022**, *22*, 2961. [CrossRef]
60. Vrochidou, E.; Bazinas, C.; Mavridou, E.; Pachidis, T.; Mamalis, S.; Koundouras, S.; Gkrimpizis, T.; Kaburlasos, V.G. Considerations for a multi-purpose agrobot design toward automating skillful viticultural tasks: A study in northern greece vineyards. In Proceedings of the 10th International Conference on Information and Communication Technologies in Agriculture, Food & Environment (HAICTA 2022), Athens, Greece, 22–25 September 2022; p. 7.
61. Pradel, M.; de Fays, M.; Séguineau, C. Comparative Life Cycle Assessment of Intra-Row and Inter-Rows Weeding Practices Using Autonomous Robot Systems in French Vineyards. *SSRN Electron. J.* **2022**, *838*, 156441. [CrossRef]
62. Beaudry, P. *Growth and Learning-by-Doing BT—Economic Growth*; Durlauf, S.N., Blume, L.E., Eds.; Palgrave Macmillan: London, UK, 2010; pp. 124–126. ISBN 978-0-230-28082-3.
63. Arrow, K.J. The Economic Implications of Learning by Doing. *Rev. Econ. Stud.* **1962**, *29*, 155–173. [CrossRef]
64. Vlachos, V.A. A macroeconomic estimation of wine production in Greece. *Wine Econ. Policy* **2017**, *6*, 3–13. [CrossRef]
65. Koutroupi, E.; Natos, D.; Karelakis, C. Assessing Exports Market Dynamics: The Case of Greek Wine Exports. *Procedia Econ. Financ.* **2015**, *19*, 184–192. [CrossRef]