Assessment of using state of the art unmanned ground vehicles for operations on peat fields

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SUMMARY

In this article a concept is presented for replacing the tractors that haul machinery during necessary operations on peat fields with centrally controlled unmanned ground vehicles (UGVs). The objective is to reduce operational costs in terms of human labour, fuel consumption and the associated CO_2 emissions. A robotic system architecture for the example of milled peat extraction has been developed and assessed on the basis of comparative analysis. Depending on the area of the extraction surface, the number of UGVs and the method of extraction, the fuel consumption and labour requirement for one season were determined using a combination of data from production records compiled by peat companies and field measurements using the UGV under assessment. It is demonstrated that utilising currently available robotic technology for milled peat extraction by either the Haku method or the 'vacuum harvester' method can reduce production-related labour requirement by 34–43 % and fuel consumption by 21–26 % with a corresponding reduction of CO_2 emissions. Future advances in UGV technology will increase the advantages of robotic technology by reducing the requirements for human intervention as well as by using green energy in fully electric UGVs.

KEY WORDS: fuel consumption, labour requirement, peat extraction, robotic and autonomous systems

INTRODUCTION

Haulage machinery is required for a variety of operations on peatlands under different land uses (agriculture, forestry, peat extraction) as well as nature conservation (Dubowski *et al*. 2014, Zembrowski & Dubowski 2019), and the requirement will continue with a future expansion of paludiculture (Schröder *et al*. 2015). The work is often seasonal and weather-dependent, which creates economic issues around availability of the most appropriate equipment and the retention of skilled operators.

In the example of milled peat extraction, operation costs depend primarily on the costs of conventional diesel-engine tractors carrying out all operations on standardised peat fields (Pakere & Blumberga 2017). Therefore, the only option for reducing costs must challenge the limitations of the tractor fleet. Most initiatives in this direction have resulted in successful but nevertheless incremental improvements, e.g. the introduction of algorithms to optimise the performance of the tractors (Johnson *et al*. 2009, John Deere 2017, Manthey 2018, Agriland 2019). An increasingly feasible alternative would be to replace manned tractors with a fleet of Unmanned Ground Vehicles (UGVs), and thus to usher in cost-reducing changes to the operational architecture.

Robotic and Autonomous Systems (RAS), and in particular UGV systems, have been used in agriculture for several decades (Lewis & Ge 2006, Bechar & Vigneault 2016, Hajjaj & Sahari 2016, Aravind *et al*. 2017, Bechar & Vigneault 2017, Roldán *et al*. 2018, Yang *et al*. 2018, Bonadies & Gadsden 2019), but so far the applications in automating field work have been limited. Current software solutions for central management of UGVs focus mainly on fleet monitoring, particularly concerning the position and status of each vehicle; they are not designed to automate production (Connolly & Jessett 2014). Furthermore, in available UGV systems for both military and civilian applications, each operator controls only one machine (BAE Systems 2017, ECA Group 2021). The capability for one operator to control a fleet of UGVs is not available on the market, but incentives to create such capabilities have been initiated at political level (JapanGov 2021).

The continuing advances in computer-assisted autonomy and UGV technology create exciting opportunities for applying these developments in large-scale field operations. In this article we consider the prospect of deploying centrally controlled UGVs in place of conventional tractors on peat fields. An underlying hypothesis is that, if smaller unmanned vehicles specially adapted for peat fields are used for peat extraction, fuel consumption will be reduced. It is also hypothesised that the use of UGVs will allow an increased level of automation, leading to a reduction in labour requirements and costs. Specifically, we propose a novel concept for milled peat extraction and on this basis evaluate the potential for reducing operational costs in terms of labour, fuel consumption and the associated greenhouse gas emissions. To this end we explored details of the peat extraction process, envisioned present and potential UGV system architectures, conducted performance comparisons and UGV field trials and developed a methodology for comparing resource costs. We then evaluated the efficiency of robotic peat extraction by comparing 'like-for-like' scenarios in terms of documented annual resource costs for conventional systems and forecasts for equivalent robotic systems.

METHODS

Essentials of milled peat extraction

All methods for milled peat extraction involve milling and harrowing of the peat fields. The first phase of a cycle is milling, during which a thin layer of peat is separated from the surface of the peatland. The separated peat is then turned repeatedly, by harrowing, to speed up drying. When the peat has dried sufficiently it is collected (extracted) by one of four different methods, namely the 're-ridging' (Peco) method, the 'conveyer belt' (Haku) method, the 'mechanical harvesting' method and the 'vacuum harvesting' method, the choice depending on factors such as quality of the peat, extraction area size, etc. (Alakangas *et al*. 2012).

Depending on weather, the extraction season for milled peat can last for 4–5 months each year (Gregow *et al*. 2019). It usually starts in May and ends in September, lasting for 18 weeks on average. In favourable (dry) weather conditions, milling and harrowing take place during the day (between 9 a.m. and 5 p.m.). Depending on peat quality and weather conditions, the peat is turned (harrowed) 1–5 times; two turns are usually sufficient in good weather and our estimate of the average number of turns per cycle is three. When the milled and harrowed peat has dried sufficiently and starts to collect moisture again in the evening, it is collected throughout the hours of daylight in dry weather.

For every 1000 ha of peat field a fleet of 25 diesel tractors with at least one human operator per tractor is needed (Giprotorf 1986, Alakangas *et al*. 2012), and in good weather they can operate for up to 16 (or even 20) hours per day. On the other hand, they may not be used at all on days when it is raining or otherwise too humid. From late September to early May, most of the tractors are idle although they may occasionally be rented out to local farmers, used for snow removal, and so on.

In general, it has become a tradition that tractor operators work flexibly as required during the (summer) extraction season. However, there is a constantly growing shortage of casual manpower (BPPF 2018) and in order to ensure sufficient availability of suitably skilled personnel when required, peat companies have to accept the costs of retaining (even seasonal) employees during non-productive periods. Outside the extraction season, tractor operators undertake tasks such as maintenance and repair of tractors and equipment in preparation for the next season but the number of personnel needed can be reduced by up to 75 %.

The tractors themselves are often over-dimensioned and consume large quantities of fuel, and this in turn makes the extraction process more harmful to the environment than is necessary (Casals *et al*. 2016, He *et al*. 2019).

Possibilities for automation of operations

The baseline system architecture of milled peat extraction (utilising conventional manned tractors) is depicted as Stage 1 in Figure 1. In the first stage of automation, we propose to automate both milling and harrowing by substituting part of the manned tractor fleet with centrally controlled UGVs. The envisaged system architecture after this transition is depicted as Stage 2 in Figure 1.

Once the concept has been validated, the field working system might be further modified by automating all operations. In temperate regions, the whole peat extraction system could then be powered by solar energy (Redpath *et al*. 2011) if the necessary infrastructure (solar station and charging docks) was added. Such a system architecture, based entirely on UGVs, is depicted as Stage 3 in Figure 1.

UGV capability

The UGV selected for this study is the Milrem Robotics 'Multiscope' (https://milremrobotics.com/Multiscope). It consists of two tracked crawler modules which are mechanically and electrically connected to each other (Figures 2 and 3). It is suitable for use on peatlands because of the tracks and the low specific ground pressure of 16.7 kPa (based on tare weight), which is less than one-third of the specific ground pressure exerted by a human foot.

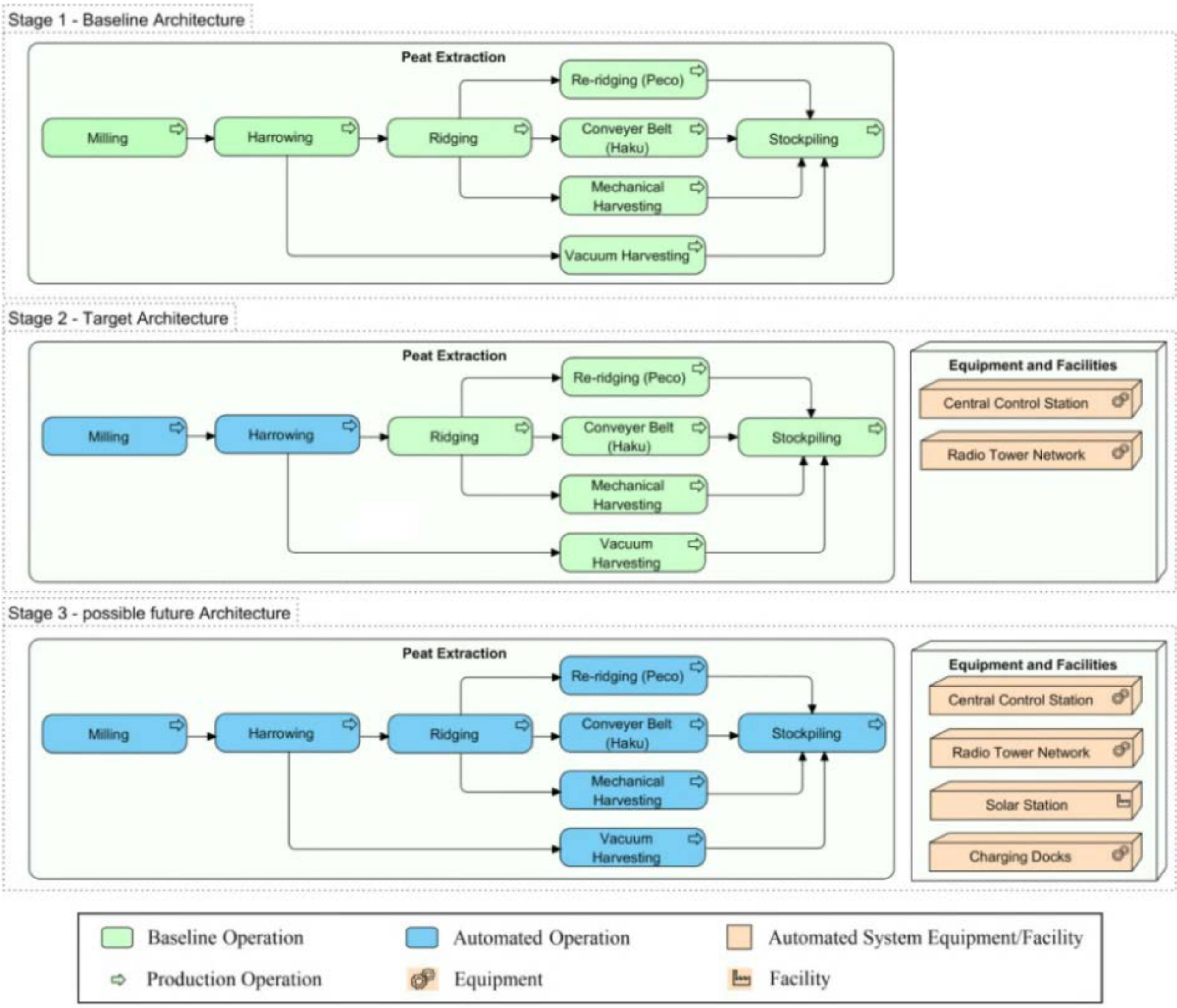

Figure 1. Evolution of baseline (Stage 1) and target (Stage 2) architecture of the robotic peat extraction system. After validation of the system architecture, automation of all peat extraction processes (Stage 3) will follow, but Stage 3 is not in scope for the present study and is not discussed any further in this article.

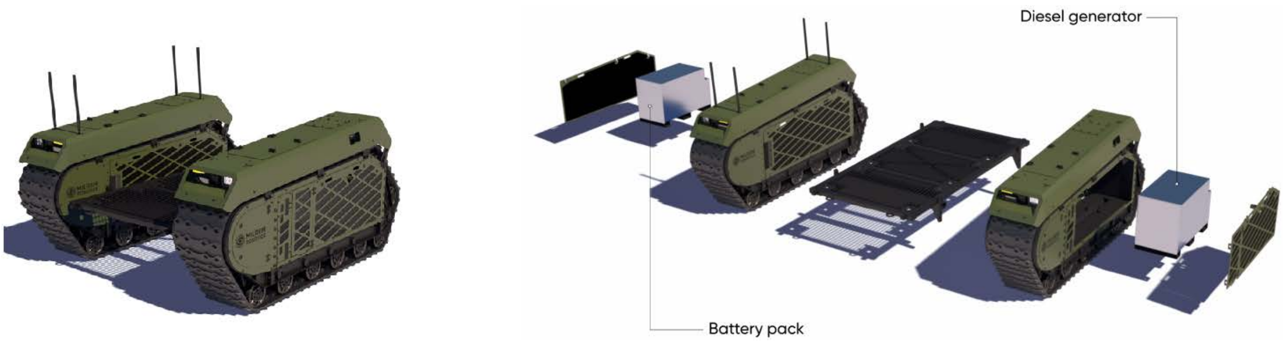

Figure 2. The Multiscope unmanned ground vehicle (UGV).

It has a turning radius of 0 m (i.e. it can turn on the spot), is capable of ascending and descending gradients of up to 60 %, and can drive sideways along gradients of up to 30 %. The net tare weight is 1630 kg, the payload capacity is 1200 kg, and the maximum traction force is in the order of 21 kN although dependent on ground conditions. It is powered by electric motors (2 × 19 kW) and can be controlled manually via VLOS (Visual Line of Sight) or BVLOS (Beyond Visual Line of Sight).

This vehicle was chosen because it is a typical medium-sized UGV on the basis of mass and traction force. The traction forces of smaller UGVs are not sufficient for the operations involved in milled peat extraction, and larger UGVs are over-sized for these tasks.

The ability of the 'Multiscope' to operate in peat fields and to carry out peat extraction operations (milling and harrowing only) was tested by conducting field trials and measurements. The field trials were conducted on the peat fields of Kraver AS in Viljandi County, Estonia (coordinates 58.542467 °N, 25.860802 °E) under dry (zero rainfall) conditions with ambient temperature 10–12 °C, wind speed 2–3 m s^{-1} and relative humidity (of air) 80 %. The towed implements (miller and harrow) were used as with a conventional tractor, i.e. no changes were made to their dimensions or other specifications. For both operations, the power consumption of the UGV and the drawbar pull of the implements (miller and harrower) were measured (Adamchuk *et al.* 2016, Bulgakov *et al.* 2020). These data were used to evaluate the hourly fuel consumption R_U (L hr^{-1}).

The potential capabilities of this UGV in relation to different peat extraction operations (milling, harrowing, ridging, harvesting, vacuum collection), as compared with conventional tractors, were assessed on the basis of the performance capabilities of tractors and UGVs and the extraction capacities of the peat extraction implements (Giprotorf 1986, Alakangas 1995, Alakangas *et al*. 2012). This enabled derivation of numbers of UGVs that would be required to replace conventional tractor fleets of different sizes for each type of extraction operation.

Methodology for estimating resource costs

Stage 1 operations (conventional tractor fleet)
The annual volumetric fuel consumption by tractors V_{fT} (L) was evaluated as:

$$V_{fT} = T \cdot N_T \cdot R_T \qquad [1]$$

where T is the total number of operating hours for one tractor during the mining season (typically 320 ± 16 hr), N_T is the number of tractors and R_T (L hr^{-1}) is the average hourly fuel consumption per tractor. Then, the annual cost of tractor fuel C_{fT} (€) is:

$$C_{fT} = V_{fT} \cdot r_f \qquad [2]$$

where r_f (€ L^{-1}) is the purchase price of fuel; and the annual CO_2 emission resulting from fuelling the tractor fleet with diesel CE_T (kg) is given by:

$$CE_T = V_{fT} \cdot c_{CO2} \qquad [3]$$

where c_{CO2} is the specific CO_2 emission for diesel fuel (2.66 ± 0.13 kg L^{-1}).

Figure 3. The Multiscope UGV towing a passive miller.

The calculation of labour cost is based on the principle that all workers are paid on a monthly salary basis. The annual total of man-months' employment required to operate the tractor fleet M_{laT} is estimated as:

$$M_{laT} = [k_1 \cdot M_S + k_2 \cdot M_{OS}] \cdot N_T \quad [4]$$

where k_1 is the number of operators per tractor during the extraction season (default value 2), M_S (months) is the duration of the extraction season (default average value 4.50 ± 0.25), k_2 is the number of tractor operators per tractor outside the extraction season (default value 0.5) and M_{OS} (months) is the duration of the off-season (default average value 7.50 ± 0.25). The annual labour cost for tractor operation C_{laT} (€) can then be calculated as:

$$C_{laT} = M_{laT} \cdot C_T \quad [5]$$

where C_T (€ month^{-1}) is the employment cost for one tractor operator.

Stage 2 operations (tractors and UGVs)

If UGVs were introduced to undertake milling and harrowing, tractors would be needed only for collection of the peat after drying. In this case, the number of tractor drivers would be reduced but it would be necessary to employ a UGV fleet operator to monitor and control the UGVs and a UGV mechanic who would mostly deal with hardware and equipment. Regardless of the number of UGVs in the fleet, the labour requirement for UGV operation during the extraction season would be for just two people; but these personnel would require specialist training (which can be expensive) and, as a result, would command higher salaries than tractor drivers. It would also be less feasible to dismiss them at the end of the season. A UGV fleet operator could undertake off-season work such as machine maintenance, software/hardware upgrades, training, planning for the next season, etc. A UGV mechanic could be involved in similar types of work, or in the maintenance of roads for the UGV system. All the same, there would probably be sufficient work for only one UGV operator in winter.

For the Stage 2 hybrid fleet, the annual volumetric fuel consumption V_{fH} (L) would be:

$$V_{fH} = T \cdot (N_{TH} \cdot R_T + N_U \cdot R_U) \quad [6]$$

where N_{TH} is the number of tractors required for collection of peat, N_U is the number of UGVs required for milling and harrowing, and R_U (L hr^{-1}) is the average hourly fuel consumption per UGV. Then, the annual cost of fuel C_{fH} (€) is:

$$C_{fH} = V_{fH} \cdot r_f \quad [7]$$

and the annual CO_2 emission resulting from fuelling the Stage 2 hybrid fleet with diesel CE_H (kg) is given by:

$$CE_H = V_{fH} \cdot c_{CO2} \quad [8]$$

The annual total of man-months' employment required to operate the UGVs M_{laU} (months) is calculated as:

$$M_{laU} = [M_S + k_3 \cdot M_{OS}] \cdot N_{UO} \quad [9]$$

where N_{UO} is the number of UGV operators employed during the mining season (default value 2) with the term k_3 = 0.5, meaning that only one UGV operator will be employed outside the extraction season. The annual total of man-months' employment required to operate the remaining tractors M_{laTH} (months) is calculated using Equation 4, inserting the number of tractors in the hybrid fleet. Then, the annual total of man-months' employment required to operate the Stage 2 hybrid fleet (consisting of both tractors and UGVs) is:

$$M_{laH} = M_{laTH} + M_{laU} \quad [10]$$

and the annual labour cost for the Stage 2 hybrid fleet C_{laH} (€) can be calculated as:

$$C_{laH} = M_{laTH} \cdot C_T + M_{laU} \cdot C_U \quad [11]$$

where C_U (€ month^{-1}) is the employment cost for one UGV operator.

Estimating potential resource savings

The initial resource savings available from introducing UGVs in place of manned tractors were estimated by comparing scenarios costed using Equations 1–11, for peat extraction conducted conventionally (Stage 1) on the one hand and with Stage 2 automation (see Figure 1) on the other. An example set of calculations is provided in the Appendix.

All of the scenarios were constructed for peat fields of two sizes (surface area 140 ha and 280 ha), which are typical for many peat extraction enterprises; and for two peat extraction methods, namely the Haku and 'vacuum harvester' methods. Data relating to the use of conventional tractors (e.g. average hourly fuel consumption per tractor, operating hours per season and salary costs) were obtained by cooperation with peat companies. The number of manned tractors (N_T) required for a surface area of 140 ha (for both extraction methods) was also derived from the production data of collaborating peat companies (Kraver AS, Estonia and Jiffy International, Netherlands). The number of tractors required for an area of 280 ha, and the numbers of UGVs (N_U) for areas of 140 ha and 280 ha, were calculated on the basis of equipment specifications (see the sub-section on 'UGV capability' above and Table 1 in Results).

The typical/default/standard values mentioned in the previous section were used (for T, M_S, M_{OS}, k_1, k_2, k_3, N_{UO} and c_{CO2}). The values adopted for other terms are provided in the relevant sub-sections below.

Fuel consumption and labour requirements

Volumetric fuel consumption was calculated using Equation 1 for conventional (Stage 1) operation and using Equation 6 for Stage 2 automation. The average hourly fuel consumption R_T (20.0 ± 2.0 L hr^{-1}) was obtained from milled peat production data provided by peat producers whereas R_U (11.0 ± 1.0 L hr^{-1}) was derived from the power consumption of the UGV and the drawbar pull forces of the implements (miller and harrower) measured in the field trials mentioned under 'UGV capability' above (authors' unpublished data). Annual employment totals (M_{laT} , M_{laH} ; in man-months) were determined according to Equations 4 and 10.

Fuel and labour costs

Equations 2 and 7 were used to evaluate the cost of fuel (C_{fT}, C_{fH}), and Equations 5 and 11 were used to calculate the labour cost (C_{laT}, C_{laH}), for working peat fields with surface areas of 140 and 280 ha throughout one extraction season. This comparison was extended beyond the two peat extraction methods and Stages 1 and 2 of automation, to encompass the difference in costs and savings that might be achievable in Canada versus Estonia. Canada was selected for this comparison because it is one of the world's leading producers of milled peat.

The purchase price of fuel r_f (1.30 € L^{-1} in Estonia, 0.80 € L^{-1} in Canada) and average employment cost of a tractor driver (employer's costs including taxes) C_{la} in the Estonian (9.85 ± 0.60 € h^{-1} = 1655 € month^{-1}) and Canadian (17.10 ± 1.19 € h^{-1}= 2873 € month^{-1}) peat extraction industries were ascertained as of 01 Mar 2020 (Andmebaas 2021, Calkoo 2021, Government of Canada 2021, Natural Resources Canada 2021, Statistics Canada 2021).

As the proposed hybrid peat collection system is still at the concept level and has not been implemented, it is not known exactly what the remuneration (and employment cost) of a UGV operator might be. Based on the expert opinions of two peat companies (Kraver AS Estonia and Jiffy International Netherlands), we estimated the cost of employing a UGV operator at 11.8 ± 0.6 € h^{-1} (= 1983 € month^{-1}) in Estonia and 25.7 ± 1.2 € h^{-1} (= 4319 € month^{-1}) in Canada.

CO_2 emissions of vehicles

The annual CO_2 omissions resulting from fuel use were determined using Equation 3 for the Stage 1 fleet of conventional tractors and Equation 8 for the Stage 2 hybrid fleet.

Statistics

All data used in the calculations were arithmetic means of the experimental data. The uncertainties of the data were calculated by the 'propagation of uncertainty' method (Damasceno & Couto 2018) and are given at a confidence level of 95 % (see Appendix for further detail and examples).

RESULTS

Solution architecture

The UGV-based solution for milling and harrowing consists of six building blocks, namely the Central Control System (CCS), the communication network, the UGV platform (or fleet), the digital twin, fleet maintenance, and fleet logistics. These main components of the architecture are depicted in Figure 4. The fleet of UGVs can be monitored (Gené-Mola *et al*. 2020) and controlled by the fleet operator from the CCS, which may be a stationary or mobile workstation. Outgoing and incoming data are transmitted either directly (LOS) or indirectly (BLOS) using the communication network. GNSS/RTK/DGNSS is used for positioning of the fleet vehicles (Kelc *et al*. 2019, Valente *et al*. 2020). In case of an emergency and where single UGVs have to be operated directly, manual remote control can be used. The production and fleet data can be collected and stored as a digital twin (Qi *et al*. 2021), meaning the data can be used by production management executives for further decision-making. The system also has a maintenance component which includes a workshop for servicing the machines and a logistics component for transportation of the UGVs.

UGV capability

The field trials confirmed that the 'Multiscope' UGV is able to operate successfully in peat fields. During the trials towing implements (miller and harrower) at speeds of 4–8 km h^{-1}, the power output required of the UGV was 26–52 % of its maximum capacity.

The sizes of the equivalent tractor and UGV fleets required for the Haku and 'vacuum harvester' peat extraction methods, and for their component operations, are shown in (Table 1). The tractors used for peat work typically weigh 3–5 tonnes, whereas the weight of the UGV is 1.6 tonnes. On the other hand, the power output of a large tractor is many times that of the UGV. Because milling and harrowing are not very demanding in terms of power, UGVs could replace tractors one-for-one in these operations. The power output of the UGV is not sufficient to handle ridging, harvesting and vacuuming so effectively, meaning that more UGVs than tractors would be required for these operations. An alternative would be to alter the specifications (dimensions, mass) of existing peat extraction implements, but this option is out of scope for the present research.

It might be expected that the ability of the machines to perform the work would be independent of the surface area of the peat field. However, the data in Table 1 show that increasing the area of the peat field does not result in a proportional increase in the number of machines required. In fact, if the area values are not large (in this case a few hundred hectares), the number of tractors (or UGVs) required is not proportional to the field area; it remains constant up to a critical value of area, then gradually increases in a stepwise manner (following a discrete step function) as successive critical values are exceeded (Figure 5a). The number of hauling machines required is related to the capability of both the tractors and the extraction implements to perform work, which is a quantised function. This means that the relationship between the need for machines and the surface area is also a quantised function (discrete step function). The expected linear relationship between the surface area of the peat field and the number of towing machines becomes apparent only at larger surface areas (Figure 5b).

Fuel consumption and labour requirements

The estimates in Table 2 indicate that Stage 2 automation of the peat extraction process could reduce fuel consumption by 23–29 %, as might be

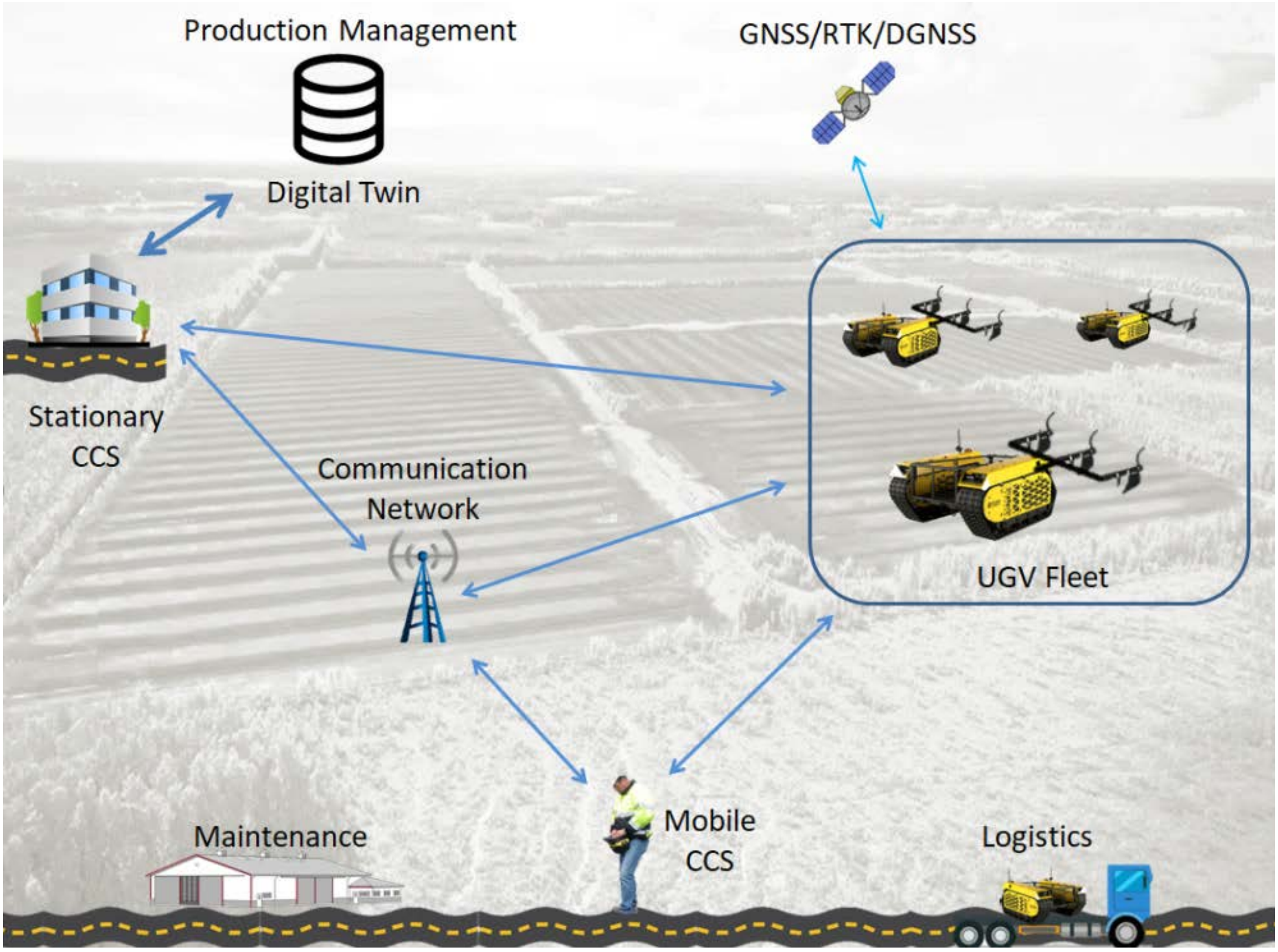

Figure 4. The robotic milled peat extraction solution architecture.

Table 1. The number of towing vehicles (conventional tractors or ‘Multiscope’ UGVs) required for the different phases of milled peat extraction according to the Haku method (milling, harrowing, ridging, harvesting) and the ‘vacuum harvester’ method (milling, harrowing, vacuum collection) for peat fields with surface areas (*S*) of 140 and 280 hectares. The information for peat fields with *S* = 140 ha was derived from the production data of peat extraction companies (Kraver AS, Estonia; Jiffy International, Netherlands), and the remaining data were calculated on the basis of available equipment specifications (Giprotorf 1986, Alakangas *et al*. 2012).

	Haku method				‘vacuum harvester’ method			
	S = 140 ha		*S* = 280 ha		*S* = 140 ha		*S* = 280 ha	
Implement	tractors	UGVs	tractors	UGVs	tractors	UGVs	tractors	UGVs
miller	2	2	3	3	2	2	3	3
harrower	2	2	3	3	2	2	3	3
ridger	2	3	3	5	-	-	-	-
harvester	1	2	2	3	-	-	-	-
vacuum collector	-	-	-	-	4	5	7	9
Total	7	9	11	14	8	9	13	15

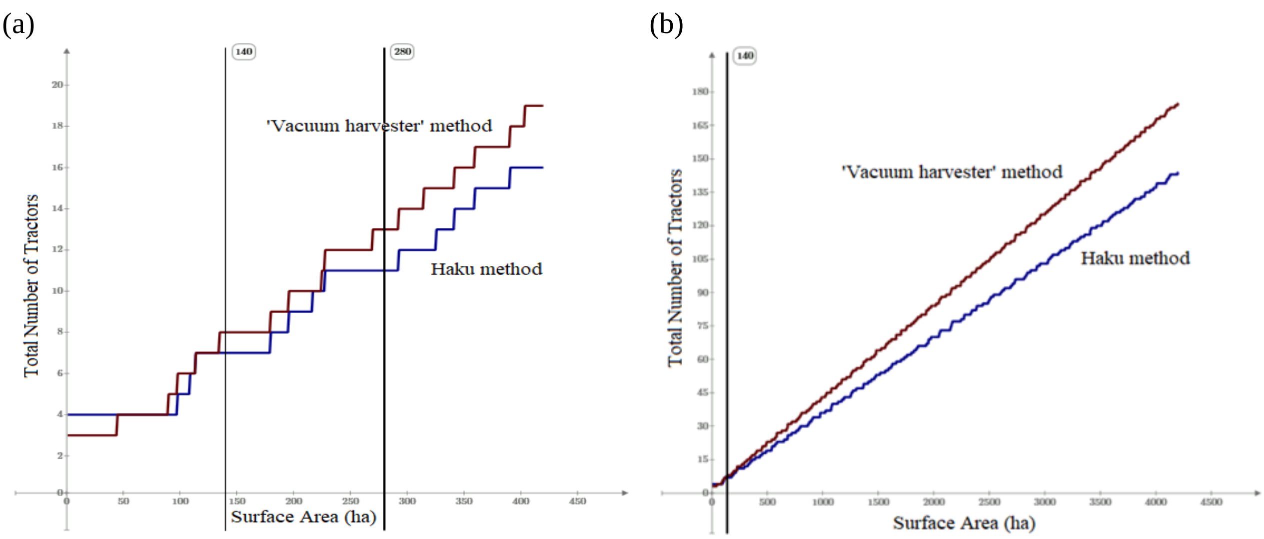

Figure 5. (a) Total number of tractors (Stage 1 fleet) required for peat extraction by the Haku and ‘vacuum harvester’ methods on surface areas up ~400 ha. Surface areas 140 ha and 280 ha are indicated by vertical markers. (b) Total number of tractors (Stage 1 fleet) required for peat extraction by the Haku and ‘vacuum harvester’ methods on surface areas up to thousands of hectares. In (b) the linear relationship between the number of towing machines and the surface area of the peat field becomes apparent.

expected given that the input (calculated) specific fuel consumption of the UGV was ~45.0 % lower than that of a conventional tractor (see Methods).

The savings on total man-months' employment required to operate the hybrid fleet (34–39 % for a 140 ha peat field and 36–43 % for a 280 ha peat field) arise because the same number of UGV operators (2) is required for milling and harrowing whether the number of UGVs is 4 or 6, whereas the number of tractor operators required is always equal to the number of tractors and so increases with area of the peat field (Table 1). In other words, when the surface area of the peat field is changed from 140 ha to 280 ha, the number of vehicles required for milling and harrowing rises from 4 to 6 (Table 1), increasing the requirement for operators by 50 % if tractors are used but making no difference to the manpower requirement if UGVs are used.

From this a general conclusion can be drawn, that the greater the surface area of the peat field, the greater the saving in man-months that can be achieved.

Fuel and labour costs

Diesel is almost 40 % cheaper in Canada than in Estonia (see Methods), and the direct effect of this difference is apparent in Table 3. Also as expected, the predicted savings in fuel costs resulting from Stage 2 introduction of UGVs in place of tractors are related to the reductions in fuel consumption (21–26 %) shown in Table 2.

In comparison with the cost savings on labour arising from the 34–43 % reduction in total man-months of employment between Stage 1 and Stage 2 of automation, the percentage savings on labour cost are smaller (31–40 %) in Estonia and even less (26–37 %) in Canada. This is because salary rates are higher for UGV operators (classed as skilled workers) than for (low-skilled) tractor drivers in both countries. Although the pay gap between low- and high-skilled workers is smaller in Estonia than in Canada, the effect is more than cancelled out by the generally higher salary levels in Canada, making the potential savings on labour higher in Estonia than in Canada. This difference persists in the calculation of total (fuel and labour) cost savings for Estonia (29–36 %) and Canada (25–36 %), making UGVs a slightly more lucrative proposition for Estonia.

CO_2 emissions from vehicles

The CO_2 emissions from diesel consumed by the Stage 1 (tractor) and Stage 2 (part robotic) fleet vehicles are compared in Table 4. The reductions in CO_2 emissions follow the changes in fuel consumption presented in Table 2. This is not surprising because, according to Equation 3, the amount of CO_2 emitted is directly proportional to the amount of fuel consumed.

Table 2. Volumetric fuel consumption of haulage machinery and man-months' employment required to operate peat fields with surface areas (S) of 140 and 280 ha by the Haku method and the 'vacuum harvester' method for the duration of one extraction season, at Stage 1 and Stage 2 of automation (see Figure 1). For Stage 2, the values in parentheses indicate the percentage change effected by using centrally controlled UGVs (instead of conventional tractors) to haul milling and harrowing implements (only), where they can replace tractors one-for-one (see Table 1).

	Haku method				'vacuum harvester' method			
	S = 140 ha		S = 280 ha		S = 140 ha		S = 280 ha	
Stage of automation	1	2	1	2	1	2	1	2
Fuel consumption (10^3 L)	44.8 ± 5	33.3 ± 3 (-26 %)	70.4 ± 8	53.1 ± 5 (-25 %)	51.2 ± 6	39.7 ± 4 (-23 %)	83.2 ± 9	65.9 ± 6 (-21 %)
Employed personnel man-months (months)	89.3 ± 3	54.8 ± 2 (-39 %)	140.3 ± 4	80.3 ± 2 (-43 %)	102.0 ± 3	67.5 ± 2 (-34 %)	165.8 ± 5	105.8 ± 3 (-36 %)

Table 3. Costs of haulage machinery fuel and labour required to work peat fields with surface areas (*S*) of 140 and 280 ha by the Haku method and the 'vacuum harvester' method for the duration of one extraction season, at Stage 1 and Stage 2 of automation (see Figure 1). The calculations reflect the purchase price of fuel and average salaries in Estonia and Canada as of 01 Mar 2020. For Stage 2, the values in parentheses indicate the percentage change effected by using centrally controlled UGVs (instead of conventional tractors) to haul milling and harrowing implements.

		Haku method				'vacuum harvester' method			
		S = 140 ha		*S* = 280 ha		*S* = 140 ha		*S* = 280 ha	
Stage of automation		1	2	1	2	1	2	1	2
fuel	Estonia (10^3 €)	58 ± 7	43 ± 5 (-26 %)	92 ± 11	69 ± 7 (-25 %)	67 ± 8	52 ± 5 (-22 %)	108 ± 13	86 ± 9 (-20 %)
	Canada (10^3 €)	36 ± 4	27 ± 3 (-25 %)	56 ± 7	42 ± 4 (-25 %)	41 ± 5	32 ± 3 (-22 %)	67 ± 8	53 ± 5 (-21 %)
labour	Estonia (10^3 €)	148 ± 10	96 ± 5 (-35 %)	232 ± 16	138 ± 8 (-40 %)	169 ± 11	117 ± 6 (-31 %)	273 ± 18	180 ± 10 (-34 %)
	Canada (10^3 €)	256 ± 19	181 ± 9 (-29 %)	403 ± 30	254 ± 15 (-37 %)	293 ± 22	218 ± 12 (-26 %)	476 ± 36	328 ± 20 (-31 %)
total	Estonia (10^3 €)	206 ± 17	139 ± 10 (-33 %)	324 ± 27	207 ± 15 (-36 %)	236 ± 19	169 ± 11 (-29 %)	381 ± 31	266 ± 19 (-30 %)
	Canada (10^3 €)	292 ± 23	208 ± 12 (-29 %)	459 ± 37	296 ± 19 (-36 %)	334 ± 27	250 ± 15 (-25 %)	543 ± 44	381 ± 25 (-30 %)

Table 4. CO_2 emissions from diesel usage during one extraction season for peat fields with surface areas (*S*) of 140 and 280 ha. The values in parentheses indicate the change in fleet CO_2 emissions that would accompany a change from Stage 1 (baseline) to Stage 2 automation, i.e. replacing conventional tractors with centrally controlled UGVs for milling and harrowing (only).

	Haku method				'vacuum harvester' method			
	S = 140 ha		*S* = 280 ha		*S* = 140 ha		*S* = 280 ha	
Stage of automation	1	2	1	2	1	2	1	2
CO_2 emission (tonne)	119 ± 15	88 ± 9 (-26 %)	186 ± 23	140 ± 14 (-25 %)	136 ± 17	105 ± 11 (-23 %)	222 ± 27	174 ± 18 (-21 %)

DISCUSSION

The main results of this case study are that the UGV trialled is capable of operating on peatlands; and the substitution of UGVs for conventional tractors could noticeably reduce labour costs, fuel consumption and the associated CO_2 emissions.

Fuel savings

The tractors currently used in the peat extraction industry (and elsewhere) are designed to be versatile for as many jobs as possible. Tractor manufacturers have adopted the concept of a universal design, aiming their products at the widest possible market. Although this may be sensible from a commercial point of view, there are tasks that do not require the use of large tractors. The two critical requirements for tractors used in peat field work are: a) power requirement (ability to effectively haul peat extraction implements); and b) terrain penetration requirement (hauling machines do not sink into the ground). If one wants to reduce the fuel consumption (and associated environmental footprint) of tractors, one possibility is to reduce their weight. As the weight decreases, the dimensions of the machine, including the dimensions of the tractor tyres, become smaller. This situation leads to a reduction in the roadworthiness of tractors.

Experiments in this study have shown that unmanned vehicles can be energy efficient. This is due to the fact that the machines themselves are smaller in size and they do not have a cab for transporting the operator. While these machines are smaller and lighter, they have enough power output capacity to haul peat extraction implements (such as millers and harrowers). The machine also has suitable off-road capabilities. All these design differences give this type of UGV an advantage over conventional tractors in carrying out operations in peat fields. The UGV trialled is considerably smaller, lighter in weight (tare weight 1.6 tonnes versus 3–5 tonnes; also without the weight of a driver) and more energy efficient than conventional tractors. When comparing the power-to-mass ratio of tractors used in peat operations with that of the trialled UGV, it turns out that these indicators are relatively equal in both cases: ~20–30 W kg^{-1} for tractors and ~23 W kg^{-1} for the UGV. This means that the UGV power-train does not perform any better (or worse) than that of tractors. The energy efficiency is achieved because the tractors are heavy and have to carry a significantly greater weight (their own weight) under the same power-to-weight ratio. This means that the tractor engines need to be more powerful and are more energy-intensive. Adding the fact that some operations (milling and harrowing) do not require much power in terms of absolute values, then it can be concluded that tractors are powerful enough but for certain jobs they are over-dimensioned.

Thus, although replacing tractors with UGVs may increase the total number of towing vehicles required (Table 1), the energy consumption of a single UGV is sufficiently low that the overall fuel consumption of the entire fleet is still reduced (Table 2). It must be emphasised that, whereas the fuel consumption data utilised for conventional tractors originated from machines working in real peat extraction enterprises, the equivalent data for the UGV were calculated from still-unpublished data collected during trials (see Methods) and are yet to be confirmed in a realistic field working situation. Nonetheless, the results obtained are highly promising, indicating that a reduction in fuel consumption in the order of 25 % can be expected from the hypothesised transition to robotic milling and harrowing.

Labour requirements and costs

The basis of the reduction in labour requirements is that only two employees are needed for the day-to-day operation of a UGV fleet, along with management and maintenance of the machinery. The positive effect is amplified as the surface area of the peat field increases. What is interesting is that, when substituting UGVs for tractors, the larger the surface area, the more labour costs are saved.

This article deals with peat fields of two sizes, 140 ha and 280 ha. The surface area of 140 ha was chosen because production data for a peat field of this size were available directly from the peat company. A theoretical peat field with a surface area of 280 ha would correspond to twice the size of the test field. If the surface area of the peat field is increased, the need for machines would also increase and at the same time labour costs would increase.

To demonstrate it further by an example, Figure 6(a) shows the relationship between the surface area of a peat field and the labour costs for milled peat extraction ('vacuum harvester' method, Estonian salary rates). The profitability of using UGVs is lowest at a certain (small) value of peat field area (in this case ~90–100 ha). This is due to the fact that if the fleet is small, the representation of UGV operators in the total personnel team is large so their (higher) salaries make up a noticeable share of the total cost of labour. If the fleet is large, the number of tractor drivers will increase but the number of UGV operators will remain the same (by default 2). Figure 6(b) shows the savings in personnel costs as a percentage. In both Figures vertical markers for 140 ha and for a 280 ha peat fields are shown.

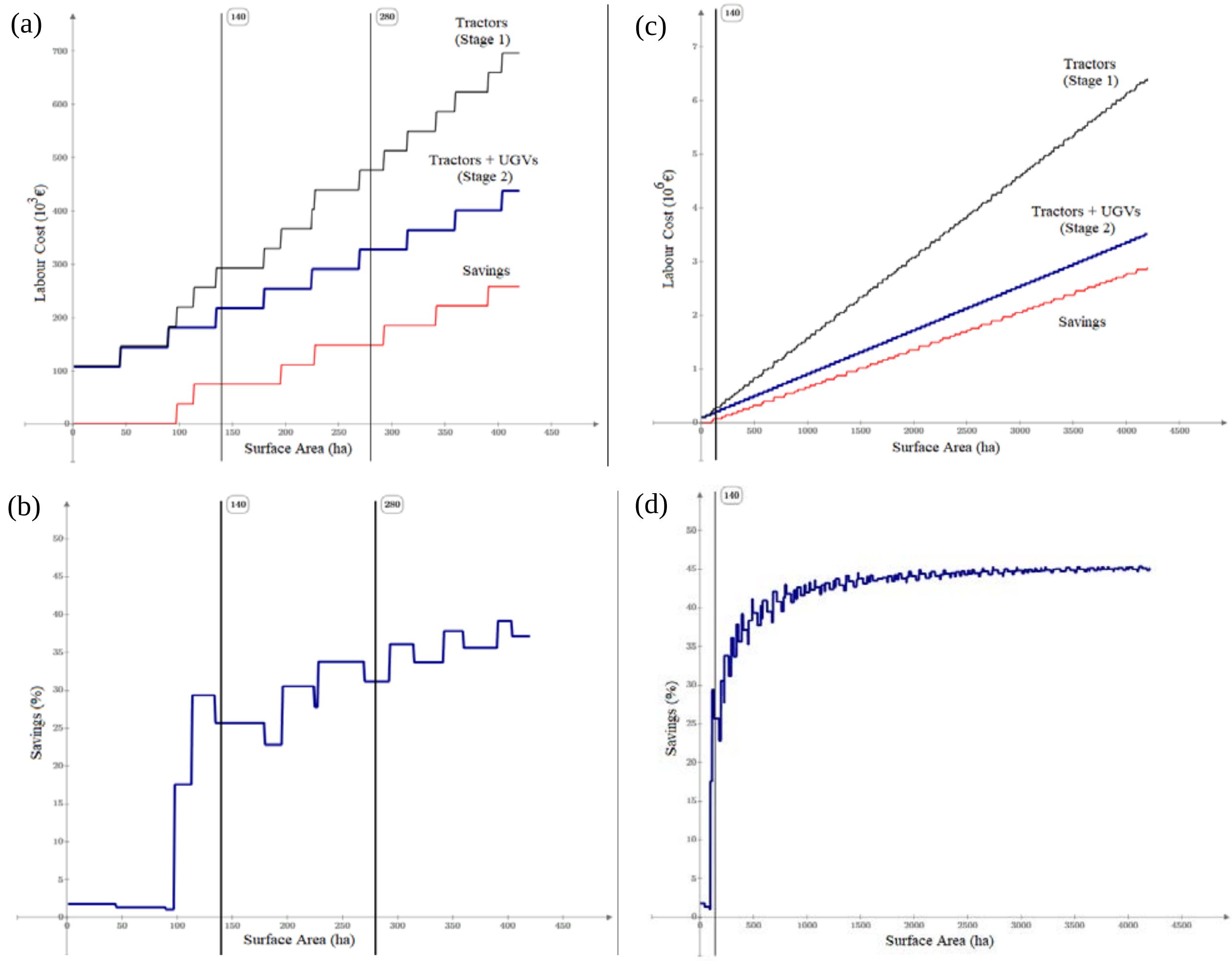

Figure 6. (a) The relationship between the labour costs and surface area of the peat field. (b) Savings in percentage on labour costs when switching from a Stage 1 fleet (tractors only) to a Stage 2 fleet (tractors and UGVs). (c) As the surface area increases to thousands of hectares the linear relationship between the labour costs and surface area of the peat field becomes apparent. (d) As the surface area increases to thousands of hectares the savings in labour costs in percentage for the Stage 2 hybrid fleet will approach an asymptote, in this case ~45 %. All figures here are given for data corresponding for the ‘vacuum harvester’ method and for Estonian salaries.

If the surface area of the peat field is large enough (thousands of hectares), personnel costs and surface area of the peat field will be linearly related (Figure 6(c)), and the savings in personnel costs for a Stage 2 hybrid fleet will reach an asymptote, in this case ~45 % (Figure 6(d)).

Implications for the peat industry

Our example application of UGVs in milled peat extraction has potential to be economically viable, meaning that this approach could be instrumental in providing a solution to three major current challenges for milled peat extraction, namely:

1) The Labour Challenge (BPPF 2018, Marinoudi *et al*. 2019), which is driven mostly by the seasonal nature of the work and by the demographic trends and migration of the workforce (Woetzel *et al*. 2016, Leeson 2018, United Nations 2019).

2) The Machine and the Fuel Efficiency Challenges, which arise from the fact that tractors are currently designed in a way that makes them universally adaptable to most field working situations, and yet this flexibility also makes them fundamentally inefficient because the degree of specialisation is low (Ueka *et al*. 2013, Janulevičius *et al*. 2019).

3) The Environmental Footprint Challenge. As the requirements for environmental protection become more demanding (Poelhekke 2019, EC 2020), all industries must embrace the challenge of reducing their greenhouse gas emissions (Grönroos *et al*. 2013).

The Labour Challenge

The fundamental idea is to eliminate the need for multiple tractor operators, by enabling a single operator to monitor and control a number of robotic vehicles. In order to progress with this solution, we employ a Central Control System (CCS) that makes use of 'Waypoint and Local Navigation' (Cariou *et al*. 2009, Reina *et al*. 2016, Silverberg & Xu 2019). The CCS has to allow extraction operations to proceed whilst simultaneously collecting production data to enable iterative process optimisations.

On the legislative perspective, neither Estonia nor Canada has adopted relevant laws prohibiting the use of these kinds of UGVs in agriculture. In Estonia this UGV is considered as a separate class of vehicle which can be legally driven even on footpaths. Although the same is true for Canada, a legislative procedure has been initiated to regulate the use of unmanned vehicles (Ontario Ministry of Transportation 2016, King 2018).

The Machine and Fuel Efficiency Challenges

It should be clarified here that the proposal for changes in the architecture of milled peat extraction does not include changes in existing peat implements. The properties of the existing implements have been developed taking into account established production practices. Most peat fields around the world are designed to fit the dimensions of already existing implements. For example, the width of a typical peat strip is 18 m (or up to 20 m) and, consequently, the widths of the implements are either 9 m or 18 m. Therefore, it would not be rational to attempt to optimise implement parameters, as this would result in a recalculation of the dimensions of the peat fields.

The use of these UGVs and our proposed solution to the Labour Challenge leads, nonetheless, to changes in the entire peat extraction architecture. The physical characteristics of the towing-engine units can be optimised even further (Yanzina *et al*. 2019) by increasing the level of specialisation; for example, by introducing a power-train/drive-train whose functioning is specifically optimised (Lee *et al*. 2016, Naik & Raheman 2019, Regazzi *et al*. 2019) for the target environment (i.e. the peat field during the extraction season). Differences between a fleet of peat extraction UGVs and a fleet of diesel tractors give rise to fuel economies favouring the UGVs (Rigitrac 2019, Solectrac 2019). This concept is also based on robotic agents (mid-size UGVs) that have readiness to be fully powered by electricity (Gerssen-Gondelach & Faaij 2012). In earlier studies electrically driven vehicles have proven more fuel-efficient than conventional diesel-fuel based vehicles (Yazdanie *et al*. 2016).

The Environmental Footprint Challenge

Environmental benefits follow from the improved performance achieved by optimising fleet attributes (reduced dimensions, weight and power consumption) which in turn leads to reduced fuel consumption. Several authors have previously indicated a causal link between fuel consumption and greenhouse gas emissions (Janulevičius *et al*. 2016, Karaoğlan *et al*. 2019, Lovarelli & Bacenetti 2019, Masih-Tehrani *et al*. 2020), and we apply the same approach in making our assessment. Again, the development of electric vehicles offers a promising outlook (Sandy Thomas 2012, Poullikkas 2015, Li *et al*. 2016) as the transition from vehicles with conventional internal combustion engines to electric vehicles can lead to further reductions of CO_2 emissions (Mousazahed *et al*. 2011, van Vliet *et al*. 2011).

Next steps

Arising from the results it becomes self-evident that further development efforts are justified and needed, such as:

1) robotic milled peat extraction system requirement analysis;

2) technical description of the system architecture and its components;

3) design modification of the current field implements to suit the needs of the proposed UGV solution; and

4) system verification and concept validation based on long-term field measurements.

Once reliability of the concept has been demonstrated, it could readily be applied in a variety of similar applications. The following possibilities are anticipated:

1) In peatland agriculture and in paludiculture, the heavy machinery used is subject to the same requirements as in milled peat extraction: the machines must be powerful enough to carry out the work, while it is necessary that they possess sufficient terrain permeability. The work done in the peat fields is repetitive in nature, so it makes sense to automate this work.

2) Forestry (silviculture) i.e. planted forest (Zhou *et al*. 2012) maintenance involves tractors and labour. Usually the planted forest must be maintained every few years. Most of the processes are repetitive, making them highly suitable for automation.

3) Power line maintenance is carried out by manual labour using hand tools, and usually repeated every five years. Due to the proximity of the high voltage power lines, the work process is potentially hazardous. Power line maintenance involves working through a specific plot of land along a predetermined trajectory.

4) Municipal services can also be described by repetitiveness, making them suitable for automation. As an example, street cleaning services include navigating similar road sections and completing similar working processes.

These examples have a common feature, in that they represent work processes of repetitive nature that must be executed over extensive areas (Moorehead *et al*. 2012). In all of these cases, the area where maintenance work is required can be mapped as the operation is completed for the first time. Then, the work-related data from earlier executions of the operation could potentially be used to achieve efficiencies during subsequent executions.

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AUTHOR CONTRIBUTIONS

RK, MN and JO developed the methodology of the research; RK and PV contributed to writing the first draft of the manuscript; EK, MN, JO reviewed and gave critical feedback on the first drafts; RK and PV designed and edited the figures. All authors contributed to final editing of the manuscript and approved the final version.

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Appendix

Table A1. Initial data for a sample problem in which Equations 1–11 are evaluated. In this task, the object of interest is a peat field with a surface area of 140 hectares and the 'vacuum harvester' collection method is used. The calculations reflect the purchase price of fuel and average salaries in Estonia as of 01 Mar 2020.

No	Term	Symbol	Unit	Value X	Uncertainty ΔX
1	Operating hours for one tractor during the season	T	h	320	16
2	Duration of the extraction season	M_S	month	4.50	0.25
3	Duration of the extraction off-season	M_{OS}	month	7.50	0.25
4	Number of tractors in Stage 1 fleet	N_T		8	
5	Number of tractors in Stage 2 hybrid fleet	N_{TH}		4	
6	Number of UGVs in Stage 2 hybrid fleet	N_U		4	
7	Number of UGV operators during the season	N_{UO}		2	
8	Number of operators per tractor during the season	k_1		2	
9	Number of operators per tractor outside the season	k_2		0.5	
10	Sets the number of UGV operators for off-season	k_3		0.5	
11	Average hourly fuel consumption per tractor	R_T	L h^{-1}	20.0	2.0
12	Average hourly fuel consumption per UGV	R_U	L h^{-1}	11.0	1.0
13	Purchase price of fuel	rf	€ L^{-1}	1.300	0.065
14	Specific CO_2 emission for diesel fuel	c_{CO2}	kg L^{-1}	2.64	0.13
15	Employment cost for one tractor operator	C_T	€ month^{-1}	1655	100
16	Employment cost for one UGV operator	C_U	€ month^{-1}	1983	100

The uncertainties ΔX of functions $X = f(a, b,\ldots, z)$ for the values of Equations 1—11 (given in Tables 1–4) are calculated by the 'propagation of uncertainty' method (Damasceno & Couto 2018) which is expressed as:

$$\Delta X = \sqrt{\left(\frac{\partial}{\partial a}X(a,b,\ldots,z)\right)^2 \Delta a^2 + \left(\frac{\partial}{\partial b}X(a,b,\ldots,z)\right)^2 \Delta b^2 + \cdots + \left(\frac{\partial}{\partial z}X(a,b,\ldots,z)\right)^2 \Delta z^2}$$

where $a, b, \ldots, z$ are the symbols of the quantities with the uncertainties of the source data determined as Δa, $\Delta b, \ldots, \Delta z$.

Stage 1 operations (tractors only)

Annual volumetric fuel consumption by tractors V_{fT} (L) was evaluated as (Equation 1):

$$V_{fT} = T \cdot N_T \cdot R_T \qquad V_{fT} = 51.2 \cdot 10^3 \text{ L}$$

$$\Delta V_{fT} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i}V_{fT}(x_i,\ldots,x_n)\right)^2 \Delta {x_i}^2\right]} \qquad \Delta V_{fT} = 5.7 \cdot 10^3 \text{ L}$$

(Relative error 11.2 %)

Annual cost of tractor fuel C_{fT} (€) is (Equation 2):

$$C_{fT} = V_{fT} \cdot r_f \qquad C_{fT} = 66.6 \cdot 10^3 \text{ €}$$

$$\Delta C_{fT} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} C_{fT}(x_i, \dots, x_n)\right)^2 \Delta x_i^{\,2}\right]} \qquad \Delta C_{fT} = 8.2 \cdot 10^3 \text{ €}$$

(Relative error 12.2 %)

Annual CO_2 emission resulting from fuelling the tractor fleet with diesel CE_T (kg) is given by (Equation 3):

$$CE_T = V_{fT} \cdot c_{CO2} \qquad CE_T = 135.4 \cdot 10^3 \text{ kg}$$

$$\Delta CE_T = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} CE_T(x_i, \dots, x_n)\right)^2 \Delta x_i^{\,2}\right]} \qquad \Delta CE_T = 16.6 \cdot 10^3 \text{ kg}$$

(Relative error 12.2 %)

Annual total of person-months' employment required to operate the tractor fleet M_{laT} was estimated as (Equation 4):

$$M_{laT} = [k_1 \cdot M_S + k_2 \cdot M_{OS}] \cdot N_T \qquad M_{laT} = 102 \text{ month}$$

$$\Delta M_{laT} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} M_{laT}(x_i, \dots, x_n)\right)^2 \Delta x_i^{\,2}\right]} \qquad \Delta M_{laT} = 3 \text{ month}$$

(Relative error 2.9 %)

Annual labour cost for tractor operations C_{laT} (€) was then calculated as (Equation 5):

$$C_{laT} = M_{laT} \cdot C_T \qquad C_{laT} = 168.8 \cdot 10^3 \text{ €}$$

$$\Delta C_{laT} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} C_{laT}(x_i, \dots, x_n)\right)^2 \Delta x_i^{\,2}\right]} \qquad \Delta C_{laT} = 11.3 \cdot 10^3 \text{ €}$$

(Relative error 6.7 %)

Stage 2 operations (tractors and UGVs)

Annual volumetric fuel consumption for the hybrid fleet V_{fH} (L) would be (Equation 6):

$$V_{fH} = T \cdot (N_{TH} \cdot R_T + N_U \cdot R_U) \qquad V_{fH} = 39.7 \cdot 10^3 \text{ L}$$

$$\Delta V_{fH} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} V_{fH}(x_i, \dots, x_n)\right)^2 \Delta x_i^{\,2}\right]} \qquad \Delta V_{fH} = 3.5 \cdot 10^3 \text{ L}$$

(Relative error 8.8 %)

Annual cost of fuel C_{fH} (€) is (Equation 7):

$$C_{fH} = V_{fH} \cdot r_f \qquad C_{fH} = 51.6 \cdot 10^3 \text{ €}$$

$$\Delta C_{fH} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} C_{fH}(x_i, \ldots, x_n)\right)^2 \Delta x_i^{\,2}\right]}$$

$\Delta C_{fH} = 5.2 \cdot 10^3$ €
(Relative error 10.1 %)

Annual CO_2 emission resulting from fuelling the hybrid fleet with diesel CE_H (kg) is given by (Equation 8):

$$CE_H = V_{fH} \cdot c_{CO2}$$

$CE_H = 104.9 \cdot 10^3$ kg

$$\Delta CE_H = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} CE_H(x_i, \ldots, x_n)\right)^2 \Delta x_i^{\,2}\right]}$$

$\Delta CE_H = 10.6 \cdot 10^3$ kg
(Relative error 10.1 %)

Annual total of person-months' employment required to operate the UGVs M_{laU} (months) is calculated as (Equation 9):

$$M_{laU} = [M_S + k_3 \cdot M_{OS}] \cdot N_{UO}$$

$M_{laU} = 16.5$ month

$$\Delta M_{laU} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} M_{laU}(x_i, \ldots, x_n)\right)^2 \Delta x_i^{\,2}\right]}$$

$\Delta M_{laU} = 0.3$ month
(Relative error 1.5 %)

Annual total of person-months' employment required to operate the hybrid fleet is (Equation 10):

$$M_{laH} = M_{laU} + M_{laT}$$

$M_{laH} = 67.5$ month

$$\Delta M_{laH} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} M_{laH}(x_i, \ldots, x_n)\right)^2 \Delta x_i^{\,2}\right]}$$

$\Delta M_{laH} = 1.8$ month
(Relative error 2.6 %)

Annual labour cost for the hybrid fleet C_{laH} (€) can be calculated as (Equation 11):

$$C_{laH} = M_{laT} \cdot C_T$$

$C_{laH} = 117.1 \cdot 10^3$ €

$$\Delta C_{laH} = \sqrt{\sum_{i=1}^{n}\left[\left(\frac{\partial}{\partial x_i} C_{laH}(x_i, \ldots, x_n)\right)^2 \Delta x_i^{\,2}\right]}$$

$\Delta C_{laH} = 6.1 \cdot 10^3$ €
(Relative error 5.2 %)