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Procedia CIRP 136 (2025) 248–253

www.elsevier.com/locate/procedia

35th CIRP Design Conference

Electrify Agriculture: Concept Design for Electric Tractors Based on Customer-Relevant Properties

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Abstract

Agriculture is responsible for up to a quarter of all greenhouse gas emissions, and agricultural machinery plays a significant role in this through the combustion of fossil fuels. To mitigate the impact of agricultural machinery, electrification of tractors is a promising way to gain fast impact. With the emergence of tractor electrification, new paths for tractor design innovation open up, driven by the newly gained design freedom. To address the requirements of such a complex machine, we emphasize putting the farmer at the center of development. This work presents a methodology to translate customer-relevant properties for agricultural tractors with a novel two-track method to early-stage tractor concepts for battery-electric tractors. The first track of our methodology develops qualitative concept decisions based on expert interviews, while the second track derives the technical functionalities in a quantitative manner with data from a tractor market analysis. We guide through the application of the methodology with a case study-specific farming scenario.

Keywords: vehicle concept development; multi-criteria decision making; smallholder farming;

1. Introduction

The agriculture, forestry, and land use sectors contribute to a quarter of all greenhouse gas emissions globally [9]. As part of those emissions, up to 25 % is expected to come from the burning of fossil fuels [12]. The use of agricultural machinery is highly dependent on fossil fuels, with mechanization through tractors having led to a significant increase in CO_2 emissions [11]. As policymakers look to drive mechanization to increase agricultural productivity and food security, the projected energy demand for tractors threatens to increase emissions and dependence on fossil fuels. As electrification of vehicles is seen as the fastest way to cut emissions, electrification of tractors is still in its infancy [10, 3]. With small and medium-sized family farms accounting for 98 % of all farms globally, they are the main actors in the advent of electric tractors. Those must be provided with suitable machinery to enable mechanization by sustainable means.

The advent of tractor electrification opens up the possibility to put the farmer at the center of the development and exploit new design freedom. This paper proposes a novel methodology to address the newly gained design freedom with customer-relevant properties (CRP) for tractors and offers two-track approach that derives (1) concept decisions for electric tractors and (2) translates customer-relevant properties into technical parameters.

Table 1. Publication overview of electric tractors

Publication	Power [kW]	Swappable battery	Purpose design	Roll-out status	Customer centricity
[19]	9	●	●	◐	○
[2]	32	●	○	●	◔
[4]	15	○	○	●	◔
[5]	3	○	●	●	○
[7]	50 - 100	●	●	○	◐

Trends in tractor electrification
The electrification of tractors has recently gained momentum in both industry and research. While traditional manufacturers are beginning to unveil prototypes, the market observations conclude that conversion design concepts, which solely replace the diesel engine with an electric motor, dominate the industry concepts so far and are not able to leverage the design freedoms of electric power trains [7]. To successfully develop a purpose de-

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10.1016/j.procir.2025.08.044

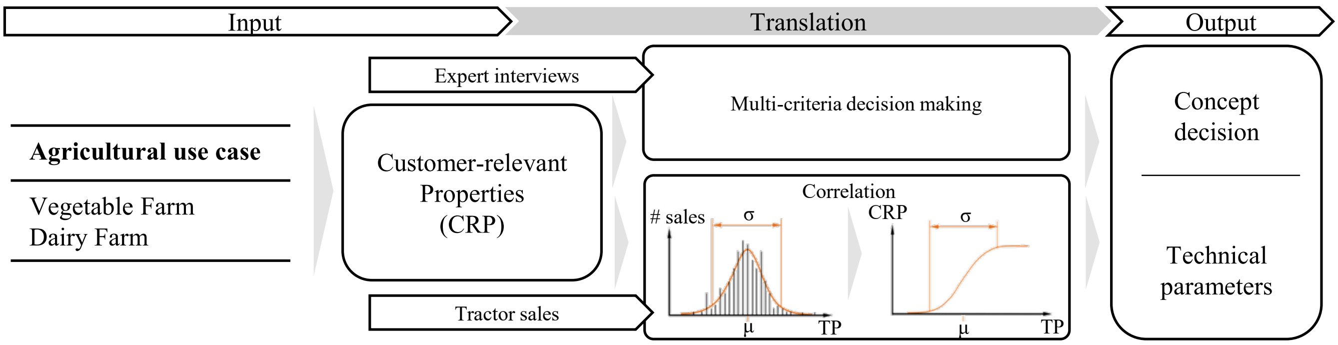


Fig. 1. Methodology to derive concept decisions and technical parameters for electric tractors from the customer.

sign for electric tractors and overcome customers' reluctance to embrace electric concepts, it is necessary to understand the farmer's needs and requirements and take advantage of electric power trains without any hindering heritage from diesel-driven concepts. The rise of numerous start-ups (e.g. Monarch Tractor, TADUS, AutoNXT, ONOX) has highlighted a significant market gap, emphasizing the need for a customer-centric approach to effectively compete with established players.
In smallholder farming, researchers have primarily focused on the feasibility of electric tractors (ET), emphasizing economic savings and energy autonomy [19, 5, 2]. Vogt et al. [19] highlight the potential of ETs for smallholder farmers, focusing on design and cost, while Das et al. [5] designed a small ET to provide a diesel-independent power source. Bagire et al. [2] demonstrated the feasibility of ETs in Rwanda through a field trial, investigating operating costs. Gao & Xue examined the life cycle costs of an electric conversion design for China's smallholder farmers. However, as can be seen in Table 1, these studies largely overlook the farmer as a key user of the technology. Our research, therefore, aims to fill this gap by proposing a holistic methodology for ET concept design that centers on customer-relevant features [7].

A common approach to include customer-centricity in the automotive industry are customer-relevant properties (CRP) which express the value of the vehicle concept from a customer's point of view [14]. However, CRPs for tractors are barely researched to date: Various authors investigated requirements of conventional tractors and the customer's tractor selection process [1, 6, 17]. They emphasize the importance of economy and functionality related to conventional tractors, however, they cannot describe the influence of user needs on the final technical concept. Given the absence of common approaches in tractor design, this paper bridges the gap by developing a framework for preliminary electric tractor concepts based on customer-relevant properties.

2. Two-track methodology for tractor design

Figure 1 shows the proposed methodology to systematically derive an ET concept based on farmer's needs: The main factor in describing the farmer's work is the agricultural use case that serves as input. We guide through our methodology on the example of dairy and vegetable farms, which are suitable for the introduction of ETs and reflect the diverse profile of family farms, which are often engaged in arable and livestock farming. We propose customer-relevant properties where the target customer group and farmers can quantitatively describe their agricultural conditions and needs. Those are then translated in a two-track approach: (1) A Multi-Criteria Decision Making (MCDM) approach derives qualitative concept decisions with the input of expert interviews. (2) Correlation functions based on market data map each customer-relevant property to a quantitative technical parameter of the tractor concept. The combination of both yields a tailored ET concept for the provided input.

2.1. Customer-relevant properties of tractors

Based on the overview of customer-relevant properties in tractor selection, automotive and heavy-duty vehicles [15, 17, 6] this work shows 23 customer-relevant properties summed up in six clusters on the vehicle level (Figure 2) to address the farmers needs: The *Ergonomics* cluster can be adopted from conventional tractors and points out the need for a user-centered workplace including visibility, noise and comfort. *Safety & Security* consists of personal safety and damage protection. This is not just relevant for the driver but also for the newly integrated battery system. *Productivity* is necessary to ensure the economic functioning of the tractor including maintenance aspects. *Dynamics* ensure the maneuverability and the power requirements for pulling tasks. *Functionality* is particularly important to ensure the tractor can power the necessary implements a farmer needs for the use case. The property *Environment* ensures that the tractor is not just able to operate in off-road conditions but also to not harm the soil. Each customer-relevant property is expressed in a range from 1 to 10, whereas values below 5 are not acceptable for the customer.

2.2. Translation of customer-relevant properties into qualitative concept decisions

The design of an ET involves conceptual decisions ([7]). Figure 2 shows how the method translates the input of the customer to place requirements in a qualitative manner: The approach can select options from the concept solution space

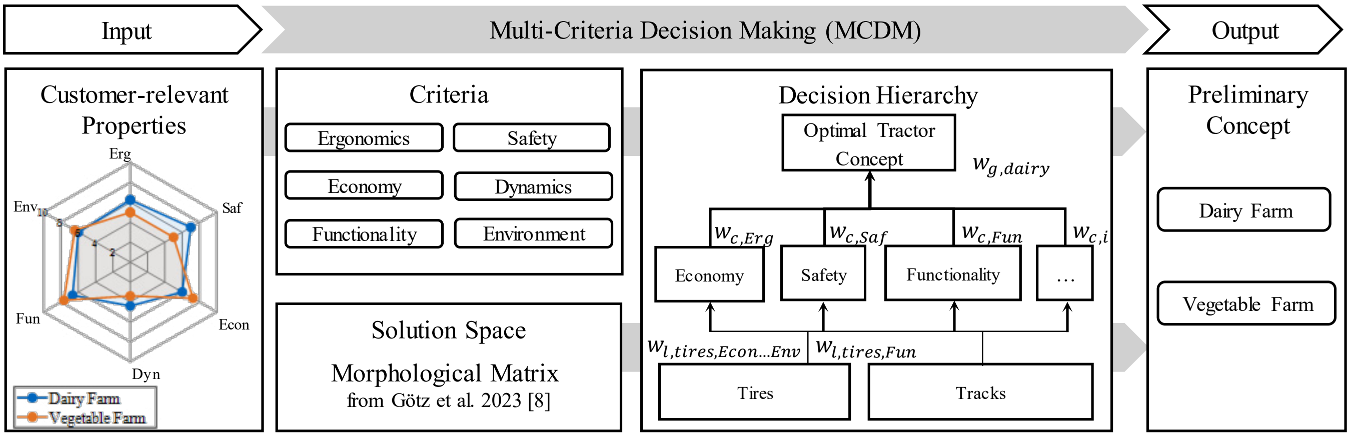


Fig. 2. Translation of customer-relevant properties into concept decisions with a decision hierarchy.

based on the input with criteria through a decision hierarchy originally developed by [13] with the Analytical Hierarchy Process (AHP). The hierarchy offers the functionality to derive the best concept based on the individual user input and their respective agricultural use case by mathematically expressing each technical option and criteria with weightings.

Solution space

Our approach which is adapted from [18] for aircraft design, combines the decision process with a morphological matrix. The morphological matrix from [7] provides the concept solution space for an ET, subdividing it into *drive system, chassis, power train, battery, auxiliary drives, tractor workplace,* and *implement interface*. Each of those includes a technical option e.g. the subsystem *drive system* includes the option of 2- or 4-wheel-drive (2WD/4WD) (Figure 3).

Decision hierarchy

We use the decision hierarchy to calculate the weightings necessary to choose between the technical options of the morphological matrix. Therefore, it is structured into hierarchical levels, which makes it possible to map user-specific preferences (mathematical implementation in [18]): The top hierarchy describes the goal of the best tractor concept (w_g)(see Figure 2). The second level describes the criteria for which every technical solution is rated (w_c), and the third contains all technical solutions (w_l). The weightings on each level indicate the importance of an element for the higher-level element.
Our MCDM approach offers the possibility to obtain the final electric tractor concept through qualitative decisions that are determined through the highest global weight for each of the 23 technical options from the solution space. The weights are calculated through the decision matrix obtained in Table 2.

Concept decision

To derive the concept decision, each technical option from the solution space (e.g. traction transmission[tires or tracks]) must be compared pairwise (according to the AHP from [13]) in their quality against the respective criteria (e.g. Economy) which results in fixed local weightings ($w_{l,tires,Econ} > w_{l,tracks,Econ}$).

Table 2. Overview of decision hierarchy weights

	Local weights w_l	Functionality weights w_f	Criteria weights w_c	Global weights w_g
Hierarchy level	Options	Options	Criteria	Best concept
Derivation	Pairwise comparisons	Experts	User profile	Calculation
Flexibility	Fixed	Variable for application	Variable for user profile	-

Our approach integrates further expert knowledge through interviews with industry, academia, and farm managers for the Functionality criteria: In contrast to the other criteria, the Functionality weighting is different for each use cases, because it maps that some technical options are more suitable or necessary for certain applications than others ($w_{c,fun}$). The criteria themselves are weighted according to the customer-relevant properties ($w_{c,i}$). To derive a comprehensive concept recommendation, the global weights ($w_{g,i}$) for each technical option must be calculated by multiplying the weights at each level:

$$w_{g,\text{tires}} = \sum w_{c,j} w_{l,\text{tires},j} + w_{c,\text{fun}} w_{l,\text{tires,fun}} \quad (1)$$

As functionality weights are computed individually for each technical option, they must be multiplied separately with the functionality criteria weight and added subsequently. We recommend the technical option with the highest weight, resulting in 23 concept decisions. Figure 3 shows an exemplary extract for the concept decisions of a dairy and a vegetable farmer in the morphological matrix.

2.3. *Translation of customer-relevant properties into quantitative technical parameters*

Additionally to qualitative concept decisions, the electric tractor design involves the determination of the technical performance data: According to Figure 1, we offer correlation functions to objectify the customer-relevant properties by translating them into quantitative technical parameters. The method describes each CRP by at least one technical property, which can have a positive or negative influence on the CRP rating (Table in Figure 4). Therefore we generate data-based and limit-based correlation functions. To obtain the data-based correla-

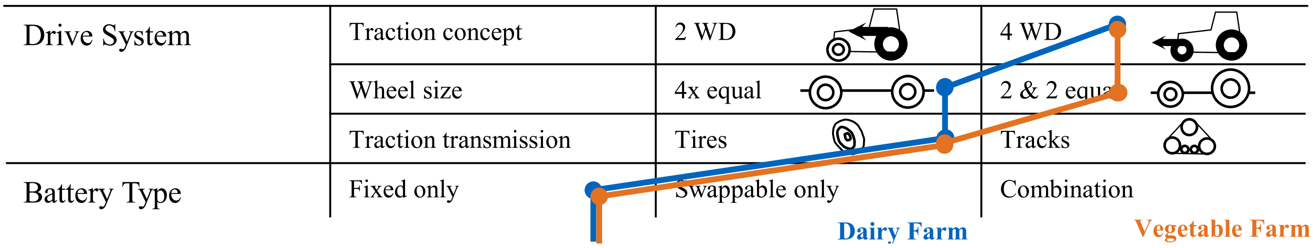


Fig. 3. Concept decisions from the decision hierarchy based on the morphological box from [7].

tion, we gathered a tractor database which contains the registration data from 2022 in Germany and all technical parameters for the sold tractor models below 100 kW (Section Appendix A). The physical characteristics of the technical properties per tractor model combined with the number of tractor models sold per year gives a histogram for each technical parameter, including the standard deviation σ and expectation value μ (Figure 2). The histogram is the basis to provide the correlation function, which puts the CRP and technical parameter into relation. Based on this curve, we can chose the most suitable technical parameter for a given CRP-value.

2.4. Correlation functions

Figure 4 guides exemplary through the process of translating customer-relevant properties into quantitative technical properties. The radar charts shows the CRPs with their characteristic specification for the two farm types *Dairy Farm* and *Vegetable Farm*. As indicated in the table in Figure 4, we assign each specification of a CRP cluster one or more technical parameters on the vehicle level. For simplicity, further clusters and their parameters are omitted in the table. In the following, we consider the two technical parameters *Ground clearance* and *Maximum mass* exemplary.

Data-based correlation functions

Data-based correlation functions access the already presented, sufficiently large tractor database. Based on the number of registrations of tractors with their specific characteristics of technical properties, we generate a histogram for each technical property. The histogram for *Ground clearance* in Figure 4 indicates, that most tractors registered in 2022 had a ground clearance of 370 mm. In contrast, the maximum mass of registered tractors is more widely distributed. We objectify the two CRPs *Functionality* and *Environment* with their technical parameters *Ground clearance* and *Maximum mass*, respectively, by the correlation function introduced from [16]:

$$CRP = \frac{1}{2}\left[1 + erf\left(\pm\frac{(x-\mu)}{\sqrt{2\sigma^2}}\right)\right]\left(UL - LL\right) + LL \qquad (2)$$

Thereby, x denotes the technical parameter, μ the expected value, σ the standard deviation and UL and LL the upper and lower limit. In alignment with the rating scale proposed by [8] for CRPs, we set the upper limit UL to 10, signifying the highest achievable customer satisfaction. The lower limit LL is set to 4, denoting a sub-optimal expression of the property that falls below customer tolerance levels.

Limit-based correlation functions

For new technical parameters, like electric tractor-specific technical features such as battery capacity and operating time, no sufficiently large database is available, as industrialized machines are currently only sporadically on the market. To overcome this issue, we chose the the approach of limit-based correlation functions which allows us to draw the correlation between a CRP and its technical parameter with a minimum of at least two available data points. By that, it is possible to foresee the customer's expectation of improvement of the new technical properties. The correlation is based on a logarithmic function as outlined in [16]:

$$CRP = \frac{UL - LL}{1 + e^{-k(x-x_0)}} + UL \qquad (3)$$

With the technical parameter x, the inflection point x_0 and slope of the curve k, which are calculated by

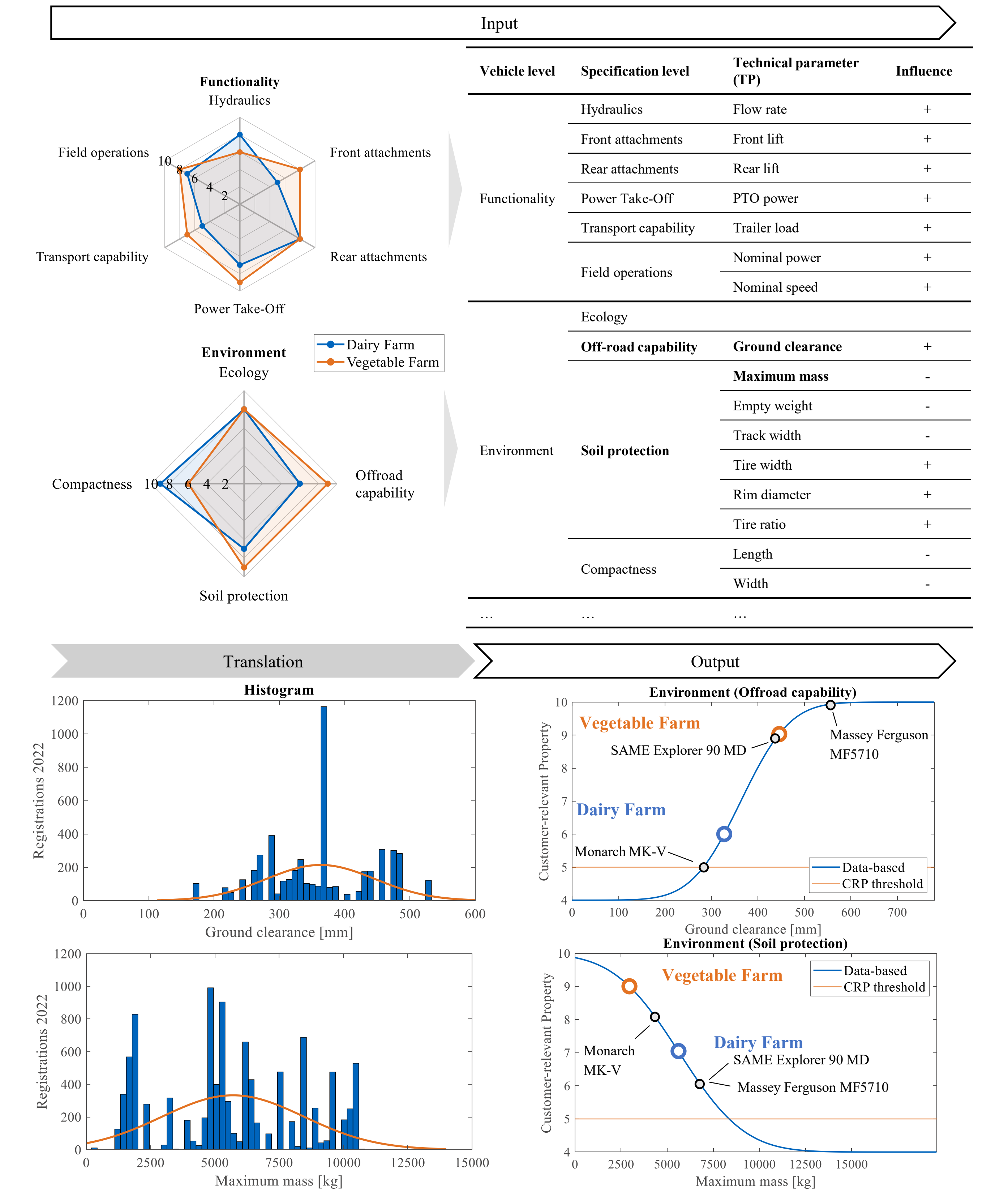
$$x_0 = \frac{a_2(x_2 - x_1)}{a_1 - a_2} + x_2 \quad \text{and} \quad k = \frac{a_2 - a_1}{x_2 - x_1} \qquad (4)$$

and the parameters a_i

$$a_i = ln\left(\frac{UL - LL}{CRP_i - LL} - 1\right), i = 1, 2 \qquad (5)$$

For determining the curve parameters, at least two tractors must be available with the specific technical property to serve as data points (x_1, CRP_1) and (x_2, CRP_2).

Figure 4 shows exemplary the application of our proposed method for the data-based correlation function by plotting the CRPs *Off-road capability* and *Soil protection* against their technical property *ground clearance* and *maximum mass*. Thereby, the ground clearance correlates positively to the off-road capability, while the mass correlates negatively to soil protection. The CRP ratings for the dairy farm from the radar charts shows a rating of 6 for *Off-road capability* and 7 for *Soil protection*. Drawing these ratings in the correlation curves, we can derive the value of the respective technical parameter on the x-axis. The most suitable ground clearance therefore results in 330 mm, while the maximum mass should be less than 5600 kg. The same procedure applies for the vegetable farm. For reference, the Massey Ferguson and SAME tractors are diesel-driven tractors, whereas the Monarch is battery-electric. The technical property shall not fall below the CRP threshold, equivalent to the customers' acceptance level.



Vehicle level	Specification level	Technical parameter (TP)	Influence
Functionality	Hydraulics	Flow rate	+
	Front attachments	Front lift	+
	Rear attachments	Rear lift	+
	Power Take-Off	PTO power	+
	Transport capability	Trailer load	+
	Field operations	Nominal power	+
		Nominal speed	+
Environment	Ecology		
	Off-road capability	**Ground clearance**	**+**
	Soil protection	**Maximum mass**	**-**
		Empty weight	-
		Track width	-
		Tire width	+
		Rim diameter	+
		Tire ratio	+
	Compactness	Length	-
		Width	-
…	…	…	

Fig. 4. Description of technical parameters with data- and limit-based correlation functions on the example of Functionality and Environment for dairy and vegetable farming.

3. Discussion and Outlook

The advent of electric tractors opens up the possibility to exploit the design freedom of electric power trains and put the farmer at the center of the development without diesel-inherited design objectives. Hence, we propose a novel two-track methodology to develop electric tractor concepts focusing on smallholder farmers in need of tailored machinery. We propose a set of 23 customer-relevant properties (CRP) to serve as an initial definition of the properties of an electric tractor and relate them to technical specifications. In the next step, actual user groups should be interviewed to collect their assessment.

The first track includes a Multi-Criteria Decision Making (MCDM) approach to derive qualitative concept decisions involving criteria weights derived from user input, while functionality and local weights are based on expert interviews. However, these expert assessments can significantly impact final concept decisions. The limited number of expert interviews conducted restricts the ability to model a vast range of agricultural use cases. To improve the framework's applicability, additional interviews covering a broader range of use cases and geographical contexts are needed.

The second track offers the functionality to derive the technical specifications of the electric tractor with correlation functions, which are based on tractor sales. However, current market characteristics, which these functions rely on, may not accurately reflect customer preferences. Future advancements in electric tractors and battery technology will necessitate regular updates to these functions. The use of data specific to Germany limits the global applicability of the correlation functions.
In general, the methodology offers not just a framework to derive electric tractor concepts based on the requirements necessary for the tractor to fulfill the farmers' needs, but with the provided database, a collected overview of existing tractor specifications. Our methodology emphasizes the technical aspects which are necessary to ensure the electric tractor's ability to suit mechanization.

Acknowledgements

K.G.: First Author, Conceptualization, Methodology, Visualization, Validation, Writing - Original Draft, Writing - Review & Editing; **L. V.**: Investigation, Methodology, Validation, Software Writing - Review & Editing; **N. K.**: Writing - Original Draft, Writing - Review & Editing; **M. L.**: Writing - Review & Editing, Resources, Supervision. This research was funded by the H2020 Grant Agreement 963530. The authors declare no conflict of interest.

Appendix A. Data availability

Supplementary information with our tractor database is provided under: https://mediatum.ub.tum.de/1756494

References

[1] Amini, S., Asoodar, M.A., 2016. Selecting the most appropriate tractor using analytic hierarchy process – an iranian case study. Information Processing in Agriculture 3, 223–234. doi:10.1016/j.inpa.2016.08.003.

[2] Bagire, F., Tennakoon, S., Kamuhinda, S., 2022. Analysis of a fully electric tractor performance through field trials in rwanda. 2022 IEEE 7th SPEC doi:10.1109/SPEC55080.2022.10058276.

[3] Beligoj, M., Scolaro, E., Alberti, L., Renzi, M., Mattetti, M., 2022. Feasibility evaluation of hybrid electric agricultural tractors based on life cycle cost analysis. IEEE Access 10, 28853–28867. doi:10.1109/ACCESS.2022.3157635.

[4] Chen, Y.C., Chen, L.W., Chang, M.Y., 2022. A design of an unmanned electric tractor platform. Agriculture 12, 112. doi:10.3390/agriculture12010112.

[5] Das, A., Jain, Y., Agrewale, M.R.B., Bhateshvar, Y.K., Vora, K., 2019. Design of a concept electric mini tractor, in: 2019 IEEE Transportation Electrification Conference (ITEC-India), IEEE, Piscataway, NJ. pp. 1–5. doi:10.1109/ITEC-India48457.2019.ITECINDIA2019-134.

[6] García-Alcaraz, J., Maldonado-Macías, A., Hernández-Arellano, J., Blanco-Fernández, J., Jiménez-Macías, E., Sáenz-Díez Muro, J., 2016. Agricultural tractor selection: A hybrid and multi-attribute approach. Sustainability 8, 157. doi:10.3390/su8020157.

[7] Götz, K., Pizzinini, C., Strauss, J., Tennakoon, S., Menelaos, M., Booysen, T., Lienkamp, M., 2023. Conception of an electric tractor for farming in sub-saharan africa, in: 7th E-Mobility Power System Integration Symposium (EMOB 2023), Institution of Engineering and Technology. pp. 221–227. doi:10.1049/icp.2023.2708.

[8] Heißing, B., Brandl, H.J., 2002. Subjektive Beurteilung des Fahrverhaltens. Vogel-Fachbuch. 1. aufl. ed., Vogel, Würzburg.

[9] IPCC, 2014. Climate Change 2014: Mitigation of climate change: Assessment Report of the Intergovernmental Panel on Climate Change.. volume WG III of *Climate change 2014*. Cambridge Univ. Press, New York.

[10] Lagnelöv, O., Dhillon, S., Larsson, G., Nilsson, D., Larsolle, A., Hansson, P.A., 2021. Cost analysis of autonomous battery electric field tractors in agriculture. Biosystems Engineering 204, 358–376. doi:10.1016/j.biosystemseng.2021.02.005.

[11] Lin, B., Xu, B., 2018. Factors affecting co2 emissions in china's agriculture sector: A quantile regression. Renewable and Sustainable Energy Reviews 94, 15–27. doi:10.1016/j.rser.2018.05.065.

[12] Olkkonen, V., Lind, A., Rosenberg, E., Kvalbein, L., 2023. Electrification of the agricultural sector in norway in an effort to phase out fossil fuel consumption. Energy 276, 127543. doi:10.1016/j.energy.2023.127543.

[13] Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. Mathematical Modelling 9, 161–176. doi:10.1016/0270-0255(87)90473-8.

[14] Schockenhoff, F., König, A., Koch, A., Lienkamp, M., 2020. Customer-relevant properties of autonomous vehicle concepts. Procedia CIRP 91, 55–60. doi:10.1016/j.procir.2020.02.150.

[15] Schockenhoff, F., König, A., Zähringer, M., Lienkamp, M., 2021. User need-oriented concept development of autonomous vehicles. Proceedings of the Design Society 1, 3349–3358. doi:10.1017/pds.2021.596.

[16] Schockenhoff, F.F., 2023. Fahrzeugkonzeptentwicklung für autonome, geteilte und elektrische Mobilität. Ph.D. thesis. Technische Universität München. URL: https://mediatum.ub.tum.de/1687122.

[17] Thiel, J., 2017. Anforderungen an Marketingkonzepte für Großtraktoren unter Berücksichtigung des Wandels landwirtschaftlicher Rahmenbedingungen. URL: https://hohpublica.uni-hohenheim.de/items/3364d590-38c5-44a8-a666-a62ceb2b37f2.

[18] Todorov, V.T., Rakov, D., Bardenhagen, A., 2022. Enhancement opportunities for conceptual design in aerospace based on the advanced morphological approach. Aerospace 9, 78. doi:10.3390/aerospace9020078.

[19] Vogt, H.H., de Melo, R.R., Daher, S., Schmuelling, B., Antunes, F.L.M., dos Santos, P.A., Albiero, D., 2021. Electric tractor system for family farming: Increased autonomy and economic feasibility for an energy transition. Journal of Energy Storage 40, 102744. doi:10.1016/j.est.2021.102744.