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DESIGN SPECIFICATIONS OF AN AUTONOMOUS ELECTRIC VEHICLE FOR USE IN FAMILY FARM UNITS

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KEYWORDS

family farming, product development, weeds.

ABSTRACT

Family farming in Brazil is responsible for the country's food security, ensuring most of the food consumed by Brazilians. However, the agricultural machinery and equipment industry has not been dedicated to providing innovations to this sector, focusing mainly on supplying large agribusiness properties with the most advanced technology equipment. Thus, the introduction of new technological solutions regarding agricultural machines for family farming is necessary. Considering the need to supply this branch of the Brazilian agricultural sector with new technologies, this study aimed to establish the design specifications of an autonomous electric vehicle that serves as a multifunction platform, which was primarily designed to remove weeds, mainly meeting the needs of family farmers. The product development methodology in its informational phase was applied to obtain and study these needs. As a result, 19 design specifications were established with their associated target values, allowing defining the physical and economic parameters that will be the basis for the development of the autonomous electric vehicle in its conceptual phase.

INTRODUCTION

Family farming is currently one of the most relevant activities in the food production industry, also being important for the food security of Brazilian families (Melo et al., 2019).

The National Institute for Colonization and Agrarian Reform (INCRA) classifies the size of rural properties in Brazil and establishes the fiscal module as the unit of measurement, depending on regulations and the location of the state (Berchin et al., 2019).

According to the Brazilian Institute of Geography and Statistics, Brazil has about 3.8 million rural establishments, with approximately 77% of agricultural properties registered. In addition, family farming establishments represent 23% of the agricultural area in Brazil and 14% of the South region. Approximately 21 million hectares in the State of Rio Grande do Sul were classified as properties for family farming, with a total of 365,094 establishments (IBGE, 2017).

Agriculture has many operations such as soil tillage, sowing, cultural management, and harvesting throughout the production cycle of a crop. The weed removal activity is among the cultural treatments (Merfield, 2016). Weed control is carried out by farmers using pesticides, cutting tools such as hoes, or simply the removal of plants by hand.

According to Shamkuwar et al. (2019), weed control by chemical or mechanical products is a complex issue, presenting technical, environmental, and social factors, being positively impacted by the implementation of systems and equipment related to digital agriculture 4.0.

Agriculture 4.0 is made up of interconnected operative technologies that have been currently related to increasing crop yield, reducing farmers' workload, and protecting the environment. The first one is the internet of things (IoT), which allows the collection of data on parameters such as soil moisture, ambient temperature, pest and disease detection, machine speed, and georeferenced coordinates through smart sensors connected to the internet. In contrast, there are cloud storage systems, where a large

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volume of data collected by sensors (Big Data) can be processed and analyzed in real time. Finally, the latest technology refers to artificial intelligence (AI), which enables the learning of cognitive and conditioning abilities in machines through algorithms. Thus, motors or actuators are activated to trigger a mechanism in the machine during its work in the field (Albiero et al., 2020).

Brazil has few machines for sale designed adequately for family farming, and, in most cases, those available in the market are large, expensive, and with power above that required by family farmers (Teixeira et al., 2009; Medeiros et al., 2015; Niemczewski et al., 2014).

According to Lambrecht et al. (2017), companies responsible for the development of agricultural machinery in Brazil generally meet the demand of farmers with large areas of land and high annual income, most of them linked to agribusiness. For this reason, most family farmers have been empirically designing and manufacturing adaptations of technologically limited agricultural tools and equipment (Reichert et al., 2015).

In this context, the Center for Innovation in Agricultural Machinery and Equipment (NIMEq) of the Federal University of Pelotas has been researching and developing technologies in low-cost agricultural machines with ergonomic characteristics that can allow easy access and use to family farmers. Consequently, their use on rural properties will allow a reduction in the high work effort of farmers, as well as an increase in the productivity of activities in the field (Machado et al., 2017).

Digital devices are already present in many devices, performing and supporting tasks such as autopilot and variable rate applications. Also, a large number of sensors monitor the crop, environment, losses, and operating parameters in real time. However, the technological advance is the adoption of emerging alternatives such as IoT, electric vehicles, and small autonomous machines, which have already been used in other areas (Reis et al., 2020).

The use of agricultural robots is not new, it is currently a trend, and many studies in the field of agricultural robotics have been developed (Albiero, 2019).

In Europe, there are autonomous electric agricultural vehicles to carry out cultural treatments such as the one manufactured by Saga Robotics in Norway, which has a modular design adaptable to perform different tasks in the field (Grimstad & From, 2017). On the other hand, Naio Technologies in France offers farmers a platform for cultural treatments carried out in planting beds or furrows. Likewise, Ecorobotix in Switzerland has developed an autonomous electric platform with a system that selectively detects and sprays weeds with minimal herbicide doses (Andersson, 2021).

As a consequence, this new technological trend will have an impact both on agricultural production chains, as expected, and on how new equipment should be developed (Reis et al., 2020).

Albiero et al. (2022) reviewed the state of the art in agricultural robots, analyzing seven aspects related to technology, which consisted of technology readiness level, configurability, adaptability, reliability, movement capacity, perception capacity, and decision autonomy. They concluded that the three most critical aspects constitute challenges for research, namely: configurability, adaptability, and decision autonomy.

Significant advances have occurred in the development of agricultural robotics with systems tested in the field, with an increase in investment for the commercialization of agricultural robots, demonstrated through the emergence of start-ups and companies already consolidated offering products and services (Ball et al., 2017). However, there is still a need to develop robots for the agricultural reality, as many systems used in the industry are unable to withstand agricultural environmental conditions, in addition to issues related to connectivity in the field due to the great distances in these areas (Albiero, 2019).

One of the main challenges of agricultural electric vehicles is their working autonomy. According to Olson (2018), the low energy density and high costs of electric batteries increase the cost and reduce the operating autonomy of electric vehicles compared to internal combustion vehicles. Current lithium-ion batteries with a specific energy of 150 Wh/kg are widely used for small-scale vehicles, but not enough to match the performance of internal combustion vehicles, in which gasoline/diesel has an energy density of 12200 Wh/kg (Diouf & Pode, 2015). However, recent studies have sought to improve the energy efficiency and autonomy of agricultural electric machines. For example, Vogt (2018) established four settings for charging a 9 kW tractor, offering an economically viable option to make an energy transition from an internal combustion tractor to an electric tractor.

The 130 kWh battery of the prototype John Deere all-electric conventional tractor based on the 6R Series chassis, adapted continuous transmission, and a speed range of 3 to 50 km/h at full power lasted four hours of operation, while the charging time was about three hours (John Deere, 2017).

According to Lagnelöv et al. (2020), conventionally sized battery-powered tractors are currently not an economically competitive option for field operations.

This research aims to establish the design specifications for an autonomous electric vehicle to provide the removal of weeds, meeting the needs of Brazilian family farmers.

MATERIAL AND METHODS

The development of this research was conducted at the Center for Innovation in Agricultural Machinery and Equipment of the Federal University of Pelotas (NIMEq/UFPel), following the order established in the informational phase of the product development methodology. Figure 1 shows the steps that make up the Informational Design Phase of the design methodology used in this study.

This methodology has recently been used at NIMEq/UFPel in the development of agricultural machinery designs such as those proposed by Lambrecht et al. (2017), Stefanello et al. (2017), Custódio et al. (2018), Spagnolo et al. (2018), and Duarte et al. (2020).

Step 1.1 establishes the product life cycle. The life cycle starts with the project (sizing, calculation, drawing, and planning), followed by production (purchasing, manufacturing, assembly, and testing), commercialization (marketing, distribution, and sales), use (operation, adjustment, and maintenance), and withdrawal (disposal or recycling). In this case, we worked specifically with users who could use the electric agricultural vehicle (family farmers) to meet their requirements. In addition, a literature review was carried out on the development of agricultural electric vehicles to remove weeds, considering commercial use.

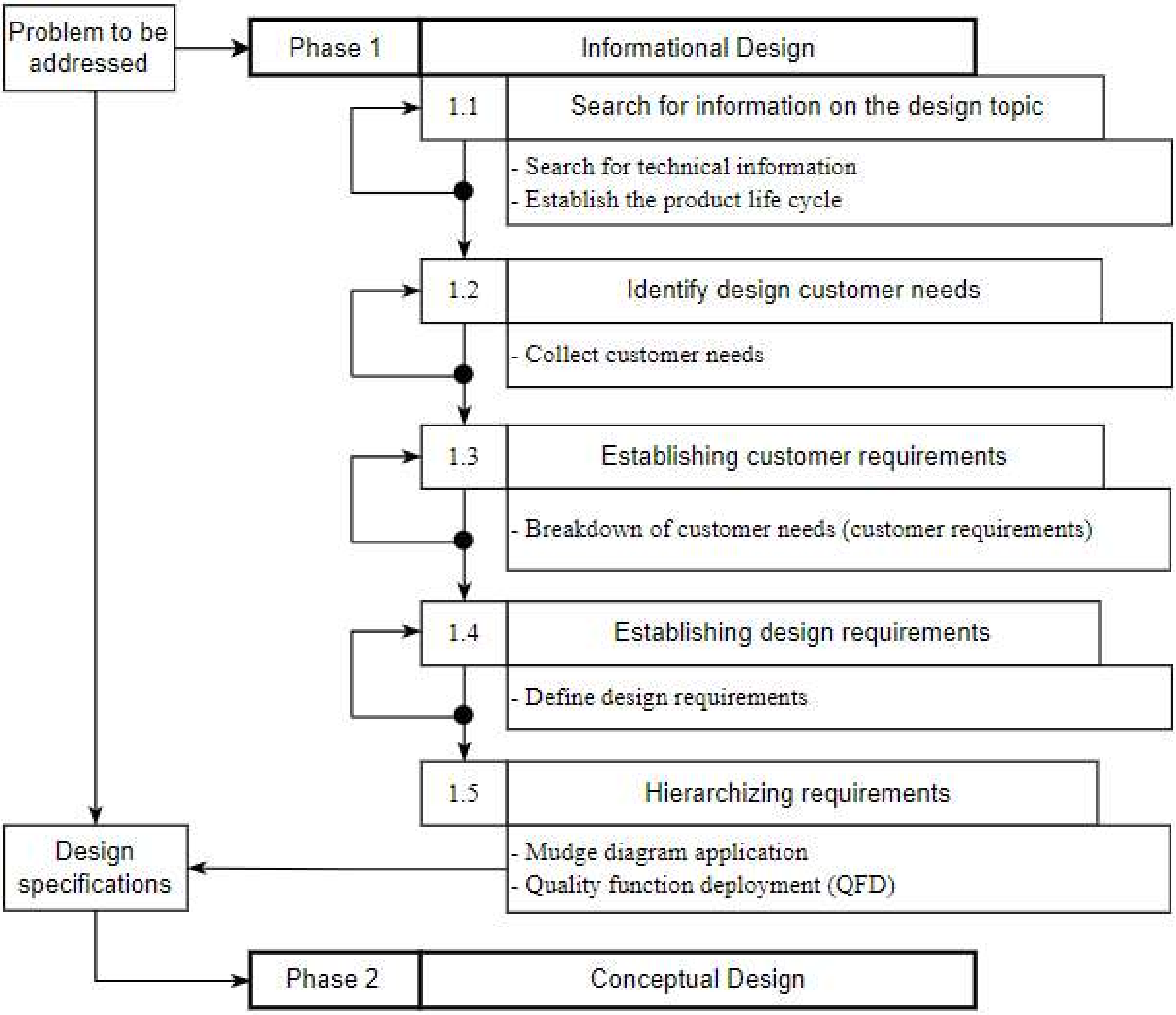

FIGURE 1. Informational design phases.

Subsequently, the needs of potential customers of the machine, that is, family farmers, were identified (Phase 1.2). A questionnaire with seven open questions was applied through the Google Forms® platform and sent online to determine the needs. Twenty-two responses were obtained from family farming units distributed in municipalities in the State of Rio Grande do Sul, of which 12 are located in Pelotas, three in Canguçu, two in São Lourenço do Sul, two in Gravataí, two in Vera Cruz, and one property located in Santa Vitoria do Palmar.

Table 1 shows characteristics such as the size of properties, main produced products, and technological level of family farmers that were the research target.

TABLE 1. Size of properties, main produced products, and technological level.

Family farms per hectare strip	<5	5-10	10-20	21-40	41-64
%	54.6	9.1	18.2	13.6	4.5
Main products produced in the family farms surveyed	Cereals - grains	Vegetables (lettuce, kale, cabbage, etc.)	Vegetables (Pumpkin, beetroot, pepper, etc.)	Fruits (pineapple, apple, peach, etc.)	Tobacco
%	56.6	46.6	40	30	23.3
Traction type used in family farms (technological level)	4-wheel tractor	Power tiller	Human traction	Animal traction	
%	84.4	28.1	21.9	12.5	

The technological level gives an idea of the technology used on the properties although some farmers can use both the four-wheel tractor and human or animal traction.

Customer needs were analyzed and deployed to transform them into requirements, which must be presented in an engineering language (Phase 1.3). According to Moura et al. (2010), the use of short sentences is necessary to translate these needs, such as a sentence composed of the verbs to be or to have, followed by one or more nouns.

Customer requirements were converted into design requirements in Phase 1.4, thus constituting the first physical decision about the designed product. Possible solution principles were defined for each of the customer requirements, considering that these principles must be represented by measurable physical properties.

Finally, Phase 1.5 establishes that the design requirements must be prioritized through the application of the quality function deployment (QFD). However, the Mudge diagram was applied to determine the order of relative importance of customer requirements to be used in QFD. The application of the Mudge diagram was performed using the software.

RESULTS AND DISCUSSION

The responses to the questionnaire allowed identifying 25 customer needs. Among the most relevant needs relative to an autonomous electric vehicle, family farmers reported the need to have access to a low-cost vehicle within their income range. In addition, it must be simple to handle and regulate, requiring basic technical training, with adaptation to different crops or planting beds, and the mechanism to carry out the cultural treatment should not damage the plant or the soil. Finally, they considered the charging autonomy of the vehicle batteries to be important after recharging.

Seventeen customer requirements were established from the 25 obtained needs. The Pareto diagram in Figure 2 shows the result of applying the Mudge diagram. User safety is always treated in all NIMEq designs as essential, regardless of whether it is considered in the assessment of requirements, being one of the most important requirements when operating an agricultural machine. On the other hand, the graphic also shows that the first 10 requirements represent approximately 80% of the 17 total requirements. In this case, user safety, planting preservation, sufficient tractive force, independence from the electrical grid, low maintenance cost, plant recognition sensors, and energy consumption, for instance, are the requirements where the greatest effort should be focused to fulfill customers' desires.

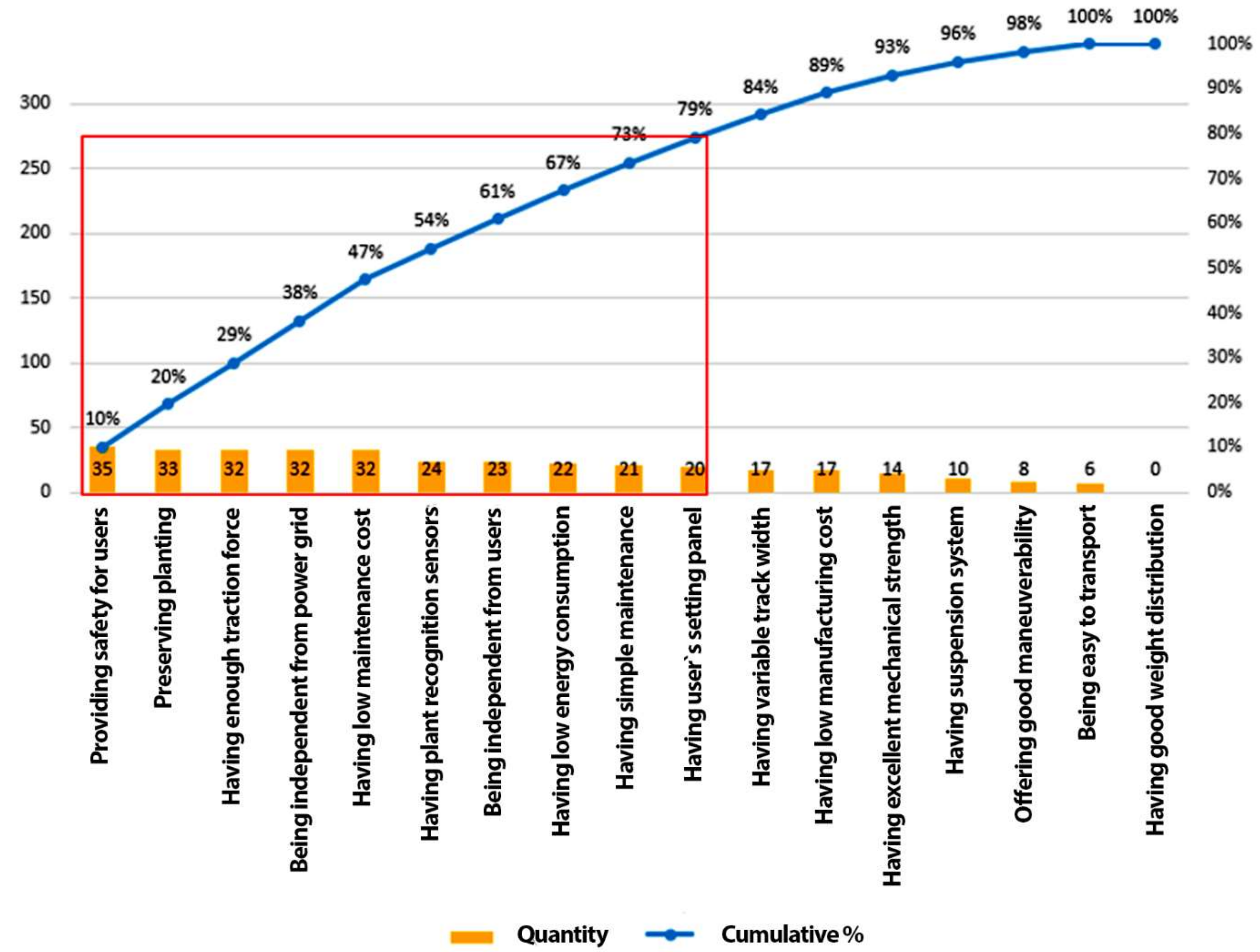

FIGURE 2. Pareto Diagram of customer requirements.

Table 2 shows the frequency distribution in five classes of the design requirements with their importance values obtained from the Mudge diagram and necessary for the quality function deployment (QFD) matrix application.

TABLE 2. Order and importance value of customer requirements.

Order	Customer requirements	% Mudge	Interval	Value
1	Providing safety for users	10,116	(4 – 5]	5
2	Preserving planting	9,538	(4 – 5]	5
3	Having enough traction force	9,249	(4 – 5]	5
4	Being independent from power grid	9,249	(4 – 5]	5
5	Having low maintenance cost	9,249	(4 – 5]	5
6	Having plant recognition sensors	6,936	(3 – 4]	4
7	Being independent from users	6,647	(3 – 4]	4
8	Having low energy consumption	6,358	(3 – 4]	4
9	Having simple maintenance	6,069	(2 – 3]	3
10	Having user's setting panel	5,780	(2 – 3]	3
11	Having variable track width	4,913	(2 – 3]	3
12	Having low manufacturing cost	4,913	(2 – 3]	3
13	Having excellent mechanical strength	4,046	(1 – 2]	2
14	Having suspension system	2,890	(1 – 2]	2
15	Offering good maneuverability	2,312	(1 – 2]	2
16	Be easy to transport	1,734	(0 – 1]	1
17	Having good weight distribution	0	(0 – 1]	1

Figure 3 shows the result of the quality function deployment (QFD) matrix. The "WHATs" represent what customers want or expect from the product. On the other hand, the list of design requirements was located in the "HOWs" segment, which will meet the "WHATs" (Andersson et al., 2014). The column "IMPORTANCE" was filled in order and with the importance values of the design requirements for the evaluation. The following scale was used for the requirement weights in the correlation matrix: 5 for strong relationships, 3 for medium relationships, 1 for weak relationships, and blanks represent no relationships.

Strong relationships	● - 5
Medium relationships	O - 3
Weak relationships	Δ - 1

	HOWS	%		min			mm				h		kW/h	R$	R$/a	Years	n°	Weeks	m/s	kW	m
THE WHATS	IMPORTANCE	Preservation of planting	Electrical system protection	Module assembly/disassembly	Wheel coupling/decoupling	Adjustment and calibration time	Lenght between the axles	Use of tolerances	Track width variation range	Height	Battery autonomy	Maintenance time	Energy consumption	Manufacturing cost	Maintenance cost	Lifespan	Number of working crops	Periodicity between maintenance cycles	Working speed	Driving power	Vehicle turning radius
Providing safety for users	5		●	O	Δ	O				O		●		O	Δ			O	Δ	●	
Preserving planting	5	●				●	Δ	O	●	O			Δ	●	O		O		●	Δ	O
Having enough traction force	5	Δ	O			O	O				●	Δ	●	●	O			O	●	●	O
Being independent from power grid	5	O	O			O					●	O	●	●	●	●		●		●	
Having low maintenance cost	5	Δ	●	●	O	O			●		●	●	Δ	●	●	●		●		O	O
Having plant recognition sensors	4	●	●	●		●				O	Δ	●	Δ	●	●	O	O	Δ	●	Δ	●
Being independent from users	4		O	●	O	●			●		●	●	●	●	O	Δ	●	O		O	●
Having low energy consumption	4		●			Δ	Δ		Δ		●		●	O	O	O		Δ	●	●	●
Having simple maintenance	3		O	●	●	●		O	●			●		O	●	O		●			
Having user`s setting panel	3	O				●			Δ		●		O	●	O		O	Δ	Δ	Δ	O
Having variable track width	3	●		O	O	●	●	●	●			O	Δ	●	●		●	Δ		Δ	●
Having low manufacturing cost	3	O	●	●	Δ			●	●		●	Δ	●	●	O	●	Δ	O	Δ	●	●
Having excellent mechanical strength	2		Δ	Δ	O		O					Δ		●	●	●		●			
Having suspension system	2	O	O	Δ	●	●		O	O	●		O	●	●	●	●		●	●		Δ
Offering good maneuverability	2	O	Δ	O	●	●	●		●	Δ	Δ		Δ	O	O	O	O		●	●	●
Be easy to transport	1			O	●	O	O			●			Δ	O	Δ	O		Δ	Δ		Δ
Having good weight distribution	1			●			O			●	●		●			O			●	●	●
IMPORTANCE OF THE REQUIREMENT		115	166	142	90	197	61	60	138	64	156	145	149	250	204	134	80	151	127	167	162
		15	5	11	16	3	19	20	12	18	7	10	9	1	2	13	17	8	14	4	6

FIGURE 3. Relationship between customer requirements and design requirements.

Finally, Table 3 shows the design specifications ranked by QFD. According to Moura et al. (2010), design specifications should be ranked with their target values in three sets: upper, middle, and lower thirds. The target values were established by the work team, taking as a reference the development available in the market and the needs of farmers.

TABLE 3. Results of the design specification ranking in QFD.

Design requirement	QDF ranking	Target value
Upper third		
Manufacturing cost (R$)	1°	55.000,00
Maintenance cost (R$/year)	2°	≤ 8.000,00
Adjustment and calibration time (min)	3°	< 10
Driving power (kW)	4°	$2 \leq P \leq 4$
Electrical system protection (%)	5°	IP55
Vehicle turning radius (m)	6°	$1 \leq r \leq 2$
Battery autonomy (h)	7°	$4 \leq t \leq 6$
Middle third		
Periodicity between maintenance cycles (weekly)	8°	16
Energy consumption (kW/h)	9°	≤ 0,42
Maintenance time (H)	10°	$1 \leq r \leq 2$
Module assembly and disassembly (min)	11°	< 30
Track width variation range (mm)	12°	$1000 \leq t \leq 1200$
Lifespan (years)	13°	≥ 10
Lower third		
Working speed (m/s)	14°	$1{,}5 \leq V \leq 2{,}5$
Preservation of planting (%)	15°	90
Wheel coupling and uncoupling (min)	16°	< 1
Number of working crops (n°)	17°	5
Height (mm)	18°	$400 \leq H \leq 600$
Length between the axles (mm)	19°	$1200 \leq d \leq 1500$

The economic aspect turned out to be the most important specification within the design, with considerable influence on the other specifications. Although the farmers expressed a desire for the amount of R$ 10,000 in the questionnaire, this amount was far below or outside the standards of values practiced for equipment that is expected to be replaced with the introduction of the autonomous vehicle. Thus, the value of the Tramontini transport platform (TTA 18) of approximately 13 kW and a cost of R$ 55,000 was used as a reference (Pronaf, 2022).

The performance of the vehicle's main components (engines, batteries, navigation system, and the plant detection system) is associated with their cost in the market, and components should be selected within the target values established in the specifications. It can considerably increase the final cost of manufacturing the vehicle.

On the other hand, specifications such as adjustment and calibration times, module assembly and disassembly, and driving wheel coupling and decoupling seek to satisfy the demands of family farmers in terms of simplicity in the use of the vehicle and its maintenance in terms of economic and time.

Dimensional specifications such as width, height, and length have variable parameters aimed at adapting the vehicle to different types of crops, especially the planting bed width.

Finally, the specification of preserving the planting intends to take care of the crop so that it is not damaged by the implement or chemically treated wrongly. The selection of plant detection technologies with a high percentage of efficiency will meet this requirement, reducing post-harvest losses.

The applied methodology allowed the work team to transform the customers' needs into design specifications, which could be partially met and evaluated in the different phases of the vehicle's development. In the short term, in the conceptual phase, the dimensional and shape characteristics of the vehicle could be met through the use of computer-aided design, allowing the visualization of conceptions that meet the ergonomic and use specifications of the vehicle. Finally, in the long term, all specifications could be evaluated during the prototype test phase in the field, especially those associated with its operation during weed control.

CONCLUSIONS

The information obtained from family farmers allowed the establishment of 19 design specifications with their associated target values and the determination of the physical and economic parameters that will be the basis for the development of the autonomous electric vehicle in the conceptual phase. The established specifications do not bring certainty, but confidence that the vehicle will be well accepted by family farmers when made available.

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