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Challenges of a Transdisciplinary Team in the Design of a Lithium-Ion Battery Pack for Small Urban Electric Vehicles: Lessons Learned

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Abstract. Electric vehicles (EVs) are becoming a viable alternative to eliminate emissions, reduce dependence on fossil fuels, and gradually replace vehicles with an internal combustion engine (ICE). The traction battery of these vehicles has the primary function of supplying the energy necessary for the electric motor to work. Its design is complex and represents one of the most significant difficulties in reducing the cost of vehicular electrification. This article describes the challenges faced by a transdisciplinary team in designing a lithium-ion battery pack with a battery management system (BMS) applied to a small urban vehicle developed in the context of the "Program Route 2030". Through the case study approach, we will present the interaction between 29 researchers from three Brazilian Science and Technology Institutions (ICT) (UTFPR-PG; UTFPR-CT; SENAI-PR) and two subsidiaries of multinationals (Renault; Clarios) in the automotive sector also based in Brazil. Preliminary results show the importance of transdisciplinary work in leveling the team's knowledge about the product, determining target specifications through applying the House of Quality (HoQ) tool, specifying cell chemistry, proposing the modules' physical arrangement, and developing the BMS.

Keywords. Transdisciplinary Engineering, Concurrent Engineering, New Product Development, Electric Vehicles, Lithium-ion Batteries.

Introduction

To reduce dependence on fossil fuels and environmental burdens, such as reducing CO2 emissions, the Brazilian government is focusing on developing the electric vehicle (EV) industry. Through Law No. 13,755/2018 and Decree No. 9,557/2018, the national program Route 2030 was established, whose objective is to support and promote technological development, competitiveness, innovation, vehicle safety, environmental protection, efficiency energy, and the quality of cars, trucks, buses, chassis with engine and auto parts [1]. The Research Development Foundation (FUNDEP) was accredited by the Ministry of Economy, Industry, Foreign Trade and Services (MDIC) as a coordinating institution to coordinate the priority program: biofuels, vehicle safety, and alternative combustion propulsion [1].

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Renault do Brasil S.A. in partnership with Clarios Energy Solutions Brasil Ltda., the Federal Technological University of Paraná – Campus Ponta Grossa (UTFPR-PG), the Federal Technological University of Paraná – Campus Curitiba (UTFPR-CT), and the National Service for Industrial Learning of Paraná (SENAI-PR) presented a proposal for Axis III - PAC: Alternative Propulsion to Combustion, and the project was selected through Public Call No. 01/2020 - Route 2030.

In this research, development, and innovation (RD&I) partnership agreement, these institutions proposed obtaining a national technological solution for developing a lithium-ion battery pack with a capacity of 25 kWh and a battery management system (BMS). To meet the energy demand of small vehicles, with a voltage between 250 V and 300 V and charging DC 25 kW and AC 11 kW [1]. In this way, this work seeks to describe the challenges a transdisciplinary team faces in designing a lithium-ion battery in the "Rota 2030 Program" context.

1. Background theory

Increasing advances in science and technology have led to a rapid increase in the complexity of most engineering systems. These engineering systems are composed of heterogeneous components, often designed and manufactured by organizations belonging to various industrial domains, such as mechanical, electrical, and software. In this sense, [2] battery packs can be considered a complex project, as they are mainly constituted by lithium-ion cells, which are temperature-sensitive devices, and their performance and life cycle can be affected by conditions of an extreme environment.

Therefore, efficient cell temperature regulation is a prerequisite for battery safety and performance. In addition, modularity in battery design is needed to offset the high production costs of electric vehicles (EVs). However, the modularity of batteries is constrained by the flexibility of traditionally used battery thermal management systems [2]. For example, the scalability of liquid-cooled battery packs is limited by the piping and auxiliary equipment used in the system. Therefore, a battery thermal management system (BTMS) is required for modular batteries.

As for complexity, the design of a BTMS involves the need to use several techniques to achieve a final result, as it is verified that it is a complex system that often presents conflicting variables, restrictions, and different objectives. Passive cooling methods are a trend in projects as they do not require any external power supply for their operation, and they use the environment to dissipate heat. As they do not need any external power supply, they are the most sought-after methods for developing the design of a thermal management system. These methods also have the advantages of being compact, less complex, safe, economic, and improved life cycle [2].

Another essential device in battery pack projects is the Battery Management System (BMS). This electronic device can be considered the brain of a battery, as it monitors current, voltage, and temperatures, and determines the available energy, state of charge (SOC), and state of health (SOH), to keep the cells within a safe operation to prevent damage, deterioration and prolong cell life [3].

1.1. Transdisciplinarity and transdisciplinary engineering

According to [4], no discipline can possess all the knowledge necessary to solve the complex problems of our age. Transdisciplinarity characterizes modern research areas in which the natural sciences are integrated with the social sciences, requiring mixed methodologies to carry out the work.

The term 'transdisciplinary' is receiving increasing attention in the academic engineering and research funding communities, but it is still poorly defined. The authors explain that there is still no single definition for transdisciplinary engineering (TE); instead, there is a transdisciplinary landscape [5], [6].

TE is an emerging field that extends and evolves the initial basic concepts known as Concurrent Engineering (CE) [7]. For [8], TE is an emerging area of research capable of evolving traditional engineering approaches and transcending technical disciplines. It can be successfully applied in different fields, combining natural sciences, applied sciences, social sciences, and humanities to achieve a higher level of understanding and awareness of the context in which industrial products, processes, systems, and services will be implemented and experienced users.

2. Methodological considerations

To address the complex challenges addressed in engineering designs, it can often be necessary for researchers to participate in the design processes rather than making observations from the outside. The participant-observer perspective is widely accepted in design research [9]. This work seeks to describe the challenges a transdisciplinary team faces in designing a lithium-ion battery pack with a BMS applied to a small urban vehicle developed in the context of the "Route 2030 Program". As the project lasts 24 months, the challenges and lessons learned during one year of its execution (09/02/2021 to 09/02/2022) will be reported from the perspective of the participating observer [9].

The information for this study was mainly collected through the R&D partnership agreement, from the project's quarterly monitoring reports (report 1 – 09/02/2021 to 09/05/2021; report 2 – 10/05/2021 to 13/08/2021 and report 3 – 14/08/2021 to 30/11/2021), the perceptions of researchers, associate coordinators and the general coordination of the project.

3. Results & Analysis

The following seeks to describe the context of the project that started on 02/09/2021, the official date of signature of the R&D partnership agreement. Two UTFPR campuses participate in this project: the Ponta Grossa Campus (UTFPR-PG) and Curitiba Campus (UTFPR-CT). UTFPR is the public university with the most significant presence in the state of Paraná and the only technological university in Brazil. It has a multicampus structure, and Figure 1 shows its location in thirteen cities in the State of Paraná. Each campus maintains courses planned according to the needs of the region where it is located [10].

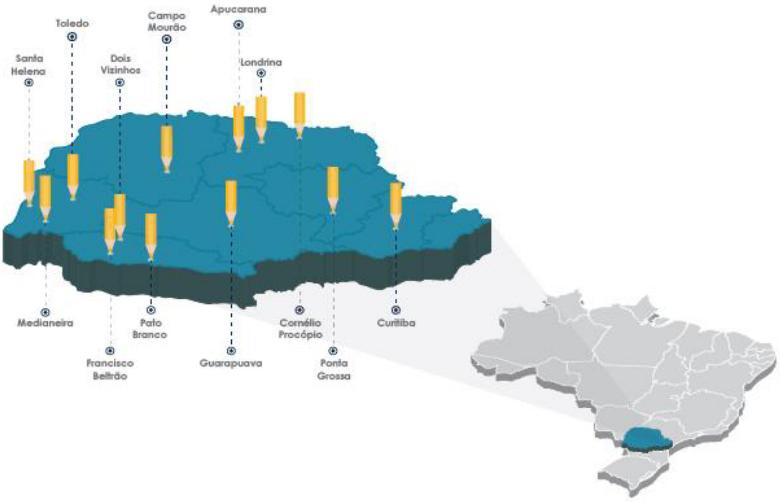

Figure 1. UTFPR multicampus structure.

The National Service for Industrial Learning of Paraná (SENAI/PR) operates in this project through three subsidiaries: the Senai Institute for Information and Communication Technology (IST), the Senai Institute for Innovation in Electrochemistry (ISI), and the Mobility Center Smart and Sustainable (CMSI). IST is located in Londrina, Paraná, where it provides services to industries across the country focused on the following topics: embedded systems (software and hardware); Internet of Things (IoT); industry 4.0; software engineering, and cyber security. ISI, located in Curitiba, provides services in batteries, smart coatings, and electrochemical sensors with a primary focus on industrial electrochemistry. The CMSI, also located in Curitiba, is the first center in the country and works to develop new technologies for the automotive industry and offer professional courses in this area [11].

As previously described, the project is part of the context of sustainable electric mobility with a national, intelligent technological solution, with connectivity and at an affordable price. One of the significant challenges for vehicular electrification is the battery pack and its management with strict monitoring and control of several parameters. Thus, Renault do Brasil SA, in partnership with Clarios Energy Solutions Brasil Ltda., UTFPR-PG, UTFPR-CT, and SENAI-PR intend to obtain a national technological solution that includes the development of a battery with a capacity of 25 kWh with a BMS to meet the energy demand of small vehicles, with a voltage between 250V to 300V and recharge DC 25 kW and AC 11 kW [1].

As shown in Figure 2, the development of this project was divided into six work packages between the institutions involved. At WBE-01, the Multiphysical Modeling and Simulation of the Battery Pack will be carried out. Conduct a simulation and modeling study of individual cells based on energy/power requirements, usage regime, and recharge rate; The work will be developed in the 3D&IA imaging laboratory located at UTFPR-CT. In this case, according to Table 1, one master's degree and two scientific initiation scholarships will be working.

The WBE-01 package includes the multiphysics battery simulation. Multiphysics modeling and simulation are fast becoming the necessary tools to develop, design, optimize and ensure the quality and safety of batteries during operation. Multiphysics is understood as the physical phenomena coupled with computer simulations. That is the study of multiple interacting physical properties. Considering batteries, mathematical models provide information about understanding physical mechanisms and simulating battery behavior under controlled conditions. It is necessary to survey the computational tools for multiphysics modeling applied to batteries. Check the mathematical models for applications in lithium-ion batteries by multiphysics simulation. Then, later apply the models to improve the thermal profile in a liquid-cooled lithium-ion battery by simulation and multiphysics modeling. It was planned to acquire a perpetual license for the three-dimensional finite element simulation software, a computational tool to perform multiphysics modeling and simulation.

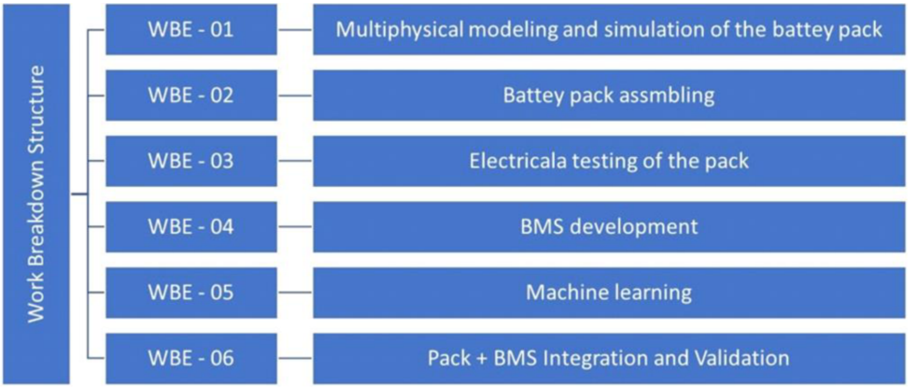

Figure 2. Work breakdown structure of the project with principal deliverables.

Table 1. Participants distributed across engineering and natural sciences disciplines.

Department	Discipline	P/S	PD	PhD	MD	SI	TS
Electrical Engineering (UTFPR-PG)	Electronic Engineering	1	1	-	1	6	-
Mechanical Engineering (UTFPR-CT)	Intelligent Manufacturing	1	-	2	-	3	-
Physics (UTFPR-CT)	Multiphysics Simulation	2	-	-	1	2	-
Chemical/TI/Smart Mobility (SENAI-PR)	Electrochemistry/TI/ Smart Mobility	4	-	-	-	-	3
Renault	Automotive	-	-	-	-	-	1
Clarios	Automotive	-	-	-	-	-	1

Note: P/S – Professor/Supervisor; PD – Postdoc. Researcher; Ph.D. – Ph.D. Student; MD – Master Degree Student; SI – Scientific Initiation Student; TS – Technical Specialist.

According to Table 1, 1 postdoctoral fellowship (PD), one master's fellowship (MD), and six scientific initiation fellowships (SI) were made available to UTFPR-PG. For UTFPR – CT, 2 Ph.D. fellowships (Ph.D.) and three scientific initiation fellowships (SI). For SENAI-PR, three fellowships for technical specialists (TS).

The WBE-02 package will assemble the battery pack. For this, it was planned to compare the different technologies of lithium-ion cells for application in the battery pack object of the project; Define the chemistry and geometry of cells; Determine capacity as a function of operating temperature and define the appropriate range during operation to meet safety requirements and pack life; Evaluate the need for cooling the pack and propose solutions if necessary; define the battery pack configuration, number of cells and groupings; Define and specify the housing of modules and the housing of the pack, geometry, size, weight, form factor; and mount the battery pack without the BMS.

The WBE-03 package provides for tests to be carried out at SENAI-PR according to current standards for electrical tests in lithium-ion battery packs under controlled conditions that involve the safety of cell operation, such as protection against overload, short circuit, thermal shock, high storage temperature, capacity, high-temperature discharge, low-temperature discharge, storage capacity, and shelf life. For this, it was planned to purchase a cycler for electrical tests in 25 kWh 1x200A lithium-ion battery packs to meet the high currents and voltages under current regulations, in addition to the acquisition of a fire-extinguishing safety chamber for tests with automatic explosion control if it occurs during electrical tests at controlled temperature.

The WBE-04 package includes the development of the BMS. This circuit is responsible for balancing the pack loads from individual measurements (voltage, current, and temperature) in each cell. For this to happen, the BMS has power electronic circuits dedicated to the charge and discharge control of the elements of the pack. These circuits are activated by the processing unit, which, using onboard control techniques, individually compensates for loads of each cell in the pack. The steps that make up the development of the BMS system are listed below: study and specification of commercial electronic components for the manufacture of BMS power circuits; the development of the electrical diagram of the BMS power circuit; the development of the stage layout of the BMS circuits; the assembly of the PCB of the power circuits of the BMS and the experimental tests with the BMS. The study and implementation of electronic instrumentation and data collection circuits for BMS systems applied to lithium-ion batteries will be carried out by the Laboratory of Computational Intelligence and Advanced Control (LICON) of UTFPR-PG in collaboration with the Laboratory of Electronics and Efficiency Energy from the Institute of Information and Communication Technology of SENAI-PR in Londrina.

The WBE-05 será developed by UTFPR-CT is composed of two sub-packages. One of them will seek to develop a car-to-cloud connectivity architecture focused on applying Machine Learning to identify packing failures. The other package will optimize the BTMS design parameters through machine learning algorithms. One of the most widespread techniques to support the design of a complex system is co-simulation, which allows the complete simulation of a product through the composition of one or more simulation components [12].

In the WBE-06 package, the last stage of the project, the battery pack will be connected to the BMS, and tests will be carried out to verify the functioning of all batteries. Thus, the following steps are performed: the connection between the battery and the BMS; operational testing of packaging with BMS; functional analysis and validation.

The total amount to be invested in the project by FUNDEP will be BRL 2,112,178.40 ($437,693.68 US Dollars, Quote on 23/03/2022 - BRL/USD - Brazilian Real / US Dollar) for the stages effectively carried out, in a total period of 24 months, referring to expenses with human resources (training and innovation grants), permanent materials and consumables. The total value of the R&D partnership agreement is BRL 3,124,782.74 ($647,529.42 US Dollars).

4. Discussion

Next, we seek to discuss the significant advances, challenges, and lessons learned during the first year of project execution. According to the report on the general coordination of the project, one of the first challenges faced at the beginning of the project was the registration and access to the project agreement system with the UTFPR Support Foundation (FUNTEF), which is the project manager accredited by the FUNDEP. There was a delay of almost two months to pass on the information for access to this system of agreements, and only from this registration the general coordinator will be able to start the payment of the scholarships and the purchase of equipment for the project.

Because this project is part of the portfolio of the first public notice of line V, launched by FUNDEP, being a development agency for this project, it was possible to perceive the low level of experience of FUNDEP in this type of program. A lot of information and procedures were changed during the execution of the project; the project execution system became available for use only four months after the beginning of the execution. Changes occur in the headings or interventions with each project, and the people are specific. However, FUNDEP responds very late to requests for changes, and these must be approved for implementation by FUNTEF, which directly impacts the execution schedule.

Another aspect highlighted by the general coordination of the project was that the delay in project activities might be due to their lack of experience in project management. Initially, many procedures were unknown to both FUNDEP and FUNTEF. The bureaucratic steps of people management also caused a delay at the beginning of the project. The issue of hiring grantees was an activity that abruptly affected the project's progress, and it is still challenging to find grantees in some categories, mainly scientific initiation, being difficult to keep them in the project or a high turnover. This may be related to the low financial incentive offered by the scholarship and the difficulty of reconciling studies and the project simultaneously.

As the project has advanced, difficulties related to the flow of information between the teams have been overcome. One of the critical points was establishing a weekly meeting coordinated by the company Renault for the follow-up of the activities carried out and the presentation of workshops on sensitive topics for the development of the project, bringing to light the premises for the beginning of the work. It is essential to highlight that the company representative is in direct contact with the researchers so that the factory experience, commercial contacts, and scientific research are walking together. Coordination between project groups and direct contact between Renault and other companies were facilitated, and the exchange of information between Renault Brasil, Renault France, and China subsidiaries.

From the simple analysis of the quarterly reports, it is impossible to say that the project develops homogeneously. The description of the activities of some teams is very succinct, and it is not possible to adequately evaluate the activities carried out and the results obtained with the participation of these teams. It is necessary to improve the interaction between the different work fronts, be they teaching and research institutions and partner companies.

During the workshops at the weekly meetings, the House of Quality matrix (HoQ) was developed with the quality requirements and design characteristics for designing the lithium-ion battery pack with BMS. This work was coordinated by the UTFPR-CT team and reviewed with the UTFPR-PG, SENAI-PR, Clarios, and Renault team members during the workshops.

The confirmation of the characteristics of the lithium-ion cells to be used in the project took place only in September/2022. There was great difficulty in obtaining an official quote (invoice/proforma) from the lithium-ion cell supplier located in China to accompany the bureaucratic purchase restrictions, which took place in February/2022. Due to the absence of lithium-ion cell suppliers in Brazil, this problem could be resolved through a representative in the country with an office to expedite the purchase process. The purchase order is expected to be processed in March/2022, and the lithium-ion cells, cycler, and test chamber will arrive in Brazil in April/2022.

During the coronavirus pandemic, exchange variation and difficulty in purchasing materials and equipment were observed due to the evolution of the scarcity of inputs, raw materials, and electronic components for the computer and electronics segment. The difficulty in accessing inputs is a problem for most companies in the sector. With the uncertainties generated by the conflict in the conflict between Ukraine and Russia that started in February/2022, this situation tends to worsen even more.

5. Conclusion

As the development of an R&D project is carried out cooperatively, it is expected that its results will contribute to the creation of technological innovations of interest to the automotive sector chain, in addition to contributing to the advancement of knowledge and the training of highly qualified human resources. Preliminary results show the importance of transdisciplinary work in leveling the team's knowledge about the product, in defining the target specifications through the application of the House of Quality (HoQ) tool, in the description of cellular chemistry, in the arrangement of modules and the development of the BMS.

As it is an area with constant technological advancement, there were difficulties for team members to find in the literature systems proposed for commercial electric vehicles, for example, details of battery sizing, cell configurations, the chemical composition used, in addition to details related to the BMS development both in terms of hardware and software. Still, additional studies may be needed to understand better the transdisciplinary approach's impact on battery pack design.

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