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# DEVELOPMENT OF THE PRODUCT STRUCTURE TREE OF A MODULAR MICRO-HYDROPOWER PLANT

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***Abstract.*** *Brazilian rural regions frequently experience issues with power outages since Brazil has a vast territory. The absence of electricity results in financial setbacks, particularly for agricultural industries that rely heavily on electrical power. Modular micro-hydropower plants (MMHP) provide an eco-friendly alternative to produce electricity when there are power interruptions. This paper aims to develop the product structure tree of an MMHP with a hydrostatic transmission, providing a hierarchical classification of its composing items. The hierarchical structure helps to establish the parts that can be embodied by off-the-shelf components. To achieve the paper's objective, the modules, assemblies, and parts of an MMHP are defined. The elements in the lowest level of the product structure tree that can be materialized by standardized components are identified and their costs are estimated. This way, a first estimate of the MMHP's manufacturing cost can be made. Besides the parts' cost, the Technology Readiness Level (TRL) and the number of parts that compose the modules and assemblies are established, helping to define the complexity of the MMHP design. The resulting product tree enables the design team to project an MMHP that truly presents the features of modularity and adaptability and is a step forward in the construction of a functional prototype.*

***Keywords:*** *micro-hydropower plant, product structure tree, modularity, hydrostatic transmission, renewable energy.*

## 1 INTRODUCTION

The Brazilian rural regions frequently experience issues with power outages since Brazil has a vast territory. The absence of electricity results in financial setbacks, particularly for agricultural industries that rely heavily on electrical power, like dairy farms, which require continuous cooling of milk and dairy products, or poultry and pig farms, which use fans and lamps for almost 24 hours a day to quickly grow the animals (Santos Junior and Sanches, 2020). Modular micro-hydropower plants (MMHPs) provide an eco-friendly alternative to produce electricity when there are power interruptions. Modularity reduces manufacturing and acquisition costs, as modular construction techniques enable the use of mass-produced parts (Offermans, 2004). Another key benefit of MMHPs is their adaptability to different rural properties, as they allow customization based on power demand and location.

One design tool that provides a foundation for modular design principles that facilitate the creation of interchangeable and easily replaceable modules is the product tree. The product tree showcases the product's composition structure. In the product tree, items are grouped into modules, assemblies, and/or sub-assemblies that make up the product. These elements are organized hierarchically at different levels. From the product tree, the concepts of parent elements and child elements are extracted. Child elements that cannot be broken down anymore are called parts and are necessarily purchased items (raw materials or commercial items) (Lustosa *et al.*, 2008; PPI, 2018).

This paper aims to develop the product structure tree of an MMHP being designed collaboratively by the Laboratory of Hardware (LHW), the Laboratory of Applied Robotics Raul Guenther (LAR), and the Laboratory of Hydraulic and Pneumatic Systems (LASHIP) from the Federal University of Santa Catarina (UFSC), and the Federal University of Ouro Preto (UFOP). A prototype of the MMHP is the final product of a project which ends in 2025. The MMHP will adhere

to the "do it yourself" culture, allowing the final user to easily assemble and maintain the plant, and the modularity will provide scalability to enable mass production.

The product tree provides a hierarchical classification of the MMHP's composing items. The hierarchical structure helps to establish the parts that can be embodied by off-the-shelf components and the assemblies that must be adjusted to meet diverse energy demands. To achieve the paper's objective, the modules, assemblies, and parts of a modular micro-hydropower plant are defined. The elements in the lowest level of the product structure tree that can be materialized by standardized components are identified and their costs are estimated. This way, a first estimate of the MMHP's manufacturing cost can be made. It must be highlighted that civil construction costs are neglected. Besides the parts' cost, the Technology Readiness Level (TRL) and the number of parts that compose the modules and assemblies are established, helping to define the complexity of the MMHP design.

The remainder of this paper is structured as follows. Sec. 2 defines micro-hydropower plants and presents their main components. Sec. 3 details the MMHP's product structure tree. Finally, Sec. 4 draws some conclusions.

## 2 MICRO-HYDROPOWER PLANTS

The Agência Nacional de Energia Elétrica (ANEEL) defines small hydropower plants (SHPs) as enterprises dedicated to self-production or independent power generation, that generate more than 3 MW and less than 30 MW (ANEEL, 2023). Micro hydropower plants (MHPs) are a class of SHP that can generate power up to 100 kW while operating with a hydraulic head of up to 50 meters (Eletrobras, 2019). One significant advantage of MHPs is that they can be installed in remote areas where centralized power supply is unavailable, presenting a viable solution in areas with limited electricity options (Azimov and Avezova, 2022). An MHP is composed mainly of the water conveyance (the pipeline that delivers the water to the turbine); the turbine (a device that converts the kinetic energy of the flowing water into rotational energy); the electricity generator (a device that transforms the rotational energy into electricity); and the wiring that delivers the electricity (USDOE, 2012).

Usually, there is a transmission system connecting the turbine to the electricity generator to transmit and adjust the rotational speed between the turbine and the generator. The most common transmission systems found in MHPs are "V" or wedge belts and pulleys, timing belts and sprocket pulleys, and gearboxes. These technologies present some disadvantages. Despite their modest construction costs, systems of belts and pulleys are not as efficient as gearboxes. However, gearboxes have higher costs associated with maintenance and alignment (Kunwor, 2012).

A suitable candidate for connecting the turbine to the electricity generator is a hydrostatic transmission, as it does not require extensive infrastructure and can be built using standardized components, aligning well with modular design principles. A hydrostatic transmission converts the mechanical energy, derived from the turbine's torque and angular velocity, into oil-hydraulic energy. This conversion is achieved using a compact hydraulic pump conveniently installed within the turbine. The resulting fluid energy, characterized by the product of flow and pressure, can be transmitted through pipes and hoses to a designated location for the electric generator. Subsequently, with the aid of a suitable hydraulic motor, this energy is transformed back into mechanical energy, driving the electric generator at a controlled speed through the utilization of control elements integrated within the oil-hydraulic system (Costa and Sepehri, 2015; Souza *et al.*, 2023). Therefore, the MMHP whose product tree is described in this paper has a hydrostatic transmission connecting the turbine to the generator.

The most innovative contribution of the project of an MMHP executed by the partnership LHW-LAR-LASHIP (UFSC) and UFOP is the use of a hydrostatic transmission to adjust the speed variations of the turbine, as hydrostatic transmissions are practically unseen in hydropower plants (Souza *et al.*, 2023). As a result, the module corresponding to the hydrostatic transmission is the technology that is the most detailed in the product tree of this paper.

## 3 PRODUCT STRUCTURE TREE

The product tree presented in this paper has four levels: final product, modules, assemblies, and parts. Before introducing the product tree, some considerations about the data contained in the product tree's building blocks must be made. Fig. 1(a) shows the block of the hydrostatic motor, a part composing the hydrostatic transmission module of the MMHP, to detail the data contained in each block. The datum designated by 1 in the top right corner of the block shown in Fig. 1(a) corresponds to the number of parts that compose the final product/module/assembly. When the block designates a part, the number at the top-right corner indicates the amount of the respective part that a given assembly/module contains. For example, considering the block shown in Fig. 1(a), the hydrostatic transmission module contains one hydrostatic motor with a displacement of 16 cc/min.

The datum designated by 2 in the bottom left corner of the block shown in Fig. 1(a) corresponds to the estimated cost of the part / assembly / module in July 2023. When the block is a part, the value corresponds to the unit cost. However, if the block identifies an assembly, a module, or the final product, the value corresponds to the sum of the costs of all the parts composing the parent element. For example, according to Fig. 1(a), one hydrostatic motor costs R$ 980,00.

Number 3 in Fig. 1(a) indicates the expected TRL, which is a tool for estimating the maturity level of a technology.
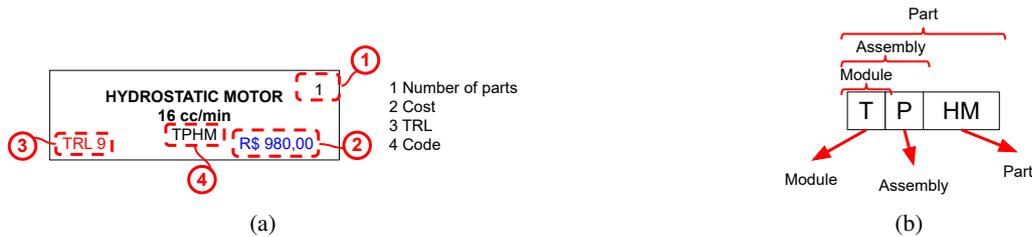
Figure 1. (a) Information contained in a given block of the product structure tree and (b) diagram explaining the blocks' code

This tool divides the technology life cycle into levels and categorizes the technology according to a definition and a description of each level, that depends on the institution that establishes them (Mavignier, 2022). TRLs are based on a scale from 1 to 9, with 9 being the most mature technology. In this paper, the TRL scale defined by the European Commission is adopted (European Commission, 2014), which is shown in Tab. 1.

Table 1. TRL scale defined by the European Commission (European Commission, 2014).

| TRL | Description | TRL | Description |
|---|---|---|---|
| 1 | Basic principles observed | 6 | Technology demonstrated in relevant environment |
| 2 | Technology concept formulated | 7 | System prototype demonstration in operational environment |
| 3 | Experimental proof of concept | 8 | System complete and qualified |
| 4 | Technology validated in lab | 9 | Actual system proven in operational environment |
| 5 | Technology validated in relevant environment | | |

Finally, the datum indicated by 4 in Fig. 1(a) corresponds to the block's code. Fig. 1(b) contains a diagram to aid to describe the code, referring to the hydrostatic motor composing the hydrostatic transmission. A module's code consists of a single letter. An assembly's code is composed of two letters: the first one indicates the module to which the assembly belongs, while the second one specifies the assembly.

A part's code contains four letters: the first letter designates the module, the second letter establishes the assembly containing the part, and the last two letters specify the part. For instance, the code of the part "hydrostatic motor" is TPHM, as shown in Fig. 1(b). T stands for the "hydrostatic transmission" module; P stands for the "power conversion elements" assembly, while HM stands for the part "hydrostatic motor".

The product tree of the MMHP considered in this paper is shown in Fig. 2 until the modules' level. The MMHP corresponds to the top block, which represents the final product that is decomposed in the product tree. The MMHP's block informs the number of parts composing the MMHP, its expected final cost, and its TRL. The MMHP has 52 parts and will have an estimated final cost of R\$ 50.882,44. The MMHP has TRL 3 as it is still in the design phase and no prototype has been built yet, so the integrated components still need proof of concept.
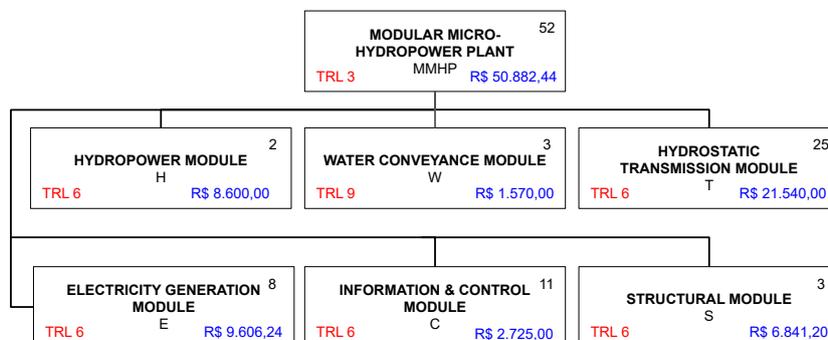


Figure 2. Product structure tree of the MMHP until the modules' levels.

The MMHP consists of six modules: "Hydropower" module, "Water Conveyance" module, "Hydrostatic Transmission" module, "Electricity Generation" module, "Information & Control" module, and "Structural" module. Each module is detailed in the following sections.

## 3.1 Hydropower module

In the MMHP system, it is planned to integrate a commercially available low-head turbine along with an electricity generator and a hydrostatic transmission. Illustrated in Fig. 3(a), there is a segment of the product tree specifically focusing on the "Hydropower" module, specifically up to the parts level. This module comprises two key components, two assemblies namely a flow machine and a flow controller. The projected cost for the hydropower module is R$ 8,600.00, while the anticipated TRL is 8.

The assembly of the flow machine elements in Fig. 3(a) includes one of the main components of the MMHP: the turbine. The turbine works to harness the kinetic energy of the flowing fluid and convert it into mechanical energy, which can then be further converted into electrical energy through the generator, creating an alternative and/or emergency source in case of supply problems in the main power grid. The estimated cost for this assembly amounts to R$ 7,000.00, while the TRL is rated at 8. Other parts will be included in the assembly "Flow Machine Elements" in the future, such as specific valves, when the MMHP concept is more mature and the turbine type, e.g. Kaplan or Pelton, is selected.

The assembly "Flow Controller" is valued at around R$ 1.600,00 and consists of the part "Distributor". The goal of the distributor in an MMHP turbine system is to achieve uniform flow distribution and load sharing among the turbine blades. By controlling the flow rate and ensuring proper distribution, the system can operate efficiently and effectively across all modules, maximizing power generation, and minimizing potential issues such as uneven stresses or power imbalances for generating electricity from small waterfalls. The assembly "Flow Controller" will have more parts in the future, such as some guide vanes or wicket gates, when the turbine type is defined.

Note that commercially available technologies were considered for the parts, such as low head turbine e.g. Kaplan bulb turbine of TRL-8 for MMHP applications in rural properties.

## 3.2 Water conveyance module

Figure 3(b) depicts the "Water Conveyance" module up to the parts level. This module comprises two assemblies, namely the "Storage Unit" and "Conduit Set," along with three individual parts. Together, these components ensure a controlled and efficient flow of water from the intake structure to the turbine, maximizing the power generation potential of the MMHP. The estimated cost for this module is approximately R$ 1.570,00, and it is expected to achieve a TRL of 9, as the system's flow rate is being sized to accommodate commercial pipe diameters.
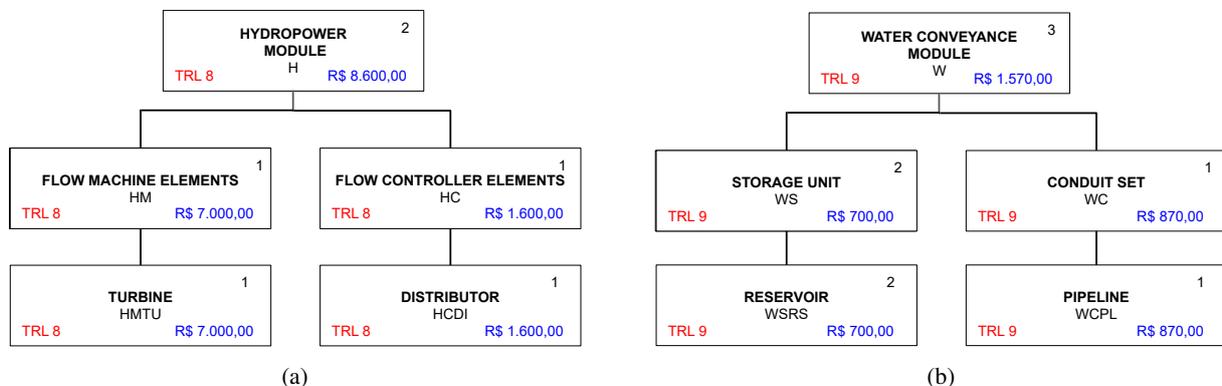


Figure 3. (a) "Hydropower" and (b) "Water Conveyance" modules.

The assembly of the storage units comprises two parts, consisting of direct and indirect reservoirs, as illustrated in Fig. 3(b). These reservoirs serve the purpose of storing water for subsequent utilization in power generation. The storage unit enables the regulation and control of water flow, ensuring a continuous and reliable water supply to the turbine. Each reservoir has been designed with a volume capacity of 1000 liters. The TRL for these storage units is 9, indicating their advanced stage of development and readiness for deployment. More parts, such as valves and pumps, will be added to the "Storage Unit" assembly when the design of the MMHP concept becomes more detailed.

The last assembly of the "Water Conveyance" module encompasses the pipeline. The distribution system in a modular MHP plays a role in delivering water from the water source to the turbine, where the energy conversion takes place. For now, it is estimated that the whole pipeline will cost R$ 1.800,00. Subsequently, other parts will be included in the "Conduit Set" assembly, such as some valves.

## 3.3 Hydrostatic transmission module

Figure 4 shows the portion of the product tree related to the "Hydrostatic Transmission" module, until the assemblies' level. The estimated cost of the hydrostatic transmission is R$ 21.540,00 and the expected TRL is 6, as the hydrostatic

transmission is being designed from scratch and it is planned that the prototype will be demonstrated in a relevant environment at the end of the project. The hydrostatic transmission is composed of 25 parts, which are distributed among four assemblies.
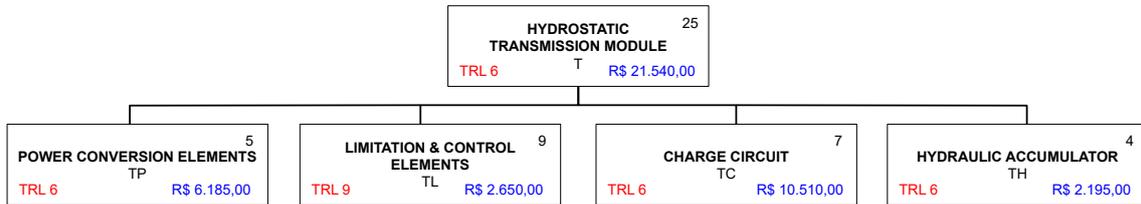


Figure 4. "Hydrostatic Transmission" module until the assemblies level.

The assembly "Power Conversion Elements" consists of the parts that convert the mechanical energy from rotating shafts into hydraulic energy and vice-versa. This assembly is valued at approximately R$ 6.185,00 and is composed of three hydrostatic pumps, one hydrostatic motor, and hydraulic fluid. The hydrostatic pumps convert the mechanical energy from the turbine's rotating shaft into hydraulic energy, which is transported by the hydraulic fluid to the hydrostatic motor. The hydrostatic motor converts the hydraulic energy into mechanical energy, rotating the shaft of the generator of the MMHP (Costa and Sepehri, 2015). The product tree's section referring to the "Power Conversion Elements" assembly is shown in Fig. 5.
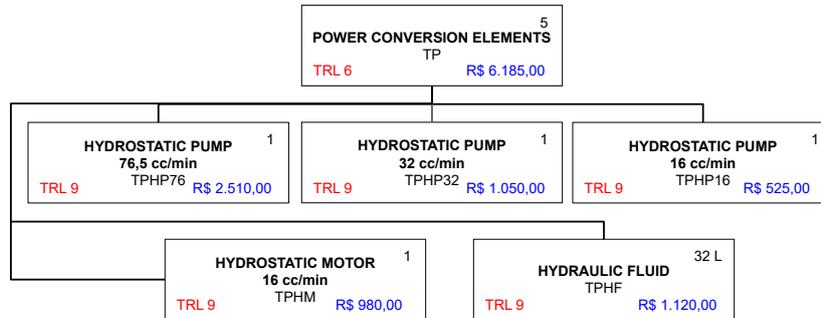


Figure 5. "Power Conversion Elements" assembly and its composing parts.

The hydrostatic pumps and the hydrostatic motor have fixed displacement. Each hydrostatic pump has a different displacement, which is indicated in its code. The hydrostatic pump TPHP76 has a displacement of 76,5 cc/min, while TPHP32 has a displacement of 32 cc/min. TPHP16 is the pump with the smallest displacement, corresponding to 16 cc/min. Since the hydrostatic transmission has only one motor, the part TPHM does not present its displacement of 16 cc/min in its code.

In the top right corner of the block of the part "hydraulic fluid", there is the expected volume of hydraulic fluid required for the hydrostatic transmission operation: 32 L. 8 L of hydraulic fluid flows in the hydraulic circuit, while the accumulator contains 24 L. The hydraulic fluid TPHF costs R$ 35,00/L, totaling R$ 1.120,00.

The assembly "Limitation & Control Elements" is valued at around R$ 2.650,00 and consists of some valves that regulate the fluid circulation on the main hydraulic circuit of the transmission, which is shown in Fig. 6(a). The hydrostatic transmission conception of Fig. 6(a) is proposed by Bolaños *et al.* (2023), which used the frugal innovation approach to generate a new conception of hydrostatic transmission that presents a compromise among cost, complexity, efficiency, and performance.
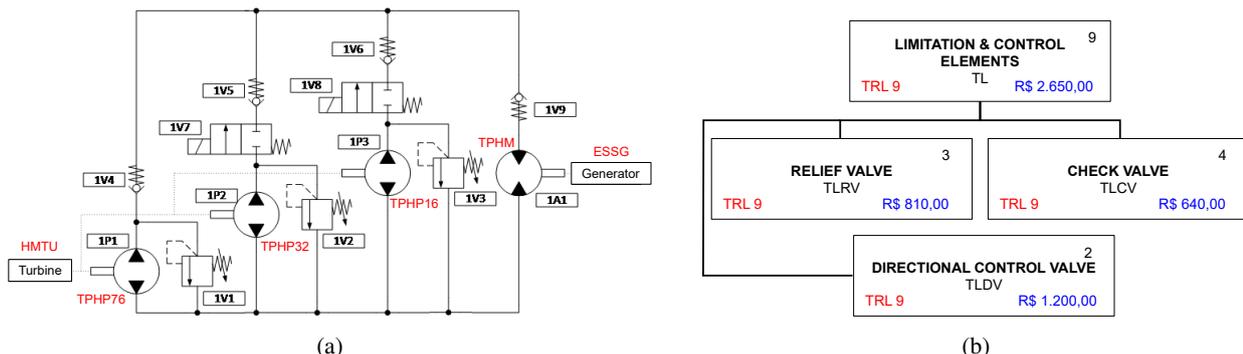


(a)                                     (b)

Figure 6. (a) Main hydraulic circuit of the hydrostatic transmission and (b) "Limitation & Control Elements" assembly.

The turbine, the generator, the hydrostatic pumps, and the hydrostatic motor are labeled with their product tree codes in Fig. 6(a). The three pumps are connected to the turbine HMTU via a mechanical transmission, such as a system of pulleys and belts, and are the input of the hydrostatic transmission. TPHM is the output of the hydrostatic transmission and is connected to the synchronous generator. The hydrostatic transmission keeps the rotor of the synchronous generator rotating within a narrow range around the rated frequency of 60 Hz by activating and/or deactivating TPHP32 and TPHP16 via two 2/2 directional control valves (on-off valves). TPHP76 is always running, while TPHP32 and TPHP16 operate when an adjustment of the speed ratio is needed.

From Fig. 6(a) and the portion of the product tree corresponding to the assembly "Limitation & Control Elements", shown in Fig. 6(b), it can be seen that the assembly's parts consist of three types of valves: relief valves, check valves, and directional control valves.

There are three relief valves TLRV to relieve the pressure in high-pressure conduits connected to the pumps. Each relief valve TLRV is priced at R$ 270,00, so the set of relief valves composing the hydraulic circuit shown in Fig. 6(a) costs R$ 810,00. With a total cost of R$ 640,00, four check valves TLCV control the fluid direction, by allowing its passage in only one direction. Finally, two 2/2 directional control valves TLDV, costing R$ 600,00 each, control the activation of the pumps TPHP32 and TPHP16 by allowing or preventing the fluid flows to the pumps.

The third assembly corresponds to the charge circuit of the hydrostatic transmission, responsible for replenishing the fluid lost through leakages (Costa and Sepehri, 2015). The charge circuit is valued at R$ 10.510,00, almost half of the total cost of the "Hydrostatic Transmission" module. The portion of the product tree corresponding to the "Charge Circuit" assembly is shown in Fig. 7.
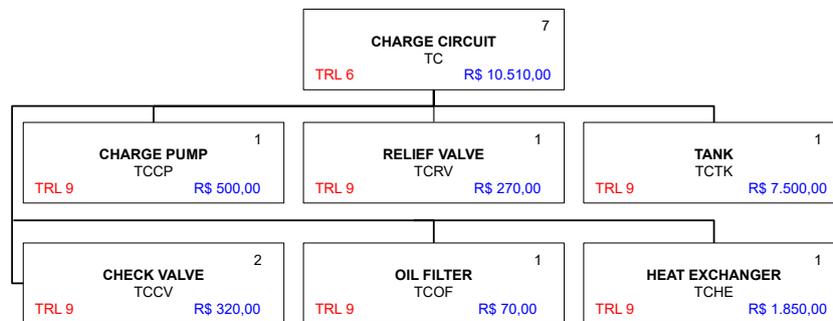


Figure 7. "Charge Circuit" assembly and its composing parts.

The charge circuit is composed of seven parts: a charge pump, a relief valve, an oil tank, two check valves, an oil filter, and a heat exchanger. As the pumps belonging to the "Power Conversion Elements" assembly, the charge pump TCCP is connected to the mechanical transmission that links the turbine to the hydrostatic transmission. The estimated cost of the charge pump is R$500,00. The relief valve TCRV limits the charge pressure and costs around R$ 270,00. The check valves TCCV are priced at R$ 320,00 and prevent the fluid in the main circuit from flowing back to the tank TCTK, which costs around R$ 7.500,00. It can be noted that the main responsible for the high cost of the "Charge Circuit" assembly is the tank's price. Therefore, a more affordable tank must be sought. The oil filter TCOF, which costs approximately R$ 70,00, is placed between the charge pump TCCP and the tank TCTK to filter out any impurity of the replenishing fluid. The heat exchanger TCHE dissipates the heat generated due to the fluid viscosity and carries a price of around R$ 1.850,00.

Finally, the last assembly composing the "Hydrostatic Transmission" module is the "Hydraulic Accumulator" assembly, which amounts around R$ 2.195,00. The hydraulic accumulator consists of four parts: three valves and one accumulator, as indicated by the section of the product tree of the "Hydraulic Accumulator" assembly, shown in Fig. 8.
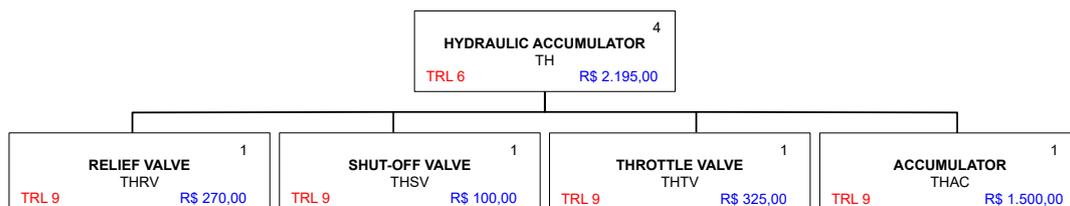


Figure 8. "Hydraulic Accumulator" assembly and its composing parts.

The relief valve THRV limits the maximum pressure inside the accumulator THAC and costs R$ 270,00. The shut-off valve THSV connects THAC to the main hydraulic circuit shown in Fig. 6, with a price of R$ 100,00. The throttle valve THTV discharges THAC to the tank TCTK in case of an emergency and has an approximate cost of R$ 325,00. THAC has an approximate price of R$ 1.500,00, corresponding to almost 70% of the total cost of its assembly.

Note that all parts composing the hydrostatic transmission have TRL 9. The parts have the highest TRL as they are commercial products that have been proven in an operational environment by their manufacturers and their users. With the exception of assembly "Limitation & Control Elements", which has TRL 9, the assemblies composing the "Hydrostatic Transmission" module have TRL 6, as the prototype will be demonstrated in a relevant environment by the project's conclusion.

## 3.4 Electricity generation module

Figure 9 illustrates the section of the product tree associated with the "Electricity Generation" module, up to the part level of the assembly "Electric Conversion Elements". This module includes the assemblies of "Electric Conversion Elements", "Electrical Components", and "Circuit Breaker Security" items. It consists of a total of 8 items, with an estimated value of R$ 10.476,24. The expected TRL for this module is 8.
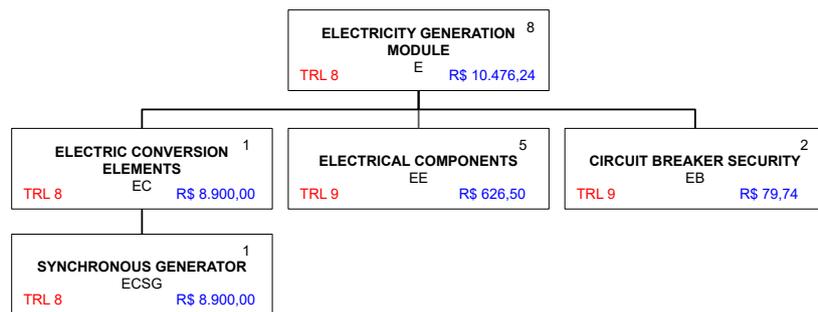


Figure 9. "Electricity Generation" module.

The assembly of the electric conversion elements encompasses the synchronous generator ECSG, which is coupled with the hydrostatic motor of the hydrostatic transmission and converts the mechanical energy from the turbine into electrical energy. It operates based on the principle of electromagnetic induction, where the rotating shaft of the hydrostatic motor drives a magnetic field inside the generator. ECSG produces a nominal power of 3 kVA and amounts to around R$ 8.900,00. Note that the ECSG is the most expensive part of the "Electricity Generation" module, corresponding to around 85% of the total cost of the module.

The second assembly corresponds to the electrical components of the MMHP and its corresponding portion of the product tree is shown in Fig. 10, which encompasses 5 parts: a rectifier, an electric distribution board, a contactor, and lastly, a power switch. The estimated cost of the "Electrical Components" assembly is R$ 626,50.
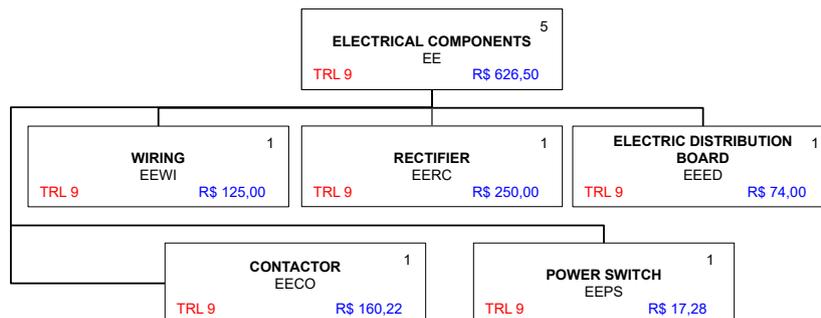


Figure 10. "Electric Components" assembly until the parts level.

The electrical components of the MMHP monitor and regulate its operation. Their assembly includes various components such as sensors, controllers, and protective devices to ensure safe and efficient operation. The control system helps manage the power output, maintain system stability, and protect against overloads or malfunctions.

In the context of a modular micro-hydropower plant, the electrical system encompasses several essential components. Wiring serves as the crucial conduit for facilitating the smooth flow of electrical current between various electrical components. Its estimated cost in the MMHP is R$ 125,00. A rectifier costs around R$ 250,00 and assumes a pivotal role by converting the alternating current (AC) generated by the hydropower turbine into the direct current (DC) necessary for the system's operation. The electric distribution board acts as a centralized control and distribution hub, enabling efficient power allocation to different loads within the plant. Its cost is estimated at R$ 74,00. Contactor units are responsible for regulating and controlling the precise flow of electrical current to specific loads, ensuring optimal performance. A contactor unit is valued at R$ 160,22. Furthermore, the power switch, a manually operated electrical switch, offers the convenience of complete power interruption to specific sections or the entire micro-hydropower plant. This feature is

invaluable for maintenance, repairs, or emergency situations, providing a reliable means to isolate the power supply as needed. The estimated cost of a power switch is R$ 17,28.

Figure 11 includes the assembly for the "Circuit Breaker Security" down to the individual parts level. This assembly comprises two components: an emergency stop button, which disables the machine's control, and a residual current circuit breaker for additional security. Circuit breakers are critical components in electrical systems as they provide protection against excessive current, which can cause damage to wiring, appliances, and electrical devices. They play a crucial role in preventing electrical fires, reducing the risk of electrocution, and ensuring the safe and reliable operation of electrical systems. The estimated costs for the emergency button and the residual current circuit breaker are approximately R$ 35,00 and R$ 44,74, respectively. Within an MMHP system, the circuit breaker security module ensures reliable and secure operation.
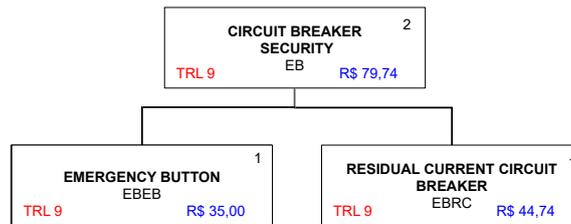


Figure 11. "Circuit Breaker Security" assembly till the parts level.

Note that this particular assembly is the most affordable option within the product tree, with a total cost of R$ 79.74. Additionally, each of the components within this assembly demonstrates a high TRL of 9, indicating their advanced development stage. As a result, they are ready for implementation in real-world emergency situations, allowing for precise measurement and automatic circuit disconnection in the event of a fault or when the current exceeds the designated sensitivity.

### 3.5 Information & control module

Figure 12 shows the three main divisions needed for the "Information & Control" module. This module focuses on the systems that are responsible for collecting, monitoring, and controlling various parameters and processes within the MMHP. It serves as the central hub for data acquisition, processing, and decision-making to ensure efficient and safe operation. Consists of a total of eight parts, costs roughly R$ 2.725,00, and the expected TRL is 6, as the MMHP prototype will be tested under conditions closely resembling an application in a rural property.
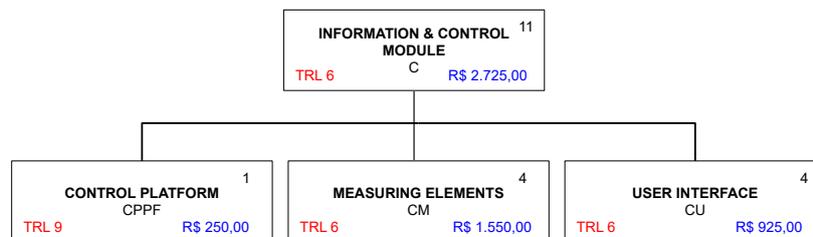


Figure 12. "Information & Control" module.

The part "Control Platform", utilizing technologies such as Arduino or ESP, aims to interface with electronic components, sensors, and actuators, to control and automate the MMHP operation through programming. The "Control Platform", with an expected TRL of 4, will be subjected to laboratory-based validations. However, further testing and refinement will be necessary to enhance its functionality at the end of the project. The estimated cost of approximately R$ 250,00 reflects the investment required for its acquisition.

The assembly "Measuring Elements", shown in Fig. 13(a), ensures accurate data acquisition and precise monitoring of essential variables for efficient and safe operation. The "Measuring Elements" assembly involves four parts: flow sensors, rotational speed sensors, pressure sensors, and torque sensors, each exhibiting a TRL of 9. Flow sensors are placed within the pipeline or the turbine inlet pipe to measure the rate of water flow entering the turbine. Rotational speed sensors are installed near the turbine's shaft and the generator's shaft to measure the rotational speed of these components. This information is essential for assessing the turbine's performance and determining the electrical output of the generator. Pressure sensors are positioned within the pipeline to monitor and measure the pressure levels, allowing for the detection of any abnormalities or inefficiencies within the system. Lastly, the torque sensor measures the torque applied to the turbine or generator shaft, enabling the assessment of mechanical stress and ensuring optimal power transmission.

The estimated costs for flow sensors, rotational speed sensors, pressure sensors, and torque sensors are approximately R$ 50,00, R$ 600,00, R$ 300,00, and R$ 600,00, respectively. The rotational speed sensors and the torque sensors
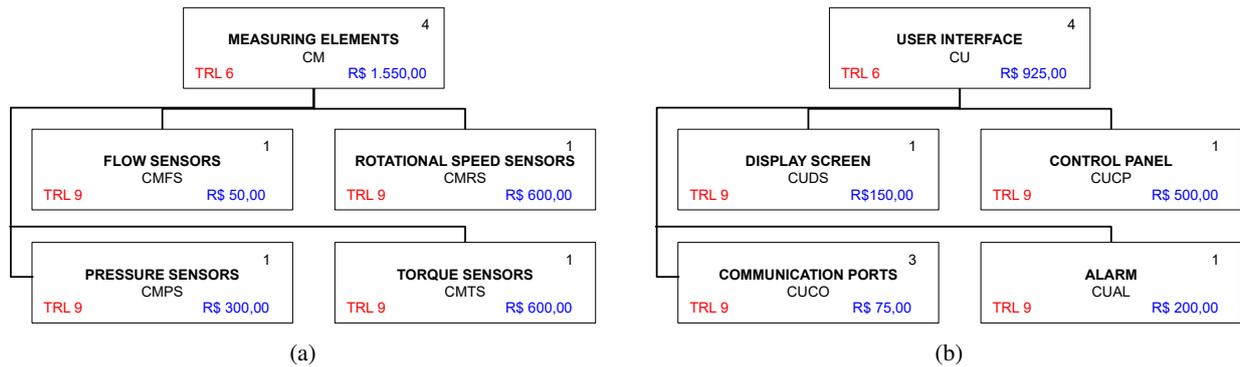
Figure 13. (a) "Measuring Elements" and (b) "User Interface" assembly.

contribute to almost 80% of the total cost of the "Measuring Elements" assembly.

The "User Interface" (CU) assembly, whose portion of the product tree is shown in Fig. 13(b), includes four parts. The display screen, the control panels, the communication ports, and the alarm each exhibit a TRL of 9. The display screen provides information to the operator, allowing him or her to monitor and assess the MMHP performance. Control panels, consisting of switches, buttons, and knobs, serve as the interface for controlling and configuring the operation of the MMHP. Communication ports enable the plant to connect with external devices or systems, facilitating data exchange and integration with broader power management systems. The alarm provides alerts to indicate abnormal or critical conditions of the MMHP that require immediate attention.

The estimated costs for the display screen, the control panels, the communication ports, and the alarm are approximately R$ 150.00, R$ 500.00, R$ 75.00 (for three ports), and R$ 200.00, respectively. In terms of cost analysis, the control panel emerges as a significant component, accounting for approximately half of the overall cost of the user interface. This emphasizes the importance of investing in the development and optimization of control panel design and functionality to ensure efficient operation and user-friendly control of the MMHP.

### 3.6 Structural module

The "Structural" module, shown in Fig. 14, maintains the stability and integrity of the MMHP. It consists of two assemblies: "Support Beams" and "Bracing Elements". Support beams are structural elements that bear the weight of various components, such as reservoirs, and provide support to the overall structure of the MMHP. Bracing elements are components that unite the support beams and provide additional support and stability to the structure. They help distribute loads, resist lateral forces, and prevent excessive movement or deformation.
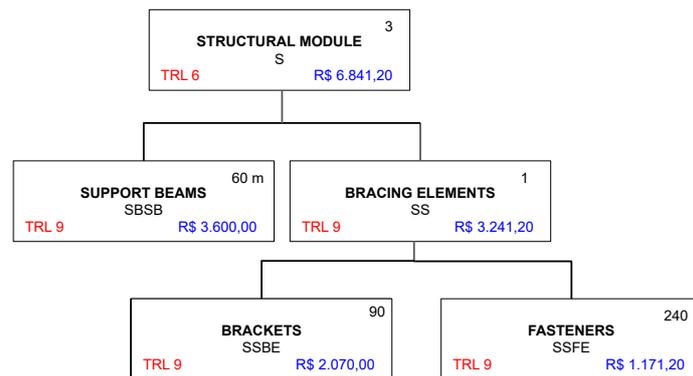


Figure 14. "Structural" module.

The "Support Beams" assembly exhibit a TRL of 9 and an estimated cost of R$60 per meter. With 60 meters of beams, the total cost amounts to R$3.600,00. The bracing elements are composed of brackets and fasteners. The project consists of 90 brackets valued at about R$23,00, totalizing R$2.070,00, and 240 fasteners, each costing R$4,88, totalizing R$1.171,20. The total amount of both bracing elements comes to R$3.241,20.

### 4 CONCLUSIONS

This paper describes the product structure tree of an MMHP containing a hydrostatic transmission connecting the turbine to the generator to transmit and adjust the rotational speed between their rotary shafts. The MMHP is composed of 52 parts, distributed among six modules and 16 assemblies. For now, the most complex module is the "Hydrostatic

Transmission" module, as it comprises almost half of all parts constituting the MMHP. As the project advances, it is expected that the remaining modules become as complex as the "Hydrostatic Transmission" module due to the inclusion of other parts. The complexity of the "Hydrostatic Transmission" module reflects in its cost, as it is the most expensive module composing the MMHP. The cost of the hydrostatic transmission corresponds to almost 42% of the total cost of the MMHP. Thus, the efforts to minimize the cost of the MMHP should be concentrated in this module.

The resulting product structure tree enables the design team to project a MHP that truly presents the features of modularity and adaptability and is a step forward in the construction of a functional prototype. By utilizing the product structure tree approach, the MMHP can be tailored to meet the specific needs of rural properties and their power demands, making them a flexible and eco-friendly energy solution. Future works include expanding the assemblies with a single part, such as the "Flow Machine" and "Flow Controller" assemblies; searching for more affordable parts; and building and testing a prototype.

## 5  ACKNOWLEDGEMENTS

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## 7  RESPONSIBILITY NOTICE

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