Powerful Advanced N-Level Digital Architecture
for models of electrified vehicles and their components

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Publishable Executive Summary

This deliverable aims to highlight the main outputs and outcomes of the PANDA project.

Firstly, a task force in PANDA has assessed the impact of the PANDA methodology on the reduction of the development times of electrified vehicles and their components. Based on the RTR experience with designing vehicles for mass production, a realistic scenario has been established for developing a completely new vehicle. The chosen scenario is in line with the RTR process, but it is not identical to keep the real development process at RTR confidential. When applying the knowledge from the PANDA industrial partners and the results from the PANDA project, the analysis shows that the lead-time of a new vehicle development can be reduced by up to 25%, given a number of assumptions and by using the PANDA methodology during all development phases. Please note that this potential gain is an estimation based on a specific reference case, and the related assumptions. The actual gain will vary for each use case, but the analysis shows that the potential benefit of using the PANDA approach can very high.

Secondly, the PANDA methodology can give a valuable perspective in the ongoing discussion is on the standardisation of I/Os of the models of electrified vehicles and components. In a number of H2020 projects interest has been expressed in strictly defining inputs and outputs of models. In PANDA, I/Os are defined according to the physical causality that lead to a seamless interconnection of virtual models, but also to a valuable organisation of the HIL testing including power interfaces. The EMR formalism has been used as a standard organization of the models to respect this natural causality, to highlight the power flows between subsystems, and to systematically deduce control organization of the different vehicles. The involvement of PANDA members in standard committees would be a valuable supplementary outcome of the project.

Thirdly, as the PANDA methodology is a disruptive model organization, training programmes are needed to educate future engineers. Since 2000, University of Lille has developed training programmes at Master and PhD level. More and more universities worldwide are now teaching EMR. The PANDA results will surely be an added value in the dissemination of the EMR formalism thanks to the impressive results obtained by the industrial study cases. Moreover, the PANDA partners have contributed to the annual international EMR summer school, increasing both the PANDA visibility as well as the EMR summer school visibility. The dissemination of the PANDA methodology will continue in these national and international education programmes. Please note that the 25% reduction in the lead-time of a new vehicle includes the extra time that is needed for training in the PANDA methodology. So whilst the additional education costs time, the benefits greatly outweigh the costs.

Finally, a carbon care action has been developed in PANDA to evaluate the environmental impact, and mitigate the GHG emission of the project. The perimeters have been clearly defined, and a carbon care methodology has been extended from previous experience of University of Lille. All PANDA activities have been considered, from the travels and meetings to the experimental tests and desk work (including commuting, videoconference, etc.). The total GHG emissions have been estimated at about 210 CO_2eq tons. A mitigation project in Romania (planting trees) has been selected to make PANDA into a carbon neutral project.

Contents

1. Introduction

The objective of PANDA is to provide a disruptive and open-access model organization for an easy interconnection and exchange of models in the development process of EVs aiming at reducing the time to market by 20%, thanks to advanced methods [PANDA 2020]. Indeed, within the W-model process of product development, two testing stages occur, the virtual testing stage which needs off-line simulation, and the real testing stage which needs real time simulation. Within the PANDA project, a unified model organisation is developed for both stages [PANDA D1.3] based on the EMR (Energetic Macroscopic Representation) formalism [Bouscayrol 2012]. This report aims to summarize the different outputs of the H2020 PANDA Project.

First, an analysis of lead-time and time-to-market's gain in the development of new vehicles thanks to the PANDA methodology is proposed. In the last months of the project, a task force has been organized to propose an analysis based on the industrial experiences and feedbacks.

In the second part, the need for a model organization is discussed from the PANDA methodology but also from other H2020 projects that were also focused on the simulation of electrified vehicles.

The third part is dedicated to the training of the PANDA methodology. The experiences of the academic partners, but also of the PANDA consortium are presented. The perspective to train future engineers are then discussed.

The last part deals with the PANDA carbon care action. All the greenhouse gas (GHG) emissions related to the PANDA project have been estimated. A specific planting action is proposed to mitigate these negative outputs.

2. Impact of PANDA on lead-time

This section is the results of the "Impact Analysis" task force of PANDA, which has conducted an in-depth analysis of the development of electrified vehicles and their components. The task force was composed of all industrial partners of PANDA (RTR, SISW, TY, VEEM, TUV-BT, Bluways, UNR) and the scientific coordinator (ULille). For confidentiality reasons, only general concepts are proposed in this section even though real figures of the development phases have been discussed within the task force.

In order to support a 40% cut of greenhouse gases by 2030 expected from road transport EU policy, vehicles must undergo important transformations. This aspect puts a high pressure on automotive industry that must develop new technologies for the market that compete with existing mature technologies. New vehicles must be able to offer the same performances in terms of comfort, driving pleasure, autonomy and reliability by emitting significant less greenhouse gases and pollutant emissions. One of the technical solutions that already arrived on the market is the use of electrical energy for vehicle propulsion.
So, today we have on the market: battery electric vehicles (BEV), fuel cell vehicles (FCV) and hybrid electric vehicles (HEV) as globally named electrified vehicles (EV). Even if the existing technology on these vehicles is not quite new, the technology is in a continuous evolution as it is still behind the existing technology on internal combustion engine vehicles (ICE vehicles) in terms of comfort, autonomy, and costs. This continuous evolution of the technology, the market competition and regulations' pressure push the automotive industry to develop new products and to put them on the market at a high speed.
In this context, PANDA project comes with innovative solutions that help automotive system developers and vehicle developers to speed up the development of their products and to optimize costs of development. PANDA project has focused its innovative proposals on simulation tools and on the combination of simulations with physical tests to provide powerful solutions for reducing the lead time of electrical systems and electrified vehicles. The lead time is the pure development time of a new vehicle, excluding the pre-business study and the production plant validation from the time to market.

The target of these solutions is to modify the V-shape of the development process of an industrial product in a W-shape model (Figure 1). The main idea is to maximize the virtual testing using an innovative simulation architecture in an open general framework for virtual and real testing of the products. Solutions developed also include the use of the cloud computing technology that is integrated in simulations organisation and in real tests.

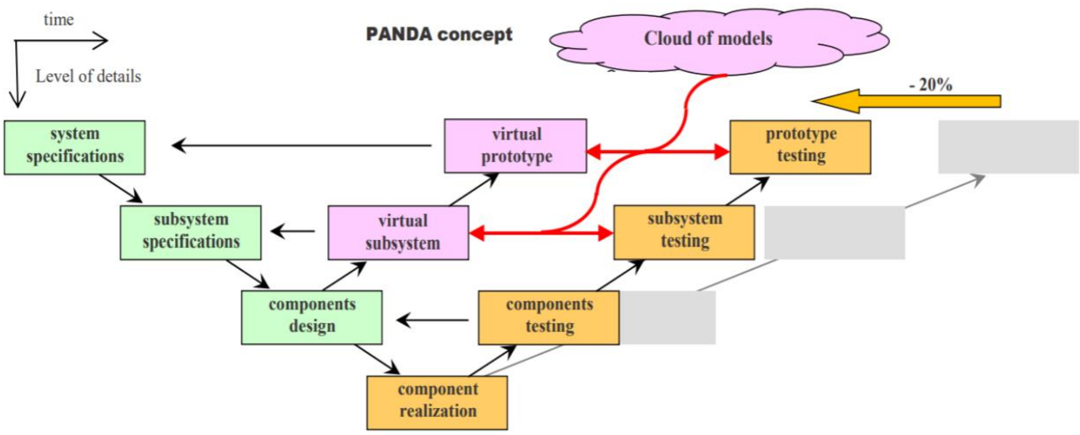

Figure 1 : Reorganisation in a W-model

The result is a significant time reduction for two important steps in the development of a new system or a new vehicle:

1) Choosing the optimal technical and economical solution
2) Validation of the components, systems, and entire vehicle

The PANDA project developed a multi-level model approach for simulation of electrical systems on electrified vehicles [PANDA 2020]. For each system and component, it is proposed a N-level model organization of all models being validated [PANDA D2.1]. Models are developed using a functional approach with causal description and fixed inputs and outputs (I/O). The use of Energetic Macroscopic Representation (EMR) formalism [Bouscayrol 2012] guarantees the reliability and efficiency of the models in terms of simulation speed and precision. Different levels of complexity were targeted for the developed models in order to have the right model at the right moment of development of a product: simpler models with less parameters for the beginning of the development process, when details of the final product are not defined, and more complex models for development and optimisation parts of the process. Finally, completed and adapted models were developed for real testing of the prototypes, ready to be used in simulations and hardware in the loop (HIL) tests [Bouscayrol 2011]. The formalism used with fixed I/O guarantees a fast change of the models in complex simulations during the development process.

All these innovations can be applied in the development process of a vehicle and its systems. The main phases of a vehicle development process are presented in Figure 2. They are related to the lead time of the vehicle development and thus do not consider the pre-business study (before the upstream, the development and validation of the plant to produce the vehicle, and the industrialization phases).

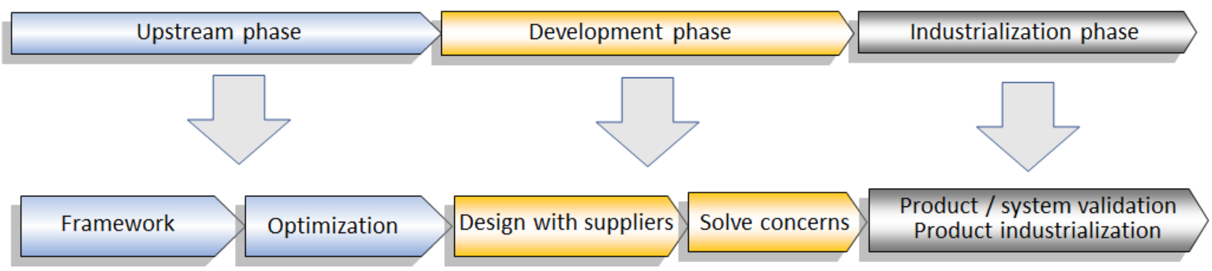

Figure 2. Main phases of a vehicle development process (lead time)

All these talks have been reorganized within the W-model by the PANDA task force to highlight the difference between the lead time and the time to market (Figure 4). Different levels of simulation are needed within this development process.

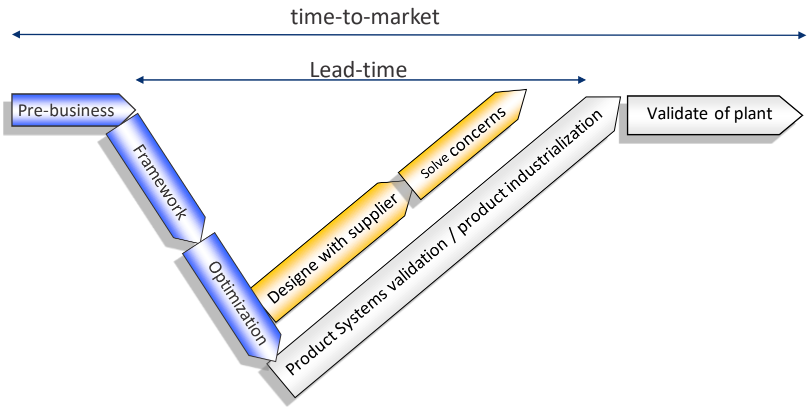

Figure 3. Time-to-market development process within the W-model

- The **Upstream phase** is divided into two parts: the Framework phase and the Optimisation phase. The Framework phase is dedicated to parallel studies of different technical concepts for choosing the technical definition of the vehicle and its systems. During the Optimization phase, the selected technical solution is studied and optimized for further developments and for the final definition of the vehicle. During the Upstream phase, the main tool is simulation. Here, the level of details available for the systems or for the entire vehicle is very low at the beginning and it increases according to the technical details studied along the phase. The N-level model organization proposed by PANDA project targets this phase and gives solutions to speed up the process.

- The **Development phase** is a phase during which components and subsystems suppliers design their products according to the technical definition decided previously (Upstream phase). The suppliers start the validation of their products. The next phase is dedicated to solving issues for subsystems that are integrated at the vehicle level. Simulations are used for iterations to solve concerns and virtual validation. Prototypes are built for systems and real test are made (HIL tests) for their validation. The solution proposed by PANDA project (to reduce HiL tests time) speeds up this phase of the process. Moreover, thanks to high fidelity N-level models, the PANDA project increases the quality of HIL tests while reducing their development time.

- The final phase, **Industrialization phase**, has two phases which are running in parallel:
  - 1) System validations on vehicles and whole vehicle validation and certification,
  - 2) the industrial preparation of the factory to produce the vehicle and the industrial preparation of the suppliers to produce components and systems for the new vehicle.

  During this phase, simulations are used only to find occasional solutions for real tests issues. PANDA solutions for simulations and tests will not have a big impact during this phase.

In Figure 4, one can identify the phases where solutions proposed by PANDA project for simulations and tests can speed up the actual process of vehicle development.

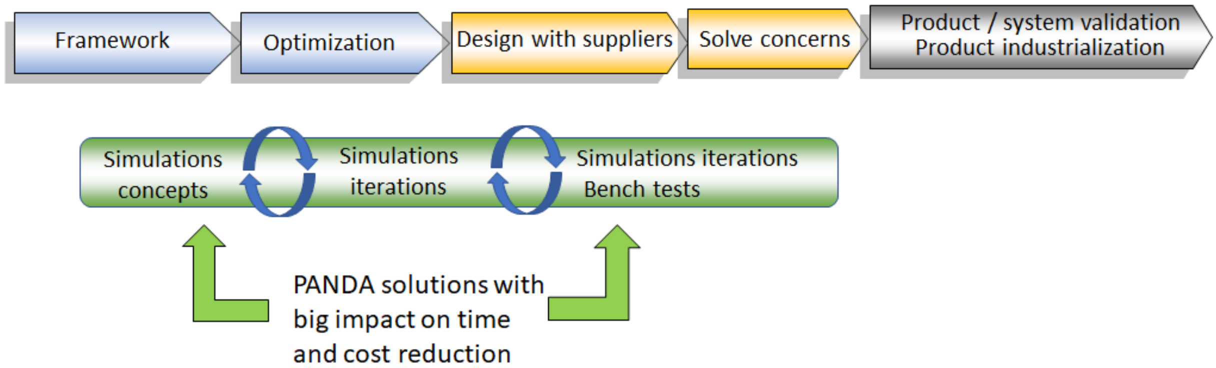

Figure 4. Development phases where PANDA solutions can be applied

The phases presented are related to global vehicle development but some of the components and systems development can shift through these phases according to their specificity and complexity. Details regarding electrical powertrains for EVs will be presented in the following sections. PANDA solutions can be applied on ICE vehicles, but the impact will be smaller, as they are focused on and validate mainly EV powertrain electrical systems. Time reductions for validation phases on test benches will significantly reduce the costs of the development process.

2.1. Context of electrified vehicles (EV) deployment

PANDA solutions were developed and validated on actual electrified vehicle (EV) types. These vehicles are battery electric vehicles (BEV), fuel cell vehicles (FCV) and hybrid electric vehicles (HEV). The schematic drawings of propulsions of all these types of vehicles are presented in Figure 5. All these vehicles have the electrical powertrain in common. It is composed of a battery, a power converter, and an electrical machine. Solutions for reducing lead time and cost for this common electrical powertrain are studied and validated in PANDA. The power, the complexity or the type of electrical powertrain components may be different among these vehicles, but they are always there and make up the propulsion system of the vehicle.

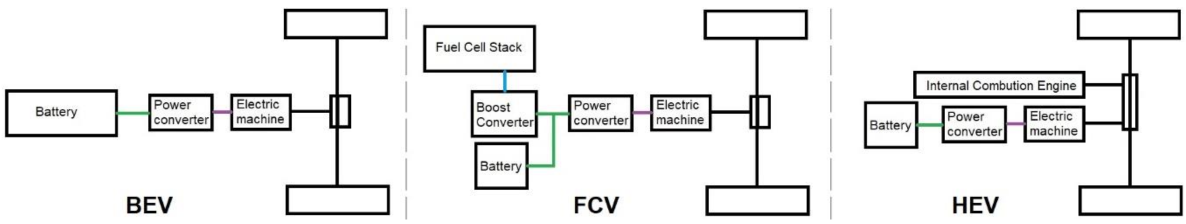

Figure 5 Electrified vehicles propulsion schematics

For example, the battery on BEV is the largest and is more powerful than the other components, as the battery is the only power source of the vehicle. The battery on FCV is smaller as it is used as a secondary source of power. For HEV vehicle, batteries are small and they are charged by the ICE or in case of plug-in HEV batteries are medium power allowing a bigger autonomy in pure electric mode.

The electric powertrain system is the most complex system on EVs and it needs more development time among vehicle systems. A significant reduction of the lead time of electric drives (or e-drive, i.e. power converter, electrical machine and their control) will have a big impact in global lead time of the vehicle.

Design of an e-drive is a challenging task because several types of components can be used with significant differences and the optimal selection for the vehicle to be build is difficult to do. Here, simulation is the main tool for this task, and PANDA organization architecture for models is a more effective mean to ensure the choice of the right components. Nowadays, for an EV, the main solutions to be used for an electric powertrain are as follows:

- Batteries – BEV and Plug-in HEV need higher power batteries. Today, the Lithium-Ion Batteries fit these applications, but the technology of these batteries is in a continuous progress. Then, modules of such batteries may have slightly different performances because the lithium-ion battery is in fact a family of several technologies. The solution of packaging and cooling (air cooling or liquid cooling) introduces many variables and the choice of the right battery is also influenced by the space available in the vehicle. For FCV and HEV vehicles, as they don't need high power batteries, Nickel-Metal Hydride batteries can be used. It can be noted that Bluways is a battery manufacturer and TUV-BT a battery testing centre for certification. These partners provide relevant information on batteries.

- Electrical machine – permanent magnet synchronous motors (PMSM) are the most used for EVs today, but wound rotor synchronous motors (WRSM) are also used, and for small vehicles asynchronous motors are used. These motors have also different construction solutions so their performances may vary a lot and their cooling (air cooling or liquid cooling) introduce other variables. Especially for HEV, the space available for electric machines is small and the right machine is not easy to find or to design. It can be noted that VEEM is a Tier 1 on electrical systems for automotive, including electrical machines. VEEM provides relevant information on electrical machines.

- Power converter – is adapted to the electric machine and must be designed to drive the electrical machine as a motor or a generator for braking and charging the battery. High switching frequencies of high currents push today high-power semiconductors industry of IGBT (Insulated-Gate Bipolar Transistor) to new Silicon Carbide (SiC) MOSFET (Metal–Oxide–Semiconductor Field-Effect Transistor). The precise currents and voltages carried by power semiconductors can be calculated by simulations and, based on these values, the design or the adaptation of an existing power converter can be done. It can be noted that VEEM is a Tier 1 on electrical systems for automotive, including power converter for e-drives. VEEM provides relevant information on power converter for e-drive.

Moreover, RTR is a well-known OEM developing and testing electrified vehicles. RTR provides a precise development case on vehicle development and related information. SISW and TY also provide other relevant cases from their automotive customers. If all the information discussed in the task force are to be kept confidential, a realistic framework has been derived to propose a fair analysis of the PANDA impact.

2.2. Reference case

For testing PANDA solutions on all three EVs, a reference case of an EV was selected – a battery electric vehicle (BEV) as it is the only one using the electrical powertrain with a big battery. The other reason is that the vehicle model validation was done after the individual validation of the main components of electrical powertrain (battery, electrical motor and power converter). In PANDA project, a Renault ZOE BEV was used for the validation of the BEV models (Figure 6) [PANDA D4.3]). Different battery models are considered: a global electrical model (level 0), a cell electrical model and their associations (level 1) and an electro-thermal model (level 2) [PANDA 2.1] [PANDA D2.3]. Different e-drive models are also considered: static efficiency map (level 0), dynamical park model with ideal control (level-1), dynamical model with practical control including estimation (level 2) [PANDA D3.1] [PANDA D3.2]. Control model was also developed according to the level of complexity of the e-drive model. All models were implemented in Simcenter Amesim© software tool [PANDA 4.1].

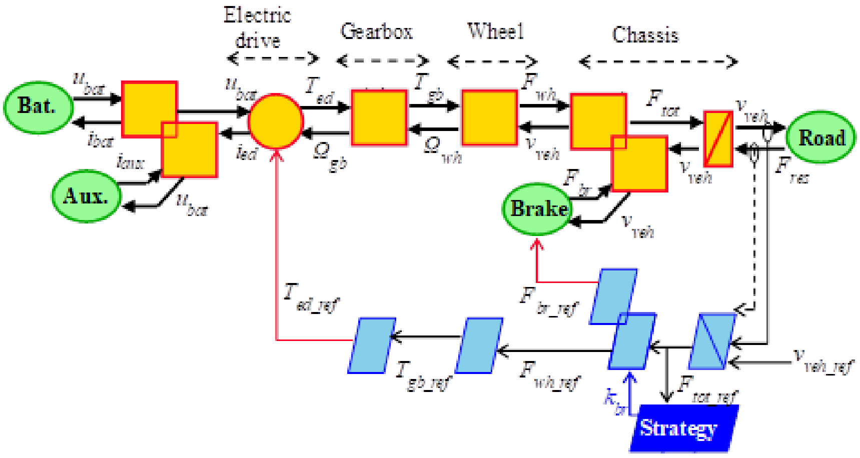

Figure 6. EMR of the studied BEV

All models of systems of all levels were individually validated with data from real tests and the global models of the BEV were validated using two use case cycles - real driving tests: a highway test and an urban test [PANDA D4.3]. Both tests were chosen because they were long enough to consume more than 50% of the energy from the battery. This was an important point to verify the precision of the models for long time simulations. Simulations of the energy consumed from the battery and state of charge of the battery (SOC) were performed using all levels of models of components. The results of these simulations compared with tests showed a high accuracy of these parameter calculations – error was less than 3% in all cases. This level of precision proved that the methodology of building models of BEV systems used in PANDA project is of greater accuracy for long-time simulations than methodologies currently used in EVs development.

Summarily here are the innovative proposals from project PANDA to be applied on the studied BEV for reducing the time to market and optimize costs of the development:

(1) Very high precision models of different complexity for the powertrain subsystems of the BEV
(2) Higher speed in simulation of PANDA models compared with structural models [Husar 2019]
(3) High flexibility in changing the models of systems with other models of the same system or models with different complexity [PANDA D4.3] [PANDA D4.4] [PANDA D4.5]
(4) Standard connections between models of systems and components
(5) Adaptability of the models for real testing on HIL – very quick change from virtual testing to real testing [PANDA D5.1] [PANDA D5.2] [PANDA D5.3]
(6) A Cloud-Computing solution for sharing models and perform simulations from all business partners involved in development of components and systems of a new vehicle [PANDA 4.2]
(7) A Cloud-Computing solution adapted to real testing – possibility of performing HIL tests using models from the cloud [PANDA D2.2] [PANDA D3.3].

All these innovative proposals were validated with real tests results on the vehicle and on HiL benches of PANDA partners. In the following sections, all proposals will be used to help to reduce the lead time and optimize BEV development costs.

2.3. Gains at the vehicle level

In this section, the impact of the PANDA proposals on the process of vehicle development is analysed (Figure 3). The vehicle manufacturer will apply proposals in all phases of the process, trying to reduce the lead-time of vehicle development.

2.3.a. Upstream phase

The framework is composed of 3 logical parts (Figure 7). The longest one is the study of different concepts and building solutions for the new product. This part is known as “Competitive analysis”.

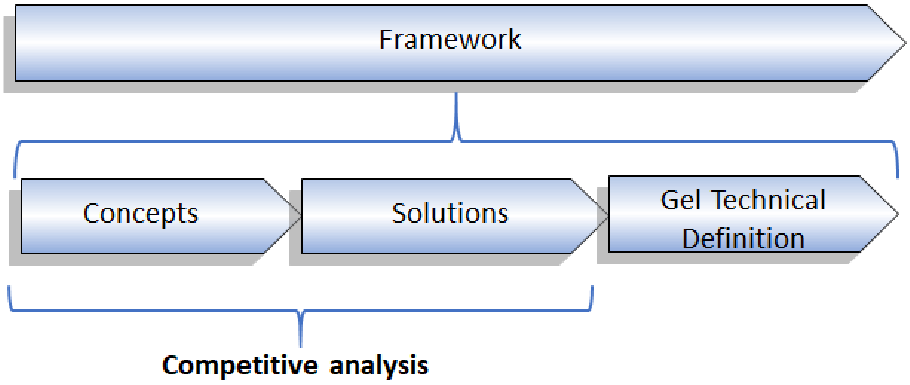

Figure 7. Framework period decomposition

During this phase, several topologies (with related hypotheses) are studied to determine the type and the parameters of the main components of the systems of the BEV powertrain. The hypotheses are simulated and their results are compared with the global parameters which are required for BEV, like the autonomy of the vehicle. Most promising topologies are selected, and virtual prototypes are built in order to decide the optimal technical definition of the powertrain the future BEV. A possible list of the technical hypotheses to be considered for a powertrain of a BEV is described below.

a) 2 battery modules from 2 suppliers, each one with an air-cooling packaging and a liquid cooling packaging.
b) At least 2 electric motor types: permanent magnet synchronous motors (PMSM) and wound rotor synchronous motors (WRSM). Asynchronous motor or even switched reluctance motor can be taken into account if there is a small BEV as the costs of these 2 motors is lower than the previous ones but efficiency and flexibility for regenerative braking is not so good. Another parameter to be taken into account is the cooling of the electric motor as stator cooling can be done using a liquid cooling or air cooling. For a WRSM the liquid rotor cooling is a costly solution so it is important to verify if it can work on appropriate temperatures without such cooling.
c) The power converter probably needs liquid cooling. Packing of such a component with liquid cooling is difficult so it must be studied as a separate component, or it will be integrated with battery charger as it needs also liquid cooling.

In this phase of the process, if an extended library of multi-level models (built with PANDA methodology including EMR formalism) for all components is available, the simulation of the vehicle can be rapidly developed (see Figure 6). The multi-level approach provides the right models with parameters available from the early phase of development. Moreover, the flexibility of simulation architecture allows to rapidly switch models of different components in the same vehicle model.

In conclusion, using PANDA innovative proposals (1), (3), and (4) during the Competitive analysis phase of the development process of the vehicle leads to the following advantages:

- All technical hypotheses of the powertrain can be quickly simulated in the same vehicle.
- High precision of the simulations will give confidence in the results of simulations: no need to build several prototypes for physical tests
- All combinations from technical hypotheses can be quickly simulated
- The convergence to the optimal technical economical solution is very rapid.

For the last part of Framework phase, mentioned as “Gel Technical Definition” in Figure 7, when during classical approach usually three solutions are detailed studied and tested with prototypes, using PANDA innovative precise simulations there will be only one technical solution selected. And for this technical solution there will be:

- only one prototype will be built for the optimal solution for real tests.

A comparison between processes with PANDA proposal and classical approach is presented in Figure 8.

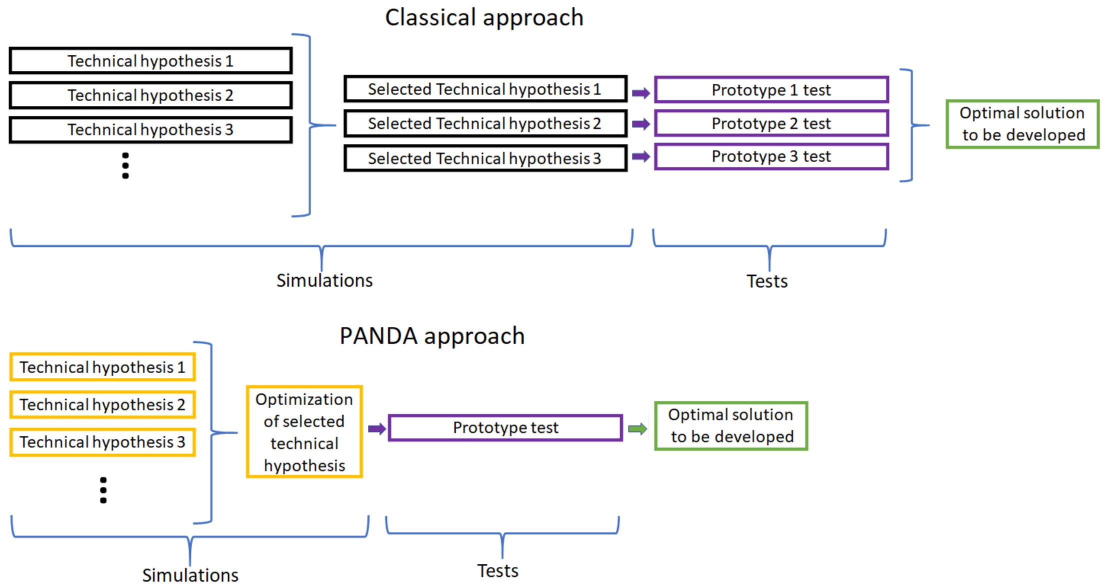

Figure 8. Classical approach vs PANDA approach for selecting optimal solution

We estimate an important cost reduction of this phase as only one prototype is built for test instead of three prototypes: up to 60% of cost reduction.

The lead-time reduction of the Framework phase is also important. A realistic time framework has been defined from the real one at RTR which has to be kept confidential. From the initial development of the two initial phases, the potential time gain has been evaluated from the PANDA task Force (Table 1).

Table 1: Potential time reduction for the “Upstream phase”

	Reference time (weeks)	Part of time with simulations	Gain lead time (%)	New phase timings (weeks)
Competitive analysis	50	100%	**40%**	30
Gel Technical definition (Tested solution)	20	100%	**50%**	10
Total time:	70		**46%**	40

2.3.a. Development phase

In this phase, the optimal solution chosen from the previous phase is detailed as much as possible. The components are detailed and simulated to be optimized. Based on these studies, the technical requirements for the components and subsystems are defined. These technical requirements will be used in the next phase by suppliers of the components and subsystems to build them. For more detailed results, 2D and 3D simulation tools are used. But 1D simulations are continuously used to verify the global performances of the vehicle and to define control requirements and communication signals from ECUs and sensors.

During this phase, thanks to the PANDA functional models (instead of structural models), the simulation time is reduced by 15% [PANDA D4.1] [Husar 2019]. But as 1D simulations are not long (about tens of minutes per simulations), the impact in lead time of the phase is marginal. However, the fact that 1) the technical solution selected in previous phase is optimized inside the vehicle company during this phase and 2) afterward the components and systems are optimized during their development inside supplier phase, we can consider these phases as “Optimization of components” phase. As PANDA innovation (6) proposes a Cloud Computing solution to be used by vehicle developer and components’ suppliers, a new business collaboration will be developed between them from this Optimization phase. This collaboration will continue up to the validation phase of all systems and components. For this reason, the gain in lead time will be evaluate for the whole period of the “Optimization of components”.

1) Design with suppliers phase – During this phase, suppliers develop components and subsystems of the vehicle according to the technical requirements that fit vehicle developer. Components and subsystems are developed using the development process of each component or subsystem manufacture. The impact of PANDA innovations for the gains at the component level is detailed in the next section 2.4. This phase can be reduced if all suppliers are able to reduce the time of their process of development as they are working in parallel and they will use the innovations proposed by PANDA project.

2) Solve concerns phase – In this phase, suppliers start to test their subsystems on HIL benches and provide prototypes to vehicle integrator. By doing so, they start testing the integration of these subsystems in vehicle environment, also by HIL testing. It can be noticed that classical experimental tests are still often used, even though HIL test are developing more and more. The ability of the flexible architecture of PANDA together with the reuse of the models from previous development phases will allow the vehicle developer to build the HIL tests rapidly and to verify the performances of the already developed systems. It is the phase of validation of the subsystems and components. As mentioned before, we will consider these last 3 phases as one logical phase dedicated to development and optimisation of components and systems (Figure 10). The impact of PANDA innovations on reducing the development time of these phases will be evaluate in the next sections.

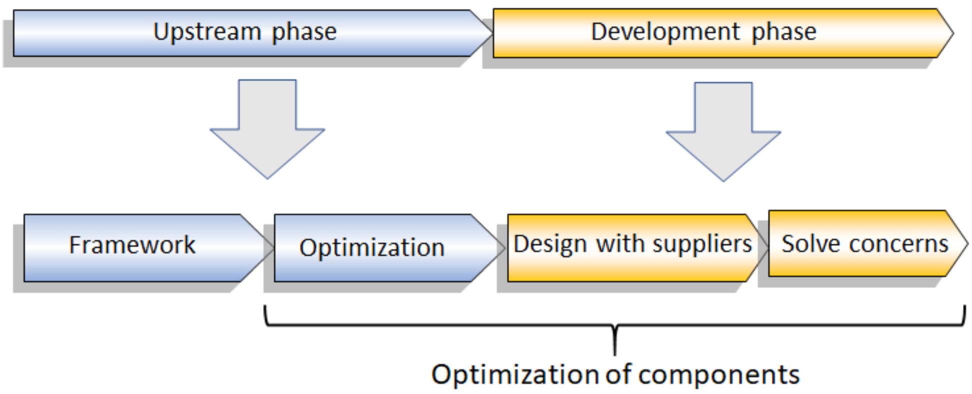

Figure 9. Optimization of components phase - collaboration between suppliers and vehicle developers

2.4. Gains at the component level

For confidentiality reasons, only global statements on the e-drive development are given in this subsection.

As explained before, the “Development phase” is shared by the OEM and the supplier. A common simulation framework will thus enable a fast development and reduce the number of issues and incompatibilities. Moreover, reusing the vehicle models can reduce the design stage of the e-drive: no need to develop a battery model or a mechanical transmission model. Finally, these reused models can also be computed in real time for HIL testing. In OBELICS project (see 2.5.b), it has been demonstrated that for e-drive, the use of HIL testing instead of classical real tests can lead to a reduction by 44% of the e-drive development time [OBELICS 2022]. But the use of HIL testing required high-fidelity models of the subsystems to be simulated in real time. As we have obtained high accuracy in the virtual prototype of BEV [PANDA D4.3], FCV [PANDA D4.4] and P-HEV [PANDA D4.5], the developed models can achieve the requested accuracy. It has been demonstrated in HIL testing of the e-drive for the P-HEV that the real-time model of the vehicle leads to relevant and accurate tests [PANDA D5.2].

From another point of view, the development of a high-fidelity model of the e-drive could also be used to achieve some virtual tests to replace real tests [PANDA D5.4]. For example, the powertrain components (battery, e-drive) required to measure efficiency maps and / or thermal maps. Each map can have more than 500 continuous functional points: the tests necessary for these maps take a lot of time. If high-fidelity models are available, it is reasonably to consider 100% of the measured points obtained from virtual tests and the 50% can be measured (or less) for checking. The accuracy of the virtual tests can thus be checked, and the experimental tests can cover the limits of functionality of systems all with a significant time reduction (up to 50%).

Therefore, it can be stated that a reduction by 50% of the development time of the e-drive is a realistic target. This global figure can be obtained by reusing simulation models (instead of redeveloping them), replacing classical experimental tests by HIL tests (with accurate real-time models) and replacing some experimental tests by virtual tests.

Another lead time reduction for components is obtained using the proposed innovation of PANDA (7): A Cloud-Computing solution adapted to real testing. This solution can have a big impact to systems’ validations as there are HIL tests done for each complex component (battery, e-drive, ECU, etc..) and for global integration on vehicle level (HIL tests done by vehicle developer). Using a common library of models and connecting HIL benches of different business partners by internet, some of the tests can be performed on upstream HIL benches and thus errors are earlier found and corrected. This will have an important impact on reduction of the time of “Solve concerns” phase from Figure 9. If this solution is extensively used, we estimated a 50% time reduction for the phase “Solve concerns” but this needs a big change in business model and collaboration between suppliers of components together with vehicle developers and the need that all business partners adopt and use PANDA models and architecture in order to guarantee physical and virtual interconnections.

2.5. Global framework

In this subsection, the potential lead-time gain is estimated by the PANDA task force from the previous studies. In the second part, the time reduction of the different phases is compared from other H2020 projects working on the same topic.

2.5.a. Potential gain in terms of lead time

From the previous studies, the potential gain in terms of lead time has been estimated by the PANDA task force. First, a realistic time framework has been established from the real case of RTR which has to be kept confidential. The reference scenario is related to the development of a completely new electrified vehicle from scratch (Table 2).

- 50 weeks for comparison of vehicle topologies (framework)

- 20 weeks for optimization of the selected topology (optimization)
- 50 weeks for components and subsystems design (development phase)
- 60 weeks for validation (and industrial process, validation phase)

The reference scenario has thus a lead time of 180 weeks (about 3 years). Some OEMs proposed shorter lead time, but it does not generally correspond to a completely new vehicle. This lead time is realistic one but cannot be considered as strict number for any vehicle development. It will just allow to estimate the potential gain of the PANDA methodology.

From the previous section, the potential gains in the selected phases are reported in Table 2. Strong assumptions are considered: the maximal gains are considered, the different teams adopt the PANDA methodology, the OEMs and suppliers work using the same methodology. Moreover, the potential gains are considered as cumulative and parallel tasks are assumed to have the same reduction gain. Of course, the assumptions are not all possible at the same time. However, this estimation will lead to a maximal potential gain that gives an idea of the benefit of the PANDA methodology. From the previous results:

- 40% of time reduction could be obtained in the comparison of vehicle topologies
- 50% of time reduction could be obtained in optimization of the selected topology
- 50% of time reduction could be obtained in components and subsystems optimization
- No time reduction is considered in the vehicle validation and certification (despite the fact that virtual prototypes could replace some real tests on vehicle prototypes; however, since it is really tricky to estimate this potential gain, this time reduction has not been considered).

Table 2: Potential gain in lead time from the PANDA methodology

	Reference weeks	PANDA Gain	New scheme weeks
Training	0		**10**
Framework	50	**40%**	30
Optimization	20	**50%**	10
Components Design & validation	50	**50%**	25
Validation	60	0%	60
Total	180		135

A supplementary phase has also been considered (see Table 2): training of the engineers in the PANDA methodology. This training phase consists of the training of the EMR formalism and the PANDA methodology, but also of the development of the cloud infrastructure and the library framework. This training phase has been estimated to 8 weeks by SISW from their work without prior knowledge on the PANDA method. The task force has considered that 10 weeks of training weeks could be a relevant estimation. Obviously, this training phase will occur on the first development. But considering that PANDA proposes a disruptive approach and there is some turnover in industry, this training phase of the PANDA methodology could be relevant.

Based on all these considerations, the total number of weeks with the ideal framework using the PANDA methodology would be 135 weeks including the supplementary training phase. Thus, the integration of the PANDA methodology in the development of new innovative vehicle would reduce the lead time up to 25%. This potential gain is based on a specific reference case, and the related assumptions. The actual gain will vary for each use case, but the analysis shows that the potential benefit of using the PANDA approach can be very high.

2.5.b. Comparison of the PANDA results with other H2020 project results

Other H2020 projects have also worked on the reduction of the development time of electrified vehicles. Unfortunately, the reference frameworks were not the same, and some projects focused only on some phases. A comparison tables has been established putting only the reduction time on the related phases when defined (Table 3).

- OBELICS[1]: focus on multi-level modelling and testing of BEV and their components including advanced co-simulation solutions and model reduction; potential gains in terms of development time have been estimated [OBELICS 2021].
- VISIONxEV[2]: focus on the development axis of the W-cycle including innovative modelling and simulation method with validation on real use cases; potential gains have been estimated [Tastchl 2022]
- XILfor EV[3]: focus on X-in-the-Loop for the real testing of the W-cycle including innovative real-time simulation methods for hardware-in-the-loop testing; the potential gain in real- testing has been estimated [Ivanov 2022].

Table 3: Comparison of reduction time of the development phase from several H2020 projects

	OBELICS gain	XILforEV gain	VISION-xEV gain	PANDA Gain
Framework	50%		25%-35%	**40%**
Optimization	50%		25%-35%	**50%**
Components design & validation	50%-75%	50%	40%	**50%**

The different time reductions are also based on the use cases of these projects and do not reflect general figures, for confidentiality reasons but also for the limited number of the studied cases. However, the different percentages are relatively close, despite being independent H2020 projects. The PANDA figures are thus consistent with the figures of the other projects.

3. Towards a standard in model organization

3.1 Key aspects of model organization

From different H2020 projects, it has been shown the interest to organized inputs/outputs of numerical models of electrified vehicles and components. In HIFI-ELEMENTS [Deppe 2018], a standardization of I/Os of models of BEV has been proposed for a seamless interconnection of models for real-time co-simulation. The proposed I/Os have also been used by OBELICS [OBELICS 2022].

In PANDA, supplementary steps have been proposed.

- The I/Os are defined from the causality principle; this
- The EMR formalism is used a framework for a unified organization of any energy conversion
- The I/Os organization lead to a systematic organization of the control of the studied vehicles
- The study cases have been extended to FCV and P-HEV (including their related subsystems)

Another solution is to develop dedicate FMI (Flexible Mock-up Interface) to avoid a unified organization of I/Os and thus avoid imposing this organization to the different users [Ponchant 2017]. But it requires a supplementary and complex software unit to adapt I/Os between the different models. Moreover, this adaptation stage requires some supplementary computation time that could be a drawback for real-time simulation.

[1] https://obelics.eu/
[2] https://vision-xev.eu/
[3] https://xil.cloud/

3.2 Potential standard actions

We have invited Mrs Corina SCHREITER on the PANDA advisory board. Mrs SCHREITER is project manager of the electro-mobility office of the department of innovation of DIN[4] (German Institute of Standardization. After the first meeting of the advisory board, she was invited to give a talk on standardization on PBM3 (Project Management Board 3, December 2019). The different process and agencies have thus been introduced to all PANDA members.

As the standardization is a very long process, it has been recommended to integrate some standardization committee such as CEN/TC 301 - Electrically propelled road vehicles of CEN-CENELEC[5], or the IES (Industrial Electronics) Standard Committee of IEEE standard association[6]. If it was an objective to contribute to this committees, the COVID-19 pandemic led to change the priorities.

But the integration of PANDA members in such standard committees remains an objective for a long-term dissemination of the PANDA results.

4. Training on PANDA method

The PANDA methodology is based on the EMR formalism and a disruptive organization of the model of energy conversion systems. Therefore, most of the classical approaches are based on a structural organization of models of the studied system, using component libraries. EMR is a graphical description based on a functional organization of the models of the studied system [Bouscayrol 2012]. EMR is based on the causality principle [Iwasaki 1994] [Hautier 2004] and the interaction principle [Paynter 1961] [Bouscayrol 2000]. From these properties, the I/Os of the subsystem are fixed and strictly defined to respect both principles. This organization enables a seamless interconnection of the models of different subsystems, the N-level organization, and their real-time operation [PANDA D1.2]. Moreover, this organization enables a strict organization of control scheme [Bouscayrol 2012] and also HIL testing [Bouscayrol 2011], which requires to interconnect power modules, power adaptation, real-time model and control modules.
As this model organization is not a classical one, a training period is required to move the PANDA methodology from a more classical simulation approach. As mentioned previously (§2.5.a. Potential gain in terms of lead time), the task force has considered that 10 weeks of training weeks could be a relevant estimation to realize the gains of 25% in lead-time for the development.

4.1. EMR education programs

EMR has been developed by L2EP of University of Lille in 2000 [Bouscayrol 2002]. Since 2000, EMR is taught at Master degree at University of Lille. EMR has then be taught at ENSAM Lille, Centrale Lille and Polytech'Lille [Bouscayrol 2007] [Bouscayrol 2009]. From that experience, several French universities and engineering schools have also included EMR in their programmes:

- Université de Franche-Comté
- Université Technologique de Compiègne
- Arts et Métiers ParisTech
- Polytech'Paris Sud
- Supelec
- etc.

As international collaborations of L2EP have used EMR for research activities, Universities worldwide are teaching more and more EMR:

- Université du Québec à Trois-Rivières (Canada)
- Ecole Polytechnique Fédérale de Lausanne (Switzerland)

[4] https://www.din.de/en
[5] https://www.cencenelec.eu/
[6] https://standards.ieee.org/

- Harbin Institute of Technology (China)
- Technical University of Graz (Austria)
- Tsinghua University (China)
- University of Sherbrooke (Canada)
- INES Coimbra (Portugal)
- University of Applied Sciences of Western Switzerland (Switzerland)
- Hanoi University of Sciences and Technology (Vietnam)
- University of Santander (Colombia)
- Technical University of Cluj Napoca (Romania)
- Etc.

As all these universities have followed the PANDA project (international conferences, Workshops, summer schools and PANDA final event), and they can contribute to train future engineers worldwide to help companies to adopt the PANDA philosophy and the EMR formalism.

4.2. Summer schools

In 2006, an international EMR summer school has been initiated with the first edition in Lille [EMR 2022]. In 2011, the summer school became an annual appointment (with odd years in Lille and even years abroad):

- 2006, Lille (France)
- 2008, Harbin (China)
- 2009, Trois Rivières (Canada)
- 2011, Lausanne (Switzerland)
- 2012, Madrid (Spain)
- 2013, Lille (France)
- 2014, Coimbra (Portugal)
- 2015, Lille (France)
- 2016, Montreal (Canada)
- 2017, Lille (France)
- 2018, Hanoi (Vietnam)
- 2019, Lille (France)
- 2020, Oviedo (Spain) –cancelled due to COVID-19 pandemic
- 2021, Lille (France)
- 2022, Sion (Switzerland)

The average attendance of the summer school is more than 50 attendees from more than 10 countries. EMR summer schools are 2-days events organized as follows [Bouscayrol 2011b]:

- First morning, lectures on general concept
- First afternoon, simulation of a specific system (modelling)
- Second morning, lectures on various applications from worldwide speakers
- Second afternoon, simulation of a specific system (control)
- Third morning, lectures on various applications from worldwide speakers
- Third afternoon, simulation of a specific system (advance topic)

Within this framework, the general concepts are introduced, advanced applications are presented as well as practical sessions. Simulation sessions were initially based on Matlab-Simulink © with the EMR library developed by L2EP of University of Lille.

In 2019, a first PANDA special session has been organized in EMR'19 (Lille). This special session has been composed of an introduction on PANDA, and 3 lectures of the simulation of the BEV, the FCV and the P-HEV, reference vehicles of PANDA. All the 84 attendees from 14 countries have thus discover the PANDA project.

Unfortunately, EMR'20 (Oviedo, Spain) has been cancelled after having been rescheduled two times. EMR'21 has been organized in Lille for the first time in hybrid mode. Two PANDA special session have been organized with advanced results on the vehicles simulation, first results on HIL testing and the presentation of the simcenter Amesim EMR library and also the one of Typhoon Control Centre. An in-presence simulation session on Matlab-Simulink © has been organized as usual. Moreover 8 on-line simulation sessions have been organized depending on the slot-time (Asia, Europe, Africa, America) including a new one using simcenter Amesim © and its EMR library. All 169 attendees from 19 countries (27 in-presence and 142 on-line) have thus learnt about the PANDA results and some of them have tested the new EMR library from SISW.
EMR'22 is organized from 20 to 23 June in Sion in Switzerland in hybrid mode. Two PANDA special sessions (lectures) are planned and simulation session using Typhoon Control centre © are also expected.

The EMR summer schools have definitively supported the PANDA projects and disseminated its results and tools. The success of the PANDA final event (150 attendees in-presence, 200 attendees on-line) can also be explained by the involvement of PANDA in these summer schools: a great number of the summer school attendees have registered for the final event.
The EMR summer schools have also strongly benefited from the PANDA project by high-level lectures on an on-going H2020 project, new simulation tools supporting EMR (Simcenter Amesim© and Typhoon Control Centre ©) and also the cloud of PANDA for on-line simulation session.

The annual international EMR summer Schools will continue to disseminate the outputs of PANDA and train future engineers in the EMR philosophy.

4.3. On-line tutorials

During the project, SISW has developed the EMR library in Simcenter Amesim ©. Help modules have been developed in collaboration with ULille. Moreover, many tutorials have also been developed by the team of SISW in order to train future users in that new simulation philosophy including the use of the cloud.

5. Ecological footprint of PANDA

The impact of PANDA is to contribute to the reduction of GHG (greenhouse gases) by increasing the number of electrified vehicles to replace pollutant thermal vehicles. Moreover, replacing some real tests on vehicle prototypes with simulations will reduce the environmental impact of the vehicle development. To fully adhere to this principle, the project needs to account for GHG emissions produced by its own activities (travels of partners, energy for testing, etc.). The GHG emitted because of the project will be lower than those it will indirectly prevent. However, there is a discrepancy between the philosophy of the project and its ecological footprint. In order to deal with this "environmental impact", a "carbon care action" has been carried out. This action aims to put PANDA as an exemplar project in agreement with its main impact, i.e. reducing the emitted GHG.
It can be noted that the proposed method is derived from the 10-year experience of L2EP of ULille [CarbonCare 2022]. L2EP has developed carbon care action since 2010 for the IEEE-VPPC'2010 conference [Allegre 2014] and the EPE'13 conference [Bouscayrol 2018] to obtain carbon neutral conferences. The carbon care methodology has been refined by the PANDA project to be applied to research projects.

5.1 Principle of carbon care

Carbon care is an effort in tackling climate change by measuring, reducing and mitigating carbon footprint. Carbon footprint is related to what are called anthropogenic emissions which is another word for human activities, among which transport is the bigger share (Figure 10).

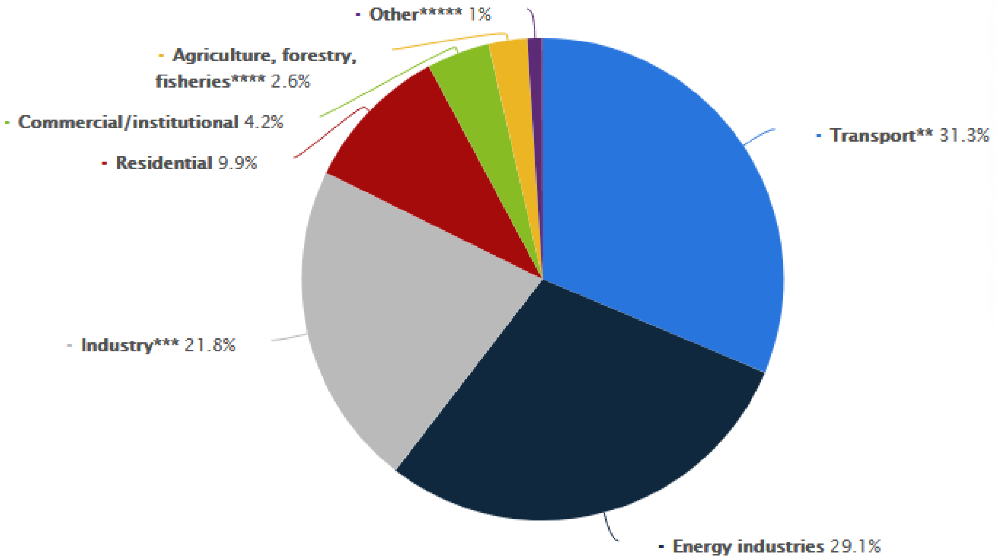

Figure 10: Distribution of carbon dioxide emissions in EU in 2019 by sector (Statista 2022)

Some initiatives exist to face climate change and global warming even if they are not easy to follow. COP21 is perhaps the most famous one, resulting in the Paris Agreement. But at our level, smaller and local initiatives are a way to face the problem, and Carbon Care is one of them.

Based on ULille previous experiences [CarbonCare 2022], the classical method for carbon assessment has been adapted to a research project. The basis is to clearly define the scope of the study and particularly the operational perimeter (Figure 11). The temporal perimeter is 3.5 years as the PANDA project has a 6-month extension. The organizational perimeter is composed of the 11 PANDA partners. The operational perimeter is related to the different PANDA activities. It can be noted that the GHG of all activities are computed within the LCA (Life Cycle Assessment) method [PANDA D1.7]. The estimations thus include the indirect GHG (manufacturing and end-of-life phases) and the direct GHG (use phase).

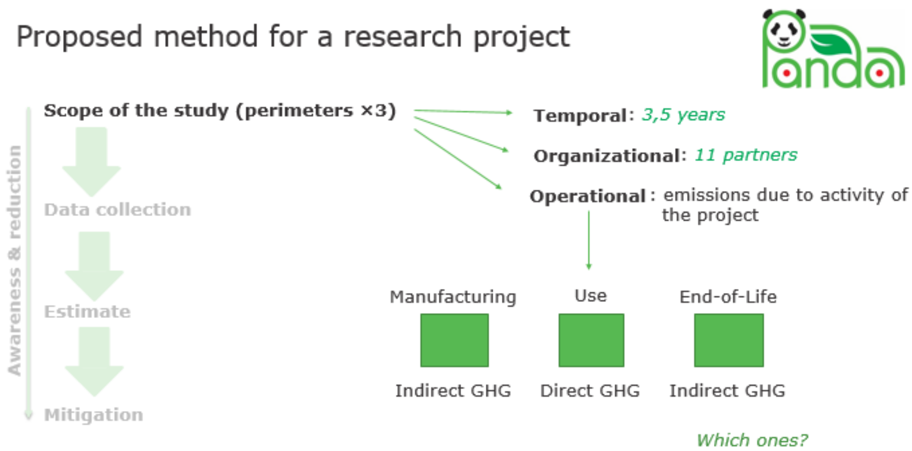

Figure 11: Organisation of Carbon Care action

5.2 Estimation of the PANDA impact

Then, it is important to organise GHG emissions to take all of them into account and only once. Therefore, it was decided to organise a carbon assessment according to the activities of a research project, namely development, management and dissemination, and to subdivide these parts into 3 subparts: functioning, travel and equipment (Figure 12). By doing so, all emissions of all the activities of a research project are covered.

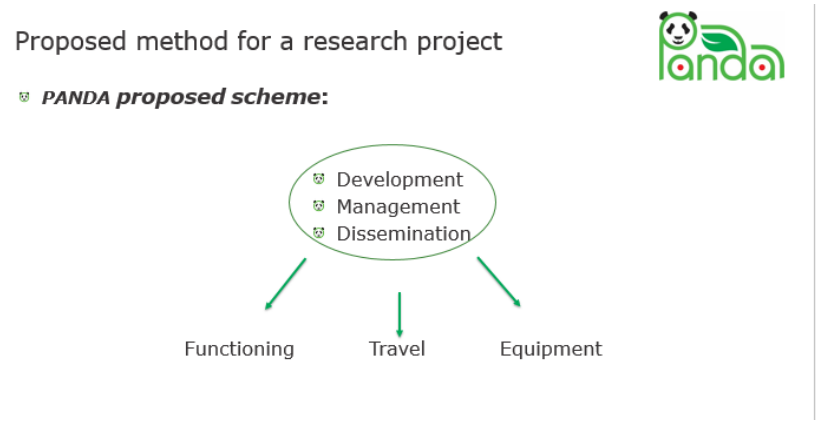

Figure 12: Organisation of a research project's GHG for carbon assessment

The estimation of PANDA-related GHG emissions has been updated all along the project thanks to carbon referents chosen by each project's partner, who gathered data needed for the carbon assessment. Inquiries have also been conducted for numerical activities (carbon cost of numerical calculation, videoconference, or website) as databases do not provide yet inputs for these relatively new topics. This collective work allows us to get the results shown in Figure 13.

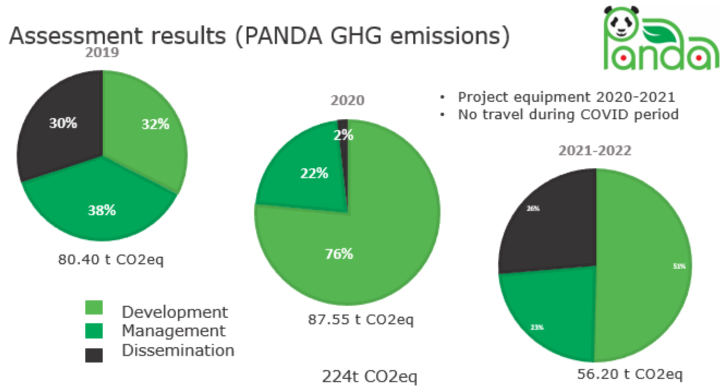

Figure 13: Assessment results per year

The relatively small contribution of the dissemination activities to the GHG emissions in the 2nd year of the project (supposedly the most active one and the worth in terms of GHG emissions) is probably due to the pandemic. We were forced to stay at home for a considerable amount of time, which reduced the amount of travels drastically. If we have a closer look at figures per activities (Figure 14), we notice that even with limited travel, this share is still the larger one (42%).

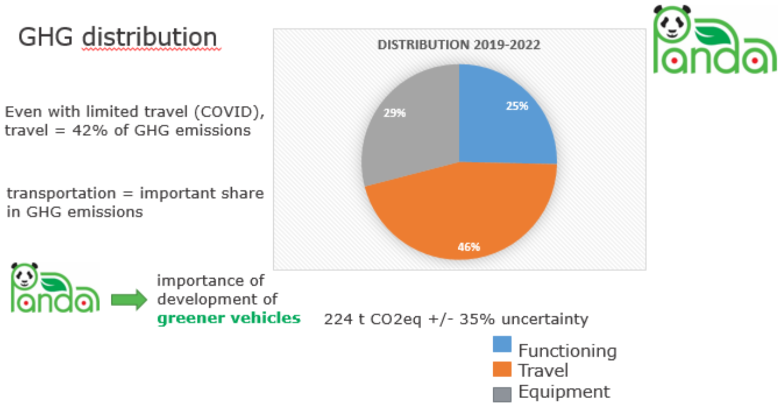

Figure 14: Assessment results per activity

The figures confirm the large impact of transport and mobility on the environment, and demonstrate the importance of developing greener vehicles and transportation, a goal to which PANDA contributes.

5.3 Mitigation action

Based on this study, we wanted to mitigate the environmental impact. With a total of 224t CO_2e and an average carbon price of 50€/ton, PANDA's budget for this mitigation action is about 11.2k€.

It was important to select a global action, in order to work together on this aspect of the PANDA project as well, and also to be able to choose a bigger mitigation project. A European location was also important because PANDA is a European project and emitted GHG mainly in Europe. After discussion of different potential mitigation projects, a project in Romaniawas selected for its ecological interest. Moreover, as 3 of the PANDA's partners are from Romania, this mitigation project is particularly relevant, and our Romanian partners could check the effective mitigation implementation. Thus, Transylmagica association https://www.forest.transylmagica.com/ is our final choice with also the possibility to take part in the planting campaigns.

In order to best fit our goal, we were recommended to select 3 climate change-related projects. 1) The Rau de Mori project is located close to the Serbian border (not far from Novi Sad where Typhoon is located); the story of the site is also of particular interest: the original vegetation was removed during the construction of the Gura Apelor dam in 1975. The project consists in planting original tree species which covered the surface before the dam construction. 2) The reintroduction of the oak species into the Ciuc Basin and the restoration of wind-damaged forests. This project will reintroduce tree species disappeared in the 17th century because of logging. The reintroduced species will be more resistant and will be adapted to the consequences of the global climate change (dryer and warmer climate in the Carpathians). 3) The last project consists in planting mixed forests in the protected areas of the Cheile Bicazului Hasmas National Park. These mixed forests will also be more resistant to the future effects of climate change (wind, less precipitation). We are discussing with the association to find the best relevant mitigation project with a planting action before the end of 2022.

As conclusion, PANDA inputs to carbon care method are:

- A new decomposition of the carbon care method
- A strong organisation with a carbon referent for each partner
- A regular update of all GHG all along the project

The Carbon Care action leads to:

- Aware contributors (with the organisation of a Climate Fresk workshop thanks to Mariam Ahmed from VEEM team)

- Estimate the GHG of all PANDA activities
- Mitigate the GHG emissions of the PANDA project

PANDA project will thus be a carbon neutral project!

6. Conclusion

This deliverable aims to highlight the main outputs and outcomes of the PANDA project.

Firstly, a task force in PANDA has assessed the impact of the PANDA methodology on the reduction of the development times of electrified vehicles and their components. Based on the RTR experience with designing vehicles for mass production, a realistic scenario has been established for developing a completely new vehicle. The chosen scenario is in line with the RTR process, but it is not identical to keep the real development process at RTR confidential. When applying the knowledge from the PANDA industrial partners and the results from the PANDA project, the analysis shows that the lead-time of a new vehicle development can be reduced by up to 25%, given a number of assumptions and by using the PANDA methodology during all development phases. Please note that this potential gain is an estimation based on a specific reference case, and the related assumptions. The actual gain will vary for each use case, but the analysis shows that the potential benefit of using the PANDA approach can very high.

Secondly, the PANDA methodology can give a valuable perspective in the ongoing discussion is on the standardisation of I/Os of the models of electrified vehicles and components. In a number of H2020 projects interest has been expressed in strictly defining inputs and outputs of models. In PANDA, I/Os are defined according to the physical causality that lead to a seamless interconnection of virtual models, but also to a valuable organisation of the HIL testing including power interfaces. The EMR formalism has been used as a standard organization of the models to respect this natural causality, to highlight the power flows between subsystems, and to systematically deduce control organization of the different vehicles. The involvement of PANDA members in standard committees would be a valuable supplementary outcome of the project.

Thirdly, as the PANDA methodology is a disruptive model organization, training programmes are needed to educate future engineers. Since 2000, University of Lille has developed training programmes at Master and PhD level. More and more universities worldwide are now teaching EMR. The PANDA results will surely be an added value in the dissemination of the EMR formalism thanks to the impressive results obtained by the industrial study cases. Moreover, the PANDA partners have contributed to the annual international EMR summer school, increasing both the PANDA visibility as well as the EMR summer school visibility. The dissemination of the PANDA methodology will continue in these national and international education programmes. Please note that the 25% reduction in the lead-time of a new vehicle includes the extra time that is needed for training in the PANDA methodology. So, whilst the additional education costs time, the benefits greatly outweigh the costs.

Finally, a carbon care action has been developed in PANDA to evaluate the environmental impact, and mitigate the GHG emission of the project. The perimeters have been clearly defined, and a carbon care methodology has been extended from previous experience of University of Lille. All PANDA activities have been considered, from the travels and meetings to the experimental tests and desk work (including commuting, videoconference, etc.). The total GHG emissions have been estimated at about 210 CO_2eq tons. A mitigation project in Romania (planting trees) has been selected to make PANDA into a carbon neutral project.

7. Deviations from Annex 1

There is no deviation in terms of content.

6. References

[Allegre 2014] A. L. Allègre, S. Astier, A. Bouscayrol, L. Chevallier, X. Cimetière, S. Clenet, B. Lemaire-Semail, P. Maussion, J. F. Sergent, “Experiences on carbon care conferences”, IEEE VPPC’14, Coimbra (Portugal), October 2014 (common paper L2EP Lille and Univ Toulouse).

[Bouscayrol 2000] A. Bouscayrol, B. Davat, B. de Fornel, B. François, J. P. Hautier, F. Meibody-Tabar, M. Pietrzak-David, "Multimachine Multiconverter System: application for electromechanical drives", *European Physics Journal - Applied Physics*, vol. 10, no. 2, pp. 131-147, May 2000

[Bouscayrol 2002] A. Bouscayrol, P. Delarue, E. Semail, J. P. Hautier, J. N. Verhille, "Application de la macro-modélisation à la représentation énergétique d’un système de traction multimachine", (text in French), *Revue Internationale de Génie Electrique*, vol. 5, n° 3-4/2002, pp. 431-453, October 2002 (article commun L2EP Lille, Matra Transport International).

[Bouscayrol 2007] A. Bouscayrol, A. Bruyère, P. Delarue, F. Giraud, B. Lemaire-Semail, Y. Le Menach, W. Lhomme, F. Locment, “Teaching drive control using Energetic Macroscopic Representation - initiation level”, EPE’07, Aalborg (Denmark), September 2007.

[Bouscayrol 2009] A. Bouscayrol, P. Delarue, F. Giraud, X. Guillaud, X. Kestelyn, B. Lemaire-Semail, W. Lhomme, “Teaching drive control using Energetic Macroscopic Representation - expert level", EPE’09, Barcelona (Spain), September 2009.

[Bouscayrol 2011] A. Bouscayrol, "Hardware-In-the-Loop simulation", Industrial Electronics Handbook, second edition, tome “Control and mechatronics”, Chapter 33, CRC Press, Taylor & Francis group, Chicago, March 2011, pp. 33-1/33-15, ISBN 978-1-4398-0287-8.

[Bouscayrol 2011b] A. Bouscayrol, P. Barrade, L. Boulon, K. Chen, Y Cheng, P. Delarue, F. Giraud, B. Lemaire-Semail, T. Letrouvé, W. Lhomme, P. Sicard, “Teaching drive control using Energetic Macroscopic Representation – Summer schools”, EPE’11, Birmingham (UK), September 2011 (common paper of L2EP, Univ Québec Trois Rivières, EPF Lausanne and Harbin Institute of Technology).

[Bouscayrol 2012] A. Bouscayrol, J. P. Hautier, B. Lemaire-Semail, "Graphic Formalisms for the Control of Multi-Physical Energetic Systems", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 3, ISTE Willey editions, October 2012, ISBN: 9781848213883.

[Bouscayrol 2018] A. Bouscayrol, L. Chevallier, X. Cimetière, S. Clenet, B. Lemaire-Semail, “EPE’13 ECCE Europe, a carbon neutral conference!”, EPE Journal, Vo. 28, no. 1, pp. 43-48, January 2018. DOI: 10.1080/09398368.2018.1425183 [IF 0,344].

[CarbonCare 2022] “Carbon care, 10 years of experience of L2EP” [Online] available: https://l2ep.univ-lille.fr/en/carbon-care (accessed May 2022)

[Deppe 2018] M. Deppe, C. Granrath, “SYNECT generated component model report”, HIFI-Elements GA# 769935, D1.3 Deliverable, public report, May 2018, https://www.hifi-elements.eu/

[EMRwebsite 2006] EMR web site, developed in 2006, [Online] available: https://obelics.eu/ (accessed May 2022)

[Hautier 2004] J.P. Hautier, P.J. Barre, « The causal ordering graph – A tool for modeling and control law synthesis”, *Studies in Informatics and Control Journal*, vol. 13, no. 4, pp. 265-283; 2004.

[Husar 2019] C. Husar, M. Grovu, C. Irimia, A. Desreveaux, A. Bouscayrol, M. Ponchant, P. Magnin, “Comparison of Energetic Macroscopic Representation and structural representation on EV simulation under Simcenter Amesim”, *IEEE-VPPC’19*, Hanoi (Vitenam), October 2019 (Siemens Software and L2EP/Univ. Lille within the framework of the H2020 PANDA project).

[Ivanov 2022] V. Ivanov, “XILforEV final results”, H2020RTR’21, Brussels, March 2022.

[Iwasaki 1994] I. Iwasaki, H.A. Simon, “Causality and model abstraction”, *Artificial Intelligence*, vol. 67, pp. 143-194, 1994.

[OBELICS 2021] OBELICS final booklet, 2021, [Online] available: https://obelics.eu/ (accessed May 2022)

[PANDA 2020] A. Bouscayrol, A. Lepoure, C. Irimia, C. Husar, J. Jaguemont, A. Lièvre, C. Martis, D. Zuber, V. Blandow, F. Gao, W. Van Dorp, G. Sirbu, J. Lecoutere, "Power Advanced N-level Digital Architecture for models of electrified vehicles and their components", *Transport Research Arena 2020*, Helsinki (Finland), April 2020 (within the framework of the PANDA H2020 European Project, GA #824256).

[PANDA D1.3] B. Lemaire-Semail, A. Bouscayrol, "Organization method for virtual and real testing", PANDA H2020 GA# 824256, D1.3 Deliverable, public report, February 2020, [Online] available: https://project-panda.eu/ (accessed May 2022)

[PANDA D1.7] M.S. Koroma, G. Cardelloni, M. Messagie, "Guidelines for forward LCA approach", PANDA H2020 GA# 824256, D1.7 Deliverable, confidential report, November 2019, [Online] Published executive summary available: https://project-panda.eu/ (accessed May 2022)

[PANDA D2.1] J. Jaguemont, C. Husar, R. German, "Multi-level knowledge models of batteries", PANDA H2020 GA# 824256, D2.1 Deliverable, public report, May 2020, [Online] https://project-panda.eu/ Accessed October 2021."

[PANDA D2.3] D. Phetsinorath, S. Khaleghi, J. Klein, M. Giraud, M. Ciocan, "Multi-level behaviour models of batteries", PANDA H2020 GA# 824256, D2.3 Deliverable, confidential report, May 2021, [Online] Published executive summary available: https://project-panda.eu/ Accessed January 2022."

[PANDA D3.1] M. Ahmed Sanchez Torres, A. Lievre, "Multi-level Behavior models of e-drives", PANDA H2020 GA# 824256, D3.1 Deliverable, confidential report, November 2019, [Online] https://project-panda.eu/ Accessed January 2022."

[PANDA D3.2] M. Ruba, C. Husar, "Multi-level knowledge models of e-drives", PANDA H2020 GA# 824256, D3.2 Deliverable, public report, October 2020, [Online] Published executive summary available:https://project-panda.eu/ Accessed January 2022."

[PANDA D4.1] C. Husar, "Simulation platform and library", PANDA H2020 GA# 824256, D4.1 Deliverable, confidential report, February 2020, [Online] Published executive summary available: https://project-panda.eu/ Accessed C. Husar October 2020.

[PANDA D4.2] M. Ciocan, R. Gavril, "Cloud facilities", PANDA H2020 GA# 824256, D4.2 Deliverable, confidential report, June 2020, [Online] published executive summary available: https://project-panda.eu/ Accessed October 2021.

[PANDA D4.3] G. Sirbu, A. Desrevaux, C. Hussar, N. Boicea, "Report on the virtual testing of the BEV", PANDA H2020 GA# 824256, D4.3 Deliverable, public report, January 2022, [Online] available: https://project-panda.eu/ Accessed January 2022.

[PANDA D4.4] F. Gao, E. Raclaru, "Report on the virtual testing of the FCV", PANDA H2020 GA# 824256, D4.34 Deliverable, public report, April 2021, [Online] available: https://project-panda.eu/ Accessed January 2022.

[PANDA D4.5], R. Vincent, W. Lhomme, C. Hussar, "Report on the virtual testing of the P-HEV", PANDA H2020 GA# 824256, D4.5 Deliverable, confidential report, January 2022, [Online] Published executive summary available: https://project-panda.eu/ Accessed January 2022.

[PANDA D5.1] R. German, A. Desreveaux, F. Tournez, A. Bouscayrol, A. Genic, C. Husar, "Real test of the battery of the HEV", PANDA H2020 GA# 824256, D5.1 Deliverable, confidential report, June 2021, [Online] Published executive summary available: https://project-panda.eu/ (accessed December 2021).

[PANDA D5.2] M. Ahmed Sanchez Torres, A. Lievre, W. Lhomme, F. Tournez, A. Bouscayrol, "Real test of the e-drive of the P-HEV", PANDA H2020 GA# 824256, D5.2 Deliverable, confidential report, February 2022, [Online] Published executive summary available: https://project-panda.eu/ (February 2022).

[PANDA D5.3] W. Lhomme, F. Tournez, S. Roquet, "Real test of the e-subsystem of the P-HEV", PANDA H2020 GA# 824256, D5.3 Deliverable, confidential report, February 2022, [Online] Published executive summary available: https://project-panda.eu/ (February 2022).

[PANDA D5.4] R. Vincent , F. Tournez, A. Bouscayrol, A. Lièvre, M. Ahmed Sanchez Torres, “Data Analysis”, PANDA H2020 GA# 824256, D5.3 Deliverable, confidential report, May 2022, [Online] Published executive summary available: https://project-panda.eu/ (May 2022).

[Paynter 1961] H. Paynter, "Analysis and design of engineering systems", MIT Press, 1961.

[Ponchant 2017] M. Ponchant, A Barella, G. Stettinger, H. Benzaoui, “Standardized model integration”, OBELICS H2020 GA# 769506, D3.1 Deliverable, public report, December 2017, https://obelics.eu/

[Tastchl 2022] R. Tatschl, “VISIONxEV final results”, H2020RTR’21, Brussels, March 2022

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Appendix 1 – Abbreviations / Nomenclature

Table 4 List of Abbreviations / Nomenclature

Symbol / Shortname	
BEV	Battery Electric Vehicle
CO_2eq	CO_2 equivalent of GHG
EV	Electrified Vehicles
EMR	Energetic Macroscopic Representation
FCV	Fuel Cell Vehicles
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicles
HIL	Hardware-In-the-Loop
I/O	Input / Output
ICE	Internal Combustion Engine

Appendix 2 – List of PANDA members

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project Partners

#	Type	Partner	Partner Full Name
1	UNIV	ULille	Université de Lille
2	IND	SISW	Siemens Industry Software SRL
3	UNIV	VUB	Vrije Universiteit Brussels
4	IND	VEEM	VALEO Equipement Electriques Moteur SAS
5	UNIV	UTCN	Universitatea Tehnica Cluj Napoca
6	SME	TY	Tajfun HIL (Typhoon HIL)
7			*TUV SUD replaced by TUV SUD Battery Testing Gmbh*
8	UNIV	UBFC	Université Bourgogne Franche-Comté
9	SME	UNR	Uniresearch BV
10	IND	RTR	Renault Technologie Roumanie
11	SME	Bluways	BlueWays International bva
12	IND	TUV	TUV SUD Battery Testing Gmbh

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