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

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Written By	Daniela CHRENKO (UBFC) Alain BOUSCAYROL (ULille) Betty LEMAIRE-SEMAIL (ULille) Calin HUSAR (SISW)	2019-05-10 2019-05-14 2019-05-19 2019-05-21
Rewieved by	Cristi IRIMIA (SISW) Maxime REYNOUARD (VEEM)	2019-06-11 2019-06-17
Approved by	Alain BOUSCAYROL (ULille) - Coordinator	2019-06-21
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Publishable Executive Summary

Leader: Dr. Daniela CHRENKO (UBFC), Participants: all except UNR.

The objective of the project PANDA is to provide a disruptive and open access model organization for an easy interconnection and change of models in the development process of EVs. Therefore, the project has to be positioned clearly among other ongoing projects. Moreover, a precise definition of the modelling approach is essential. After an introduction about existing projects in the field, modelling approaches, their philosophies and consequences on the model are presented. Based on these observations the organization tool is presented in detail. Thereafter, different existing simulation tools are presented with an emphasis on Amesim software, that will be used in the context of the project PANDA. The Report closes with discussion and conclusions.

Contributions:

No	*Who*	*Description*	*Date*
1.1	Daniela CHRENKO	D1.1 report creation and outline	2019-05-10
1.2	Daniela CHRENKO	Section 1 – Project objective	2019-05-10
1.3	Alain BOUSCAYROL	Section 2 - H2020 projects	2019-05-14
1.4	Alain BOUSCAYROL	Section 3 – Modelling approaches	2019-05-18
1.5	Betty LEMAIRE-SEMAIL	Section 4 – Organisation tools	2019-05-19
1.6	Calin HUSAR	Section 5 – Simulation tools	2019-05-21
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1. Introduction

The project PANDA will provide a disruptive and open access model organization for an easy interconnection and change of models in the development process of EVs. In order to achieve this goal it is important to start the project with an evaluation of the state-of-the-art. This state-of-the-art analysis naturally has to start with an overview on existing H2020 projects.

In order to prepare the other tasks inside the WP1 Methods (Organisation methodology & testing scenarios) the state-of-the-art report also provides an introduction on modelling approaches covering the different aspects of system modelling. Based on this foundation the representation tool that will be used in the context of the project is introduced in detail. Finally an overview of existing simulation tools is given. A first part is focused on industrial software package that is used in the scope of the PANDA project, before providing and overview of other simulation tools in the domain.

2. Project objective

The objective of the project PANDA is to provide a disruptive and open access model organization for an easy interconnection and change of models in the development process of EVs with the goal to help to reduce the time to market by 20% due to advanced methods. This approach can be represented by the structure presented in Figure 1 with a second V-leg including the possibility to develop virtual subsystems and a virtual prototype that is linked to subsystem and prototype testing by a cloud of models.

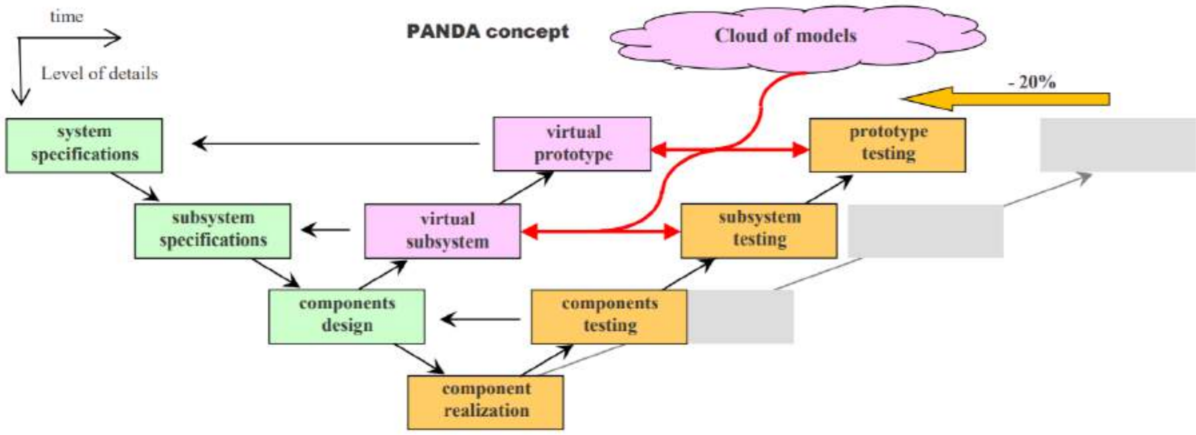


Figure 1: Panda concept and project objective

This approach requires the development of an open organization methodology for virtual and real testing of electrified vehicles. This method will enable a smart integration of any model of any subsystem (plug & play) in the virtual and real testing and will enable a significant reduction of the testing time by replacing some real tests by virtual tests.

The unified organization of the models that are used in the V-model process will provide the seamless integration of the different components/systems no matter the task inside the V-model. This enables the smart transfer of models from virtual to real testing allowing a seamless change of the scale of the model of the same component/subsystem. Moreover, this allows the integration of environmental impact indicators for models of each component.

Based on this method, it is planned to achieve a reduction of the development time and cost of different vehicles by 20% and to support circular economy through an integrated method that will also include the environmental impact of the different components/subsystems.

Moreover, the developed method will be integrated in an industrial software package for a seamless virtual or real testing using Stand-Alone or Cloud-Computing real-time simulation in function of the user request. Amesim, a well know structural software in automotive industry, has been selected. The challenge is to develop a dedicated functional causal library to enable the coupling of existing software

with this disruptive model organization. The aim is not to replace actual simulation tools but to offer a new perspective for virtual and real testing.
This industrial software package will be extended to provide a library of models organized following the proposed method available on a cloud, the use of the same real-time models for virtual or real testing, facilities for cloud-computing towards industry 4.0. Based on this approach, a multi-power platform for complex and modular electrified vehicles will be developed and made available on the cloud for both virtual and real testing. This smart and seamless virtual and real testing of their concept products through the cloud of models increases the integration of suppliers, both SMEs and research institutes, into the automotive product development. The acceleration uptake of innovation leads to an increase in the penetration of the market of electrified vehicles by faster development using the association of virtual and real testing.

This method will be applied on existing vehicle and virtual testing will be validated based on measurement of these real vehicles. Moreover, an innovative concept of Plug-in HEV (P-HEV) will also be considered with virtual and real testing of its electrical subsystems. In order to check the interest of the proposed methods, different cases will be studied.

1) A BEV (Battery Electrical Vehicle), provided by RTR, a Renault Zoe with available calculus parameters are and with an instrumented vehicle with 32 km of different road profiles for driving tests. The virtual testing will be compared with the previous development.
2) A light Fuel Cell Vehicle (FCV) from the FP7 MobyPost project, provided by UBFC. All parameters and Fuel Cell test bench are available, as some driving tests. The virtual testing will be compared with the previous development.
3) An innovative Plug-in Hybrid Electric Vehicle (P-HEV), based on a demo car of Valeo (VEEM). A series-parallel HEV with a 48V battery and low-voltage electrical machines will be considered. The new electrical subsystems (batteries and e-drive) will be studied both in virtual and real testing.

<u>As an outcome of these case studies, the following objectives of the project PANDA will be validated: First, the reduction of the development time and cost of the reference electrified vehicle by 10% to 30%</u>[1]. Second, the validation of the innovative P-HEV concept through virtual and real testing.

First, the PANDA project is situated with regard to other H2020 projects. In order to achieve the goal to develop a standard organization for flexible simulation and testing of innovative EVs and components, it is important to have a clear and common understanding of the baseline of model organization. Therefore, an extensive state-of-the-art of modelling approach is required. As soon as this foundation is laid, a stat of the art of representation tools helps to see how representation tools can answer the demands of the project. With the objective of the integration of these representation tools into existing simulation tools, an overview is given with an emphasis on the simulation tool used in the context of PANDA.

3. Other H2020 projects on EV simulation

Many H2020 projects have already been conducted on simulation of electrified vehicles. A non-exhaustive review is proposed (Table 1). Some projects are relevant to one aspect of PANDA and other projects (labeled with *) are relevant to several aspects of PANDA.

Globally some projects aim to develop a common frame for the simulation of BEVs and HEVs in order to better design and control them (ASTERICS, CASTOR, OpEneR, MAENAD, SafeAdatp, etc). These projects generally deal with unified models, but there is no generic development of the virtual and real testing of subsystems. On the contrary, some projects are dedicated to subsystems, especially batteries, where

[1] 10% for BEV (single source vehicle) to 30% for FCV (multi-source vehicle with Fuel Cell as sensitive technology)

different testing facilities and procedures are developed (BATTERIES2020, COSIVU, FIVEVB, DEMOBASE, etc). In these projects, there is no common organization of testing of different subsystems. PANDA could thus be considered an extension of these projects, and could benefit of their development to propose a real generic method.

Moreover, other projects could provide relevant inputs for PANDA on batteries (BATTERIES2020, COSIVU, FIVEVB, DEMOBASE, etc), e-drive models (ALNEMAD, DEMOTEST-EV, EMDA_LoOp, etc), energy management including consideration of real driving cycles (e-DAS, OPTEMUS, OSEM-EV, etc) and safety (EFUTURE, OSEM-EV, DEMOBASE, etc.). It is sure that PANDA will not develop all these aspects, but could take benefit of their development (if available) to better focus on the open generic method for virtual and real testing of electrified vehicles.

Specific on-going and relevant projects are described in the next subsection.

Table 1: Relevant projects related to PANDA

Project Name / URL	Related program	Main developments	Position vs. PANDA
ALNEMAD www.alnemad.utcluj.ro	PNCDI II 2012 Romanian program	Open architecture co-simulation-environment for design, **modelling and testing** of low-noise **electrical drives** for automotive.	Only focused on e-drive.
* ASTERICS www.asterics-project.eu/	FP7-SST-2012-RTD-1	Modelling EV components. **Integration of different kinds of models in a unique environment**	Not dedicated to real testing, even has a unique simulation environment
BATTERIES2020 www.batteries2020.eu/	FP7-2013-GC-MATERIALS	Development of **testing methodologies** for better under-standing batteries degradation	Dedicated to the testing of batteries
COSIVU	FP7-2012-ICT-GC	Development of a smart e-Drive for an EV including new power electronics unit, novel control and health monitoring	Uses HiL for testing components but not focused on the testing organization
* DEMOBASE https://www.demobase-project.eu/	H2020-GV-2017	Development & **testing of electrical subsystems of BEV** with improvement in efficiency and safety.	Various independent software tools and global HiL real testing.
eDAS edas-ev.eu/	FP7-2013-ICT-GC	Development of new systems and global **energy management** for EVs. Focus on thermal management	Not dedicated to vehicle components testing procedures
FIVEVB http://cordis.europa.eu/	H2020-GV-2014	Develop new battery technology. Development of **test procedures** to reduce the development time.	Focused on battery tests. Not related to model organization and HiL
GIANTLEAP http://giantleap.eu/	FCH- 700101	Improving the lifetime and reliability of **fuel-cell systems in city buses** using EMR based system model	Focused on influence of component aging.
iCOMPOSE http://www.i-compose.eu/	FP7-2013-ICT-GC	**Improve energy efficiency** using more efficient, **safe** and comfortable energy managements	Focused on control and strategy. Not related to models and no HiL organization
* Hifi-Elements http://www.hifi-elements.eu/	H2020-GV-2017	standardization of model interfaces for common e-drive components only for BEV	Uses co-simulation, no coupling of virtual and real testing, no

			cloud.
* OBELICS https://obelics.eu/	H2020-GV-2017	Innovative **multi-scale modelling** of EV components based on **co-simulation for real-time testing**	Only focused on BEV. Based on co-simulation of structural simulation tools.
OPTEMUS http://cordis.europa.eu/	H2020-GV-2014	Developed optimised **energy management** (including thermal aspects) and combine **virtual** and **real-life prototyping**	Mainly dedicated on energy management. Not related to model organisation and HiL
OSEM-EV http://cordis.europa.eu/	H2020-GV-2014	**Improvement of mileage** and predictable range without adding further cost and weight. Focused on better electro-thermal management.	Not related to model organisation, test procedures and safety
* SafeAdapt http://www.safeadapt.eu/	FP7-2013-ICT-GC	Novel architecture concepts, system **modelling, design and validation**, for EVs regarding **safety**, reliability and cost (based on AUTOSAR).	Not related to the development of a methodology to model organisation and HiL

3.1. OBELICS

Name: Optimization of scalaBle rEaltime modeLs and functIonal testing for e-drive ConceptS
Framework: Horizon 2020, GV-07-2017, GA # 769506
Coordinator: AVL, Austria
URL: https://obelics.eu/

OBELICS proposes real testing for BEV in the framework of the V-model (Figure 2). It is also based on multi-level models from physical principles. A systematic scalable approach will be used for real-time models to be used for Hardware-In-the-Loop testing.

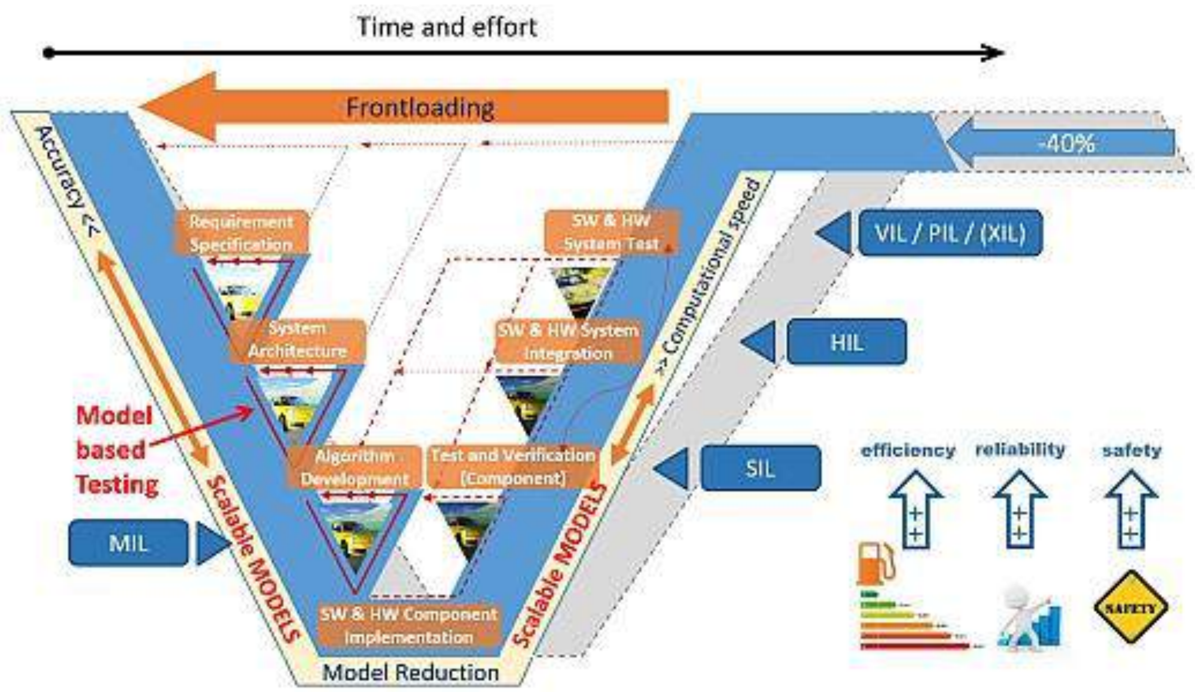


Figure 2: OBELICS project overview [Ponchant 2017]

The concept of OBELICS is to implement systematic modelling and testing of the system from the beginning phase. The different structural-based software tools of some partners are coupled through co-simulation (Figure 3) and FMI (Flexible Mock-up Interface) that facilitates the interconnection but increase the computation time [Ponchant 2017]. Moreover, model reduction is conducted to reduce the complexity for certain simulation and testing in real time.

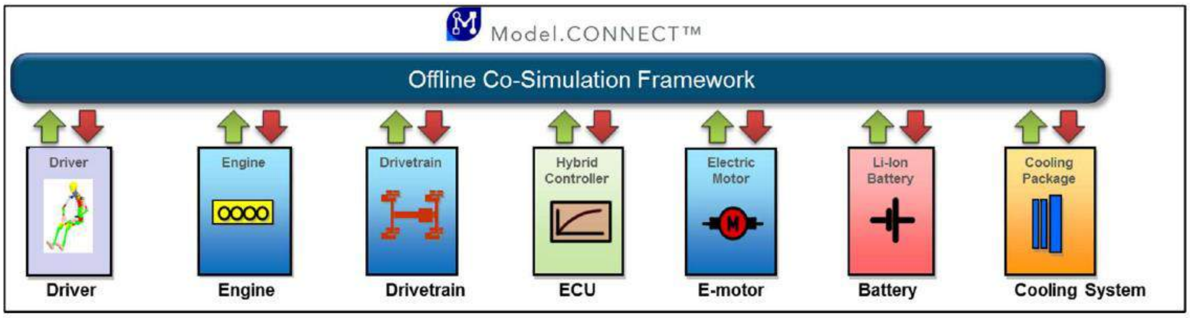


Figure 3: OBELICS project: co-simulation principle [Ponchant 2017]

From the main presentation, a comparison table can be proposed for OBELICS and PANDA (Table 2). The common objective is to propose methods for interconnection of models for the development phase of electrified vehicles. The main difference is that OBELICS is focused on the coupling of different structural software packages while PANDA is focused on a cloud based on a unique software using a functional description. Moreover, PANDA is not a modelling approach but a model organization. It could be of interest to compare both approaches and develop common work in the future.

Table 2: Comparison between OBELICS and PANDA

OBELICS	PANDA
Modelling approach	**Model organization**
Co-simulation (through FMI)	**Cloud of models**
Structural Software	Functional software
RT based on simplified models	**RT based on causality**
Only for BEV	BEV, **FCV, HEV**

3.2. HIFI-Elements

Name: High Fidelity Electric Modelling and Testing
Framework: Horizon 2020, GV-07-2017, GA # 769935
Coordinator; FEV, Germany
URL: https://www.hifi-elements.eu/hifi/

HIFI-Element aims to propose standardization models and workflows for power components of electric vehicles to face the fragmentation of tools and facilitate model reuse, interoperability and scalability. This aim will be achieved by the development of 1) standard interfaces for models and 2) workflow method for linking existing tools.

A system engineering methodology based on the V-model is used (Figure 4). Basic principles of abstraction and decomposition will lead to the simulation model development and interfaces.

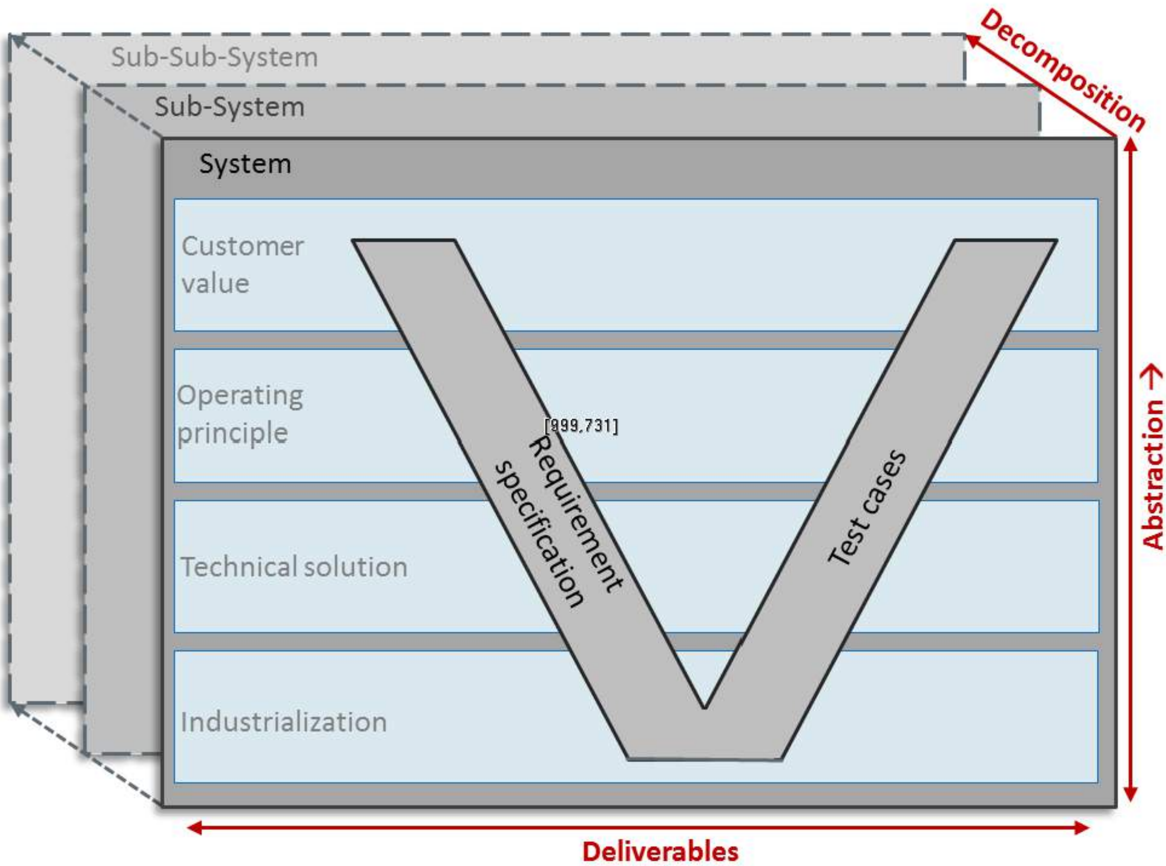


Figure 4: HIFI-Elements and system engineering methodology [Santanori 2018]

The proposed standardization model interfaces will define boundaries, signal and data to be exchanged. This interface will be added to the model in the selected software (Figure 5). They will be crucial elements towards consistency and seamless use of models by connecting various modelling and simulation tools.

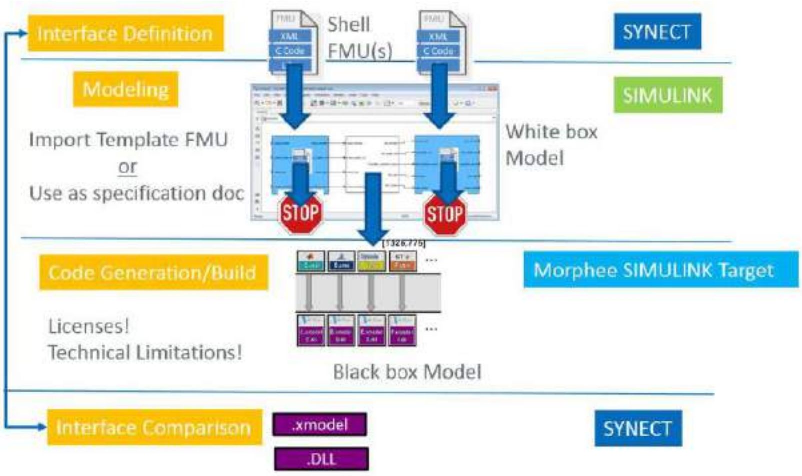


Figure 5: HIFI Elements and strandization of model interface [Deppe 2018]

Based on the architecture model à 150% system model has been created. To be able to derive the 100% architectures from the 150% system model the usage information for the specific architecture is attached to each Input/Output Port, Submodel and Port Connection. Moreover, a management tool will be developed for co-simulation and real testing in order to reduce the development and testing effort. Automatic testing is targeted.

From the main presentations, a comparison table can be proposed for HIFI-Element and PANDA (Table 3). The common objective is to propose standards for model interconnections for the development phase of electrified vehicles. The main difference is that HIFI-Element is focused on the coupling of different software packages and modelling approaches while PANDA is cloud-based simulation package using a unique software as an example. It could be of interest to compare both approaches and develop common work in the future.

Table 3: Comparison between HIFI-Elements and PANDA

OBELICS	PANDA
Model organization	Model organization
Multi-software applications	**Mono-software target**
RT co-simulation (trough FMI)	**Cloud of models**
150% interface (1 interface for several models)	**100% interface (1 interface for 1 model)**
Only for BEV	BEV, **FCV, HEV**

3.3. Other GV-02-2018 projects

The Call LC-GV-02-2018[2] was entitled "Virtual product development and production of all types of electrified vehicles and components". It aims to propose significant advances in digitization offer new opportunities for the automotive industry in terms of virtual product development and production, reducing the time-to-market of all types of electrified vehicles at lower costs. Four different proposals have been selected and funded by the European Commission, including PANDA. If the contents of the other projects are not yet detailed, it is sure that they are related to the same global objective.

3.3.1. UPSCALE

Name: Upscaling Product development Simulation Capabilities exploiting Artificial inteLligence for Electrified vehicles
Framework: Horizon 2020, GV-02-2018, GA # 824306
Coordinator: IDIADA Automotive Technology SA, Spain
URL: https://www.upscaleproject.eu/

UPSCALE aims to integrate Artificial Intelligence (AI) methods directly into traditional Computer Aided Engineering (CAE) software and methods for the development of electrified vehicles. Novel modelling methods such as reduced order modelling will be used to further reduce simulation time and ease optimization tools.

3.3.2. XILforEV

Name: Connected and Shared X-in-the-loop Environment for EV Development
Framework: Horizon 2020, GV-02-2018, GA # 824333
Coordinator: TU Ilmenau, Germany
URL: https://xil.cloud/

XILforEV aims to develop a complex experimental environment for designing electric vehicles and their systems, which connects test platforms and setups from different domains and situated in different geographical locations. XILforEV will include novel techniques for connecting experimental labs and dedicated case studies for designing EV motion control and EV fail-safe control. It will develop hardware

[2] LC-GV-02-2018 https://cordis.europa.eu/programme/rcn/703865/en

and software components for XIL, use machine learning to improve real-time model accuracy and performances, develop high-confidence models, etc.

3.3.3. VISION-xEV

Name: Virtual Component and System Integration for Efficient EV Development
Framework: Horizon 2020, GV-02-2018, GA # 824314
Coordinator: AVL, Austria
URL: https://vision-xev.eu/

ISION-xEV project aims to develop and demonstrate a generic virtual component and system integration framework for the efficient development of all kinds of future electrified powertrain systems. It aims to develop novel high-fidelity reduced models, coupling and interfaces of these models for in-house research code, model integration and co-simulation approach.

4. State-of-the-art on modelling approach

From a real system to its simulation, several steps are required [Bouscayrol 2008] (Figure 6). The first step is the modelling step where a model is built considering assumptions, i.e. phenomena to consider or to neglect. The second step is representation, where the model is organized for a better understanding. The last step is simulation, where the representation is implemented in simulation software selecting the solving method and the simulation step.

The steps of modelling and of representation (i.e. model organisation) should thus be differentiated. It is especially relevant when the system is complex. Nowadays, due to powerful simulation software, the three steps are often merged. In case of systems composed of multiple subsystems, the representation step could be a way to organize the different models to be interconnected in a proper manner. The systems decomposition is thus a key point.

The following subsections are dedicated to remind key concepts for the simulation of multidisciplinary systems such as power train of electrified vehicles.

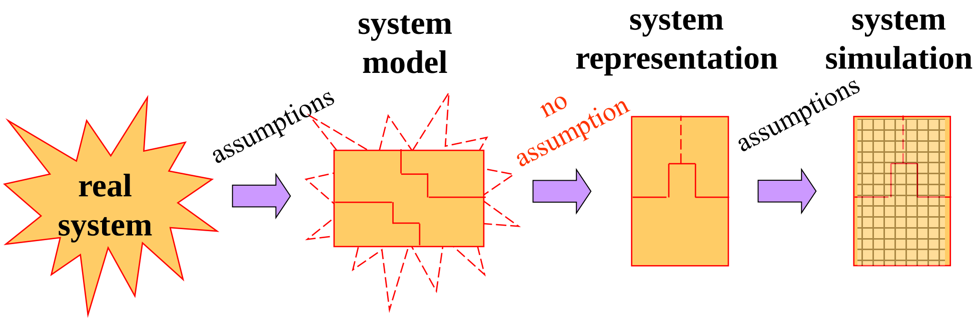


Figure 6: Different steps before simulation [Bouscayrol 2008]

4.1. Cartesian and Systemics approaches

The classical way to study a system is called the Cartesian approach. It is based on the principle of superposition, which enables an independent study of their subsystems. The global behaviour is then assumed to be the superposition of the local behaviours of subsystems. This approach is valid under the assumption of weak interactions between subsystems.

On the contrary, the Systemics approach (or System theory) requires a global study of subsystems in order to consider their interaction [Von Bertalanffy 1968] [Astier 2012]. This interrelation leads to the notion of complexity and to the holism principle, which indicates that some system properties can only appear at the global level [Le Moigne 1995]. Many principles have been developed in Systemics but only two main principles are considered in this chapter.

First, the interaction principle states that any action from a subsystem to another subsystem leads a reaction from the second to the first one. In physical domains, this principle is extended by the notion of power, which is the product of the action and the reaction. As an example, if a battery imposes a voltage to a load (action), this difference of potential leads to a current flowing thought the load, and this current will also flow through the battery (reaction). As well known in electricity, the power exchanged by both elements is the product of the voltage and the current. This interaction principle is valid in the different fields of Physics.

Second, the principle of Holism states that when connecting two subsystems, some local properties disappear and global properties appear. As an example, the direct connection of two rotating shafts (Figure 7) leads to global static and dynamical parameters, which is not the superposition of the ones of each initial element. A unique equivalent shaft should thus be considered to have a better understanding of the global behaviour of this association. The notion of conflict of associations is generally used: both elements would impose their behaviour to the other (conflict) but only an equivalent element will define the right global behaviour [Bouscayrol 12]. One problem of this approach is the replacement of a physical element by a fictive equivalent one that leads to a lack of visibility on the system real topology.

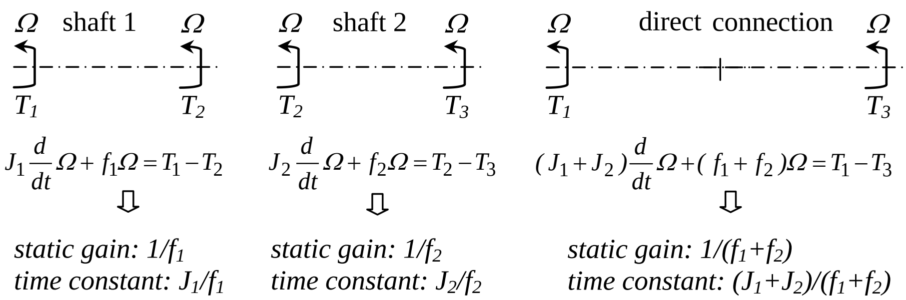


Figure 7: Principle of holism: example of two connected shafts

One can conclude that a Cartesian approach can only be used if there are weak interactions between subsystems. In other cases, first the right interaction should be considered and the global properties should be defined. In modern simulation tools, the solvers should detect the conflicts of association and resolve them. It was the basis of electrical circuit software based on the “state space representation” in the 80’s [Greenwood 1991]. The main idea is to keep the real topology of the studied circuit, while simulating mathematical equations of equivalent elements. Nevertheless, some conflicts are difficult to detect and resolve, especially in multi-domain applications.

4.2. Static vs. dynamical model

Different kinds of models can be used to describe systems in function of the considered phenomena. In this chapter, the difference between static and dynamical model is discussed.

A dynamical model describes the dynamical behaviour of a system, i.e. the steady state but also the transient state. For example, the model of a coil can be described by a resistance *R* and an inductance *L* with classical assumption. The following mathematical relationship links the voltage *u* and the current *i*:

$$u = Ri + L\frac{d}{dt}i \tag{1}$$

This first order equation leads to a first order response of the current evolution for a voltage step. Between the two steady states, a first order transient is thus considered without overshoot and with response time (delay) related to the time constant *L/R* (Figure 8.a).

A static model does not take into account the transient state. Any change is considered as instantaneous. In the example of the coil, if the current is assumed constant, the following simplified equation can be considered:

$$u = Ri \qquad (2)$$

In this case for a voltage step, the current has also a step response without overshoot and delay (Figure 8.b). That means that, in this case, the transient is neglected. This assumption can be made if, in the study objective, the transient of this component has no effect on the global behaviour of the system.

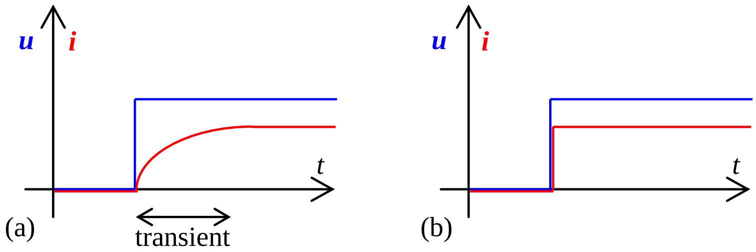


Figure 8: Current response of a coil in case of a) dynamical model, b) static model.

4.3. Structural vs. functional representation

The representation of a model is a specific organisation without changing any assumption. Different classifications of representation can be proposed. First structural and functional representations are discussed. Second causal and acausal representations are presented.

A structural representation describes the system by components connected by physical links. In that way, the physical organisation of the system (topology, electrical circuit, 2D or 3D shape, etc.) is highlighted. This kind of representation is more related to the design phase of the realization of the system. However, more and more simulation packages have adopted this kind of representation due to an easy building of the system model following its physical organisation. In this case components are “pick and drop” from dedicated libraries and physical links are drawn between them, as in the real life (e.g. two links represent two wires of an electrical circuit).

In a functional description, the system is described by functions, which are connected by virtual links (i.e. variables). The functionality of the system is then highlighted. This kind of representation is more related to systems analysis and control design. The associated simulation packages are composed of libraries of functions. In that case, the different functions are connected by variables (i.e. virtual links). It could lead to a lack of visibility of the physical organisation of the system, but the understanding of the system behaviour is easier.

Another classification of representations can be related to the causality. The causality principle defines the cause (input) and the effect (output) in a physical way: the effect can only appear after the cause, or the output is obtained from the input after a delay [Iwasaki 1994]. It has been demonstrated that this behaviour is associated with the energy storage in components, and that the output is an integral function of the input in that case [Hautier 2014]. It is thus stated that the derivative operator is a mathematical function but has not a physical sense (the effect cannot anticipate the cause). It can be noted that in components without energy storage, there is no a priori input and output. In a causal representation, the causality principle is respected and I/Os are fixed to ensure that the outputs are always integral functions of inputs (the effect precedes the cause). The advantage is that this description leads to a better understanding of the system behaviour. The drawback is that it is sometimes difficult to interconnect some subsystems, which would like to impose the same variable (i.e. conflict of association). In this case the holism principle should be applied and equivalent fictive elements should be defined.

In an acausal description, I/Os are floating for any subsystem. In this case, it is very easy to interconnect components whatever their compatibility in terms of causality. When a conflict of association occurs, different solving methods can be used, such as describing one of the components using a derivative relationship. The advantage is that interconnections of components are very transparent for the user; that is why most of structural software packages use acausal descriptions. The drawback is that the understanding of the system behaviour is more difficult as well as the control design (see section 5, EMR). Moreover, solving methods require more calculation and/or computation time to solve this conflict of association [Rubin 1997]. However, with the high capacity of the actual simulation tools and computers, this computation time is often non-prohibitive for users. Nevertheless, it can lead to some difficulties when real-time simulations are used like in HIL testing.

If structural representations are generally associated with acausal description, functional representations can use both causal and acausal descriptions (e.g. in Matlab/Simulink© - functional software – the derivative operator is available and more and more used).

4.4. Forward vs. backward simulation

In a forward approach (direct simulation), the simulation is defined to obtain the system's outputs from the imposed inputs. The real system behaviour is thus respected. For this purpose, in order to get the correct output (or set point or reference), a control of the system should be used to define the right input to cancel the error between the targeted output and the system output. The design of a controller is thus required, butleads to additional work. For example, in the study of a traction system of an electric vehicle, a forward approach requires a control of the velocity to define the electrical machine torque, as in real life (and to estimate the global energy consumption).

In a backward approach (inverse simulation), the system target (output) is considered as initial information to find the cause (input) that leads to this target. An anticipation process is considered with the following assumptions: 1) the target is known in advance and no disturbance is considered, 2) the control of the system is considered as ideal as the target is well achieved. The advantage is that no control step is required. The drawback is that any deviation cannot be taken into account. As the backward approach is a reverse causality (from the effect to the cause), acausal (or non-causal) representations are often used in that case. Moreover, as derivative operation can lead to high computation time, as the control dynamics is neglected (ideal control), static (or quasi-static) models are often used in this case.

For forward approach, if dynamic models and causal representations seem more relevant, it can be noted that the different kinds of models and representations are used.

5. State-of-the-art on representation tools

Different representation tools are widely used for system study from the graphical well-know "Bloc diagrams" to the mathematical "State Space Representation". More recently, many graphical descriptions have been developed to propose other view of systems, such as Bond Graph (BG) [Paynter 1961], Causal Ordering Graph (COG) [Hautier 1996], Power Oriented Graph (POG) [Zanassi 1996], Multimachine Multiconverter System (MMS) formalism [Bouscayrol 2000], Energetic Macroscopic Representation [Bouscayrol 2002], Power Flow Diagram (PFD) [Schoenfeld 2004], etc. A valuable comparison has been proposed in [Gawthrop 2007] to compare Bond Graph and classical Block Diagrams that can be extended to any structural/functional or causal/acausal representations. Another comparison [Bouscayrol 2005] demonstrates that the main differences consist in the resolution of conflict of association.

In this section, only BG and EMR are presented because BG is a structural acausal description and EMR is a functional causal description. One can note that POG, PFD and many other tools and software (such as Amesim) are derived from BG. On the other hand, EMR can be considered as an extension of Bloc Diagram, COG and MMS formalism.

5.1. Bond Graph (BG)

The aim of this subsection is only to give a global overview on Bond-Graph. More details can be found in [Karnopp 1975] [Gawthrop 2007], numerous other papers and book chapters on the very used graphical formalism. If BG was initially developed in Mechanics Engineering [Paynter 1961], it is nowadays used in most of the engineering sciences due to its transdisciplinary approach.
Numerous applications use BG since a long time, including electrified vehicles [Filippa 2005] [Silva 2011]. It can be noted that several software packages are dedicated to BG such as 20sim [20S 2019] developed by the Technical University of Twente (Netherlands) in the 70's and now used worldwide by BG specialists with its last release 4.7 in 2018.
BG is a graphical description based on a Systemics approach (interaction principle) for modelling physical systems. If the causality is defined in BG, the natural causality (i.e. integral causality) is not systematically chosen. Indeed, the topology of the system is a priority that leads to use derivative causality [Gawthrop 2007]: BG is thus a structural description.

The bond graph (BG) modelling tool [Karnopp 1975], based on energy and information flow, uses a uniform notation for all types of physical systems. Power exchanges are represented with half arrows ("bonds") bringing a pair of conjugated variables called effort and flow whose product is the instantaneous power exchanged between elements or subsystems.
Different graphical elements have been defined (Figure 9). Three "passive" elements represent the systems: energy dissipation (R element) and energy storage (I element for kinetic storage, and C element for potential storage). Two "active" elements model power supplies (Se, source of effort, and Sf, source of flow). Four power conservative or junction elements enable the connections between the other elements (O, common effort, 1, common flow, TF, transformer i.e. conservation of effort and flow, GY, Gyrator, i.e. change in effort and flow). Other elements based on the previous ones are also developed, but this part is focused on the main principle. The structures of the model are then composed of bonds linking the different elements.

Bond Graphs			
Source of effort Se ⇀ E	$e = E$ $f \rightarrow$ fixed by the system	**Source of flow** Sf ⇀ F	$f = F$ $e \rightarrow$ fixed by the system
Capacitor C ↽ C	$e(t) = \frac{1}{C}\int_0^t f(\tau)d\tau + e(t_0)$	**Inertia** I ↽ I	$f(t) = \frac{1}{I}\int_0^t e(\tau)d\tau + f(t_0)$
Resistor R ↽ R	$e - Rf = 0$	**Resistive source** 1 RS 2 R	$e_1 - R f_1 = 0$ $f_2 = \frac{1}{e_2} f_1 e_1$
1-Junction 1 2 … n	$f_1 = f_2 = \dots = f_n$ $\sum_{j=1}^{n} \pm e_j = 0$	**0-Junction** 1 0 2 … n	$e_1 = e_2 = \dots = e_n$ $\sum_{j=1}^{n} \pm f_j = 0$
Transformer 1 TF 2 K	$e_2 - K e_1 = 0$ $f_1 - K f_2 = 0$	**Gyrator** 1 GY 2 K	$f_2 - K e_1 = 0$ $f_1 - K e_2 = 0$

Figure 9: BG graphical elements [Silva 2014]

Causality information is shown above each half arrow by means of the causal stroke drawn perpendicularly to the bond. However, the integral causality is not exclusive. The first step is to develop the BG structure without considering the causality; the causality is only defined in a second step without changing the system structure [Gawthrop 2007]. In that aim, if the integral causality (natural causality) is preferred, the derivative causality can be used to preserve the system structure. Of course, the model can be rewritten to avoid derivative causality, but it is not the initial aim of BG. The derivative causality is imposed to solve a conflict of association while keeping the physical scheme of the system [Bouscayrol 2005].

BG is a power graphical description for modelling and analyses of complex multidisciplinary systems. It is connected to many other tools. For example, the BG of a system can systematically translate in state space representation (mathematical description) that can be used for analysis and global control design (state space feedback).

An example of the BG of a traction system is given in section 5.3.

5.2. Energetic Macroscopic Representation (EMR)

The aim of this subsection is only to give a global overview on Energetic Macroscopic Representation (EMR). More details can be found in [Bouscayrol 2012] and numerous other papers on this new graphical formalism. Whilst EMR was initially developed in electrical engineering [Bouscayrol 2002], it is nowadays used in many other engineering sciences due to its transdisciplinary approach.
EMR is a graphical formalism to describe energy conversion systems (Energetic) in a cognitive[3] systemics approach (global view i.e. Macroscopic) by a specific organization (Representation) of the models of its subsystems for a purpose of control organization (functional representation).

Even though EMR is a recent formalism developed in 2000, it has already been used in various applications (non-exhaustive list of journal papers):

- Original power electronics structures [Delarue 2003] [Bouscayrol 2005]
- Original electrical drives [Chen 2010], including multi-phase drives [Semail 2003] [Sandulescu 2014]
- Piezoelectric actuators [Nguyen 2014] [Ghenna 2018]
- Fuel Cell systems [Chrenko 2009] [Boulon 2010] [Agbli 2011]
- Various energy storage systems [Azib 2011] [Heidrai 2015] [Castaings 2016] [Lopez 2017]
- Renewable energy applications [Bouscayrol 2009] [Solano 2016] [Barakat 2019]
- Automatic (electric) subway [Allegre 2010] [Mayet 2016]
- Hybrid locomotive [Mayet 2014] [Baert 2014] [Agbli 2016]
- Various Hybrid electric trucks [Boulon 2010] [Lhomme 2017] [Mayet 2019]
- Thermal vehicle [Lhomme 2011] [Horrein 2015]
- Various Hybrid Electric Vehicles [Letrouvé 2013] [Cheng 2013] [Horrein 2016]
- Various Electric Vehicles [Silva 2014] [Horrein 2017] [Nguyen 2019]
- Various Fuel Cell vehicles [Solano 2011] [Depature 2018]

The EMR formalism is composed of 4 main graphical pictograms (*Figure 10*): energy source (green oval), energy accumulation (crossed orange rectangle), energy conversion (orange square for mono-domain conversion and orange circle for multi-domain conversion) and energy distribution (overlapped orange squares for mono-domain distribution and overlapped orange circles for multi-domain conversion). Other elements can be found in [Bouscayrol 2012], but only the main elements are described in this report in order to give a global overview of EMR. All these elements are connected by two arrows, which represent the action and reaction vectors between elements. The scalar product of the action and reaction vector leads to the instantaneous power exchanged by elements.

[3] A cognitive approach is based on the internal knowledge of the system on the contrary of a cybernetics approach (i.e. black box approach).

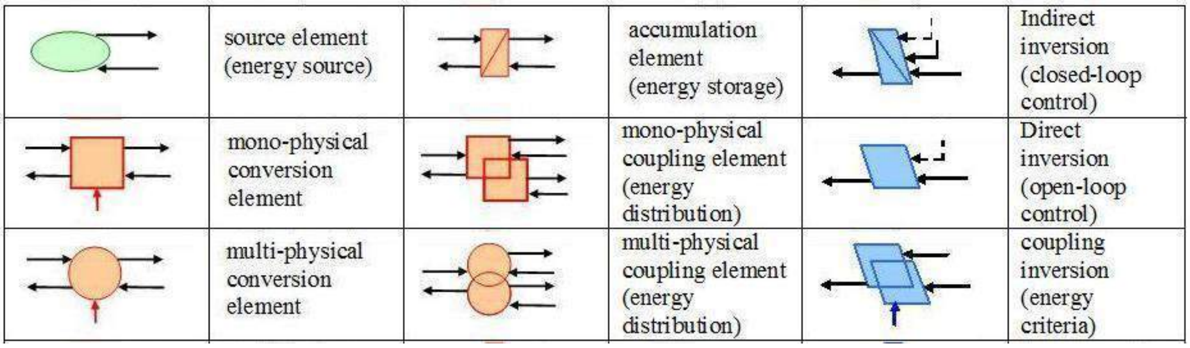


Figure 10: EMR graphical elements [EMR 2019]

In terms of causality, only the physical causality (i.e. integral causality) is accepted. It has been demonstrated that the causality is related to energy storage [Hautier 2004]. That is why only accumulation and source elements have fixed I/Os respecting the exclusive integral causality. As other elements (conversion and distribution elements) do not store energy by definition, their I/Os are floating and are defined by their connections with source and accumulation elements.

In case of conflict of association, in order to keep the physical causality, merging and permutation rules have been defined to find the fictive equivalent elements (Holism principle). That is why EMR is a causal and functional description.

These properties enable a systematic deduction of control scheme from the EMR of a system [Bouscayrol 2012], and this is really a key-point for EMR. Each element is inverted step-by-step to find the Maximal Control Structure (MCS), which is the maximal organization of the control defining the measurement and close-loop control location. Different practical control schemes can be deduced by simplification from that MCS. All control pictograms are described by light blue parallelograms (see *Figure 10*). The inversion of an accumulation element requires a close-loop control. The inversion of conversion elements is realized by direct mathematical inversion. The inversion of distribution elements (or coupling elements) leads to define weighting or distribution inputs to be imposed by a strategy level (higher hierarchical control level). It can be noted that the inversion of the EMR leads to a control organization, but a supplementary step of control design is required (e.g. selection and tuning of the controllers).

An example of the EMR (and the control) of a traction system is given in the next subsection.

5.3. BG vs. EMR

Different comparisons of structural and functional descriptions are available in the literature. The most relevant is [Gawthrop 2007], which compares BG and block diagrams. Most of the differences indicated in this paper can be extended for any structural and functional comparison. It is mainly stated that in BG the description should first be developed before the definition of the natural causality in order to respect the system topology. Moreover, when defining the causality, if there is a conflict of association, a derivative “causality” should be used to keep the topology unchanged.

Other comparisons have been done such as comparison of BG, PFD, COG and EMR in [Bouscayrol 2005], BG, POG and EMR in [Lhomme 2008], POG and EMR in [Zanasi 2008], etc. In these papers, it is underlined that both types of description (i.e. structural or functional) are identical if there is no conflict of association. The fact is that the natural causality can always be respected in this case. When there is a conflict of association, two elements would impose the same state variables if they are described by integral relationship (i.e. physical causality).

Both descriptions can be combined for specific applications. For example, POG and EMR have been combined to describe non-linear tire-road behaviour and anti-slip control [Grossi 2009]. BG and EMR have also been combined to study fault tolerant operation of an electric vehicle [Silva 2014]. In this last example, the switching between normal and fault model is ensured by BG without the need to respect the physical causality, while the control scheme is defined using EMR. These examples demonstrate that the two types of descriptions (structural or functional) are not concurrent but complementary: they have their own dedicated applications and some case could use both to solve them.

In order to highlight the main differences of structural and functional description, the case of a traction system of an automatic subway is considered. This comparison has been already proposed in [Bouscayrol 2005], where all modelling equations are provided. However, a simplified version of this subway is considered in this report in order to focus on a conflict of association.
The studied traction system is composed of an input filter (*L,C*), a chopper, two permanent magnet DC machines, two bogies and the chassis of the vehicle (Figure 11). In the complete structure, DC machines with field winding are considered that requires two field choppers [Bouscayrol 2005]. It is the traction system the VAL 206 subway of Siemens [Mercieca 2006].

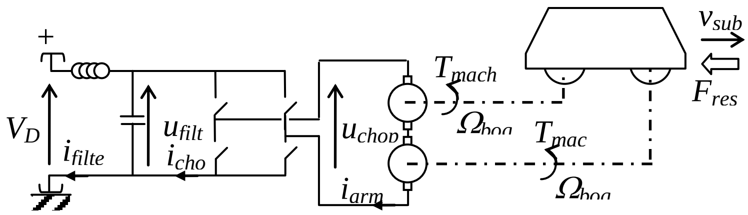


Figure 11: Structural description of the studied systems using electrical schemes

Let us focus on the series connection of the armature winding of the DC machines. The armature equations of each machine are the fowling:

$$L_1 \frac{d}{dt} i_{arm} + R_1 i_{arm} = u_{chop1} - e_{arm1} \quad (3)$$

$$L_2 \frac{d}{dt} i_{arm} + R_2 i_{arm} = u_{chop2} - e_{arm2} \quad (4)$$

Where *L* and *R* are the inductance and resistance of the winding, u_{chop} the supply voltage, i_{arm} the common armature current and e_{arm} the electromotive force.
The static gain and time constant of each winding can thus be deduced:

$$\begin{cases} K_1 = \dfrac{1}{R_1} \\ \tau_1 = \dfrac{L_1}{R_1} \end{cases} \quad (5)$$

$$\begin{cases} K_2 = \dfrac{1}{R_2} \\ \tau_1 = \dfrac{L_2}{R_2} \end{cases} \quad (6)$$

In a natural causality, each armature current would impose the current to the other winding as output of both relations. As the chopper voltage is the sum of u_{chop1} and u_{chop2}[4], a global equation can be rewritten (holism principle):

$$(L_1 + L_2)\frac{d}{dt} i_{arm} + (R_1 + R_2) i_{arm} = u_{chop} - e_{arm1} - e_{arm2} \quad (7)$$

A new equivalent inductance and resistance can be obtained. A new static gain and time constant are thus derived:

$$\begin{cases} L_{eq} = L_1 + L_2 \\ R_{eq} = R_1 + R_2 \end{cases} \text{ and } \begin{cases} K_3 = \dfrac{1}{(R_1 + R_2)} \neq K_1 + K_2 \\ \tau_3 = \dfrac{(L_1 + L_2)}{(R_1 + R_2)} \neq \tau_1 + \tau_2 \end{cases} \quad (8)$$

[4] In a series connection, the current is the same for both elements, and the global voltage is the sum of initial voltages.

Thus, the steady state of the series connections of the DC machine is not a linear combination of the steady states of each machine, as well for the transient states. It is the principle of holism in Systemics: global properties must be considered.

In BG, this conflict of association is highlighted: all variables are defined in an integral causality except the inductance of the second armature winding L_2 (Figure 12). This derivative causality for this inductance enables a structural organization by keeping the two inductances as in the real system. However, this derivative causality required a specific solver and a low simulation step [Silva 2014]. The complete BG of the studied system can be found in [Bouscayrol 2005].

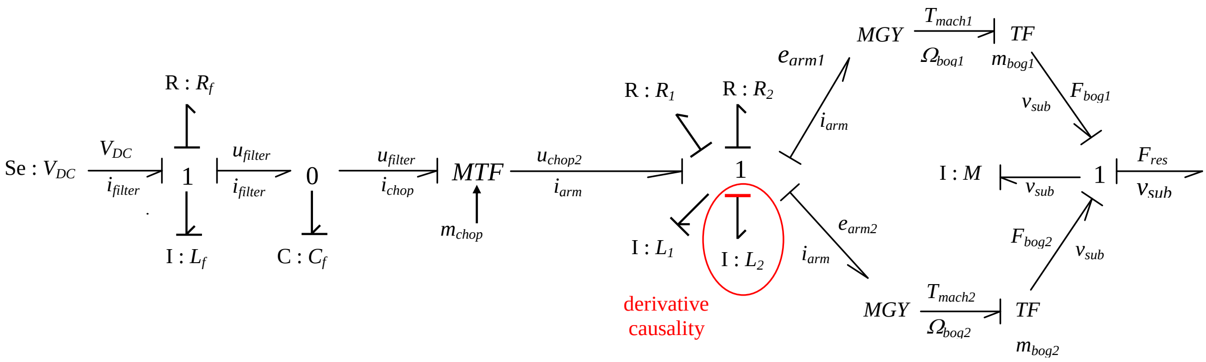


Figure 12: Structural description of the studied system using Bond-Graph [Bouscayrol 2005]

On the contrary, in EMR, the equivalent inductance and resistance are considered to ensure the physical causality with the armature current as output (merging rule):

$$i_{arm} = \frac{1}{L_1 + L_2} \int \left[u_{chop} - e_{arm1} - e_{arm2} - (R_1 + R_2) i_{arm} \right] dt \qquad (9)$$

In this case, a unique accumulation element is considered in the EMR (Figure 13). The system can thus be simulated using a classical solver and reduced computation time because of the exclusive integral causality. Moreover, a control scheme can be systematically deduced. However, the physical topology of the system is not respected because an equivalent fictive winding is considered instead of the two real ones, which are located in the front and rear part of the subways. The complete EMR of the study system can be found in |Bouscayrol 2005].

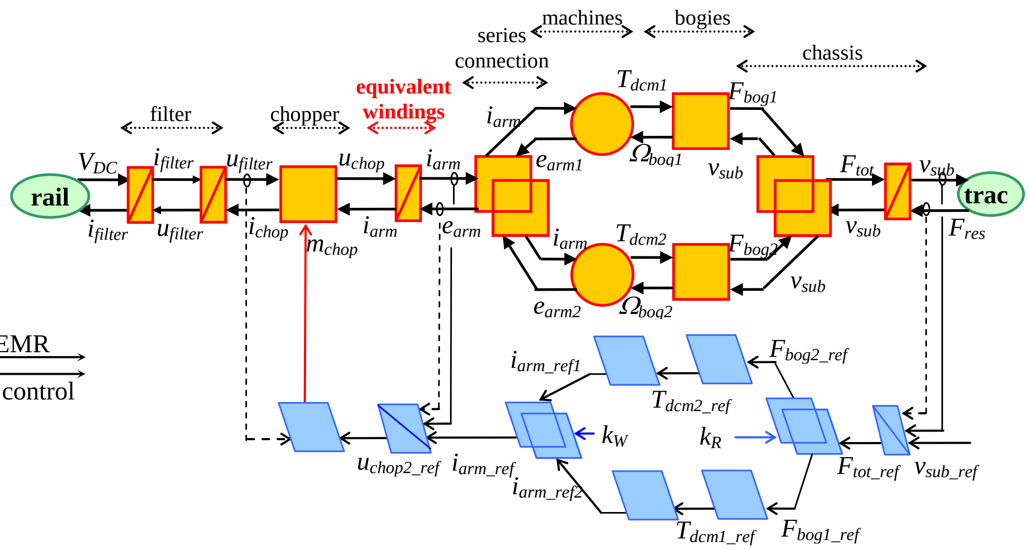


Figure 13: Functional description of the studied system using EMR [Bouscayrol 2005]

It can be noted that EMR has been already used in many HIL simulation and testing studies [Allegre 2010] [Letrouvé 2013] [Lhomme 2017] [Castaings 2016] [Depature 2018] [Nguyen 2019]. Indeed a graphical formalism is a valuable way to organize the numerous parts of HIL (subsystem to be tested, subsystem to be simulated, control of the system, interface system, control of the interface system, etc). Moreover, a causal functional description avoids derivative relationships; this reduces the computation time facilitating real time simulations.

6. State-of-the-art on simulation tools

Product representation has evolved over the last 30 years, from drafting to full digital mock-ups of the product assembly.
Performance verification has evolved from a build-and-break approach to the current practice that includes significant CAE[5] work as well as test. Therefore, product description evolved to full system mock-ups that cover not just mechanical but also electrical, software, and controls descriptions. Moreover, these must be fully integrated into an overall PLM[6] system to ensure we can close the loop from requirements to as-designed behaviour and beyond to manufacturing and usage (Figure 14).

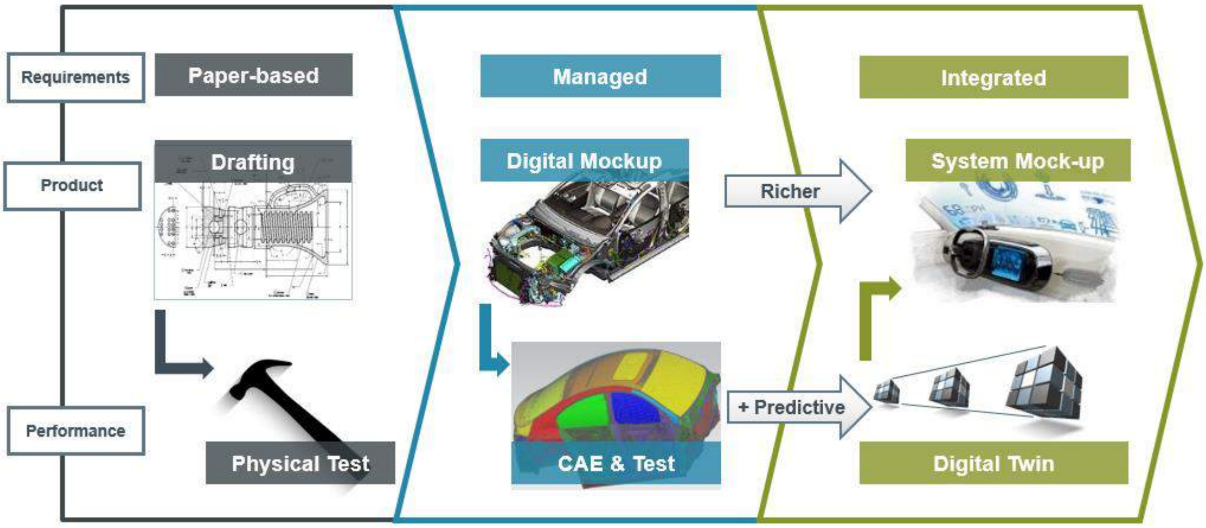


Figure 14: Evolution of product engineering

Many simulation packages have been developed in that philosophy to provide a large panel of coupled tools for engineers. The success of all these simulations packages is related to the quality and the diversity of their libraries of components and subsystems. These elements are thus easily connected together by physical links (structural approach) without a predefinition of their I/Os (acausal approach). However, most of these tools include functional libraries mainly to develop control parts. Therefore, the system remains developed in a structural and acausal approach.
On the contrary to initial simulation tools that focus on a 0D view (only time dependence without space dependence), the tendency is to develop a 1D view (including 1 dimension of the space) up to 3D view (3 dimension of the element). By definition, this space organisation is related to a structural approach.
As Simcenter Amesim will be used in PANDA a specific emphasis on this simulation package is proposed in this report. However, other simulation tools are also briefly described. The main idea is not to compare advance simulation environments that are improving every day, but to propose a global view of these tools thanks to a detailed description of one.

6.1. Simcenter Amesim

Simcenter Amesim stands for **A**dvanced **M**odelling **E**nvironment for performing **Sim**ulations of engineering systems. It is based on an intuitive graphical interface in which the system is displayed throughout the simulation process (Figure 15).
Simcenter Amesim is an integrated, scalable system simulation platform, which allows system simulation engineers to virtually assess and optimize the mechatronic systems' performance. It boosts overall system

[5] Computer -Aided Engineering
[6] Product Lifecytcle Management

engineering productivity from the early development stages until the final performance validation and controls calibration. It is composed of library of physical systems that will be used to define a global system. It is thus a structural software mainly based on acausal elements, even though a functional library is available to define control parts.
Ready-to-use multi-physics libraries combined with application and industry-oriented solutions supported by powerful platform capabilities let system simulation engineers rapidly create models and accurately perform analysis.
Simcenter Amesim is an open environment that can be integrated into enterprise processes. It is easily coupled with major CAE, CAD[7] and controls software packages, can interoperate with the functional mockup interface (FMI) Modelica, and connect with other Simcenter solutions as well as Teamcenter.

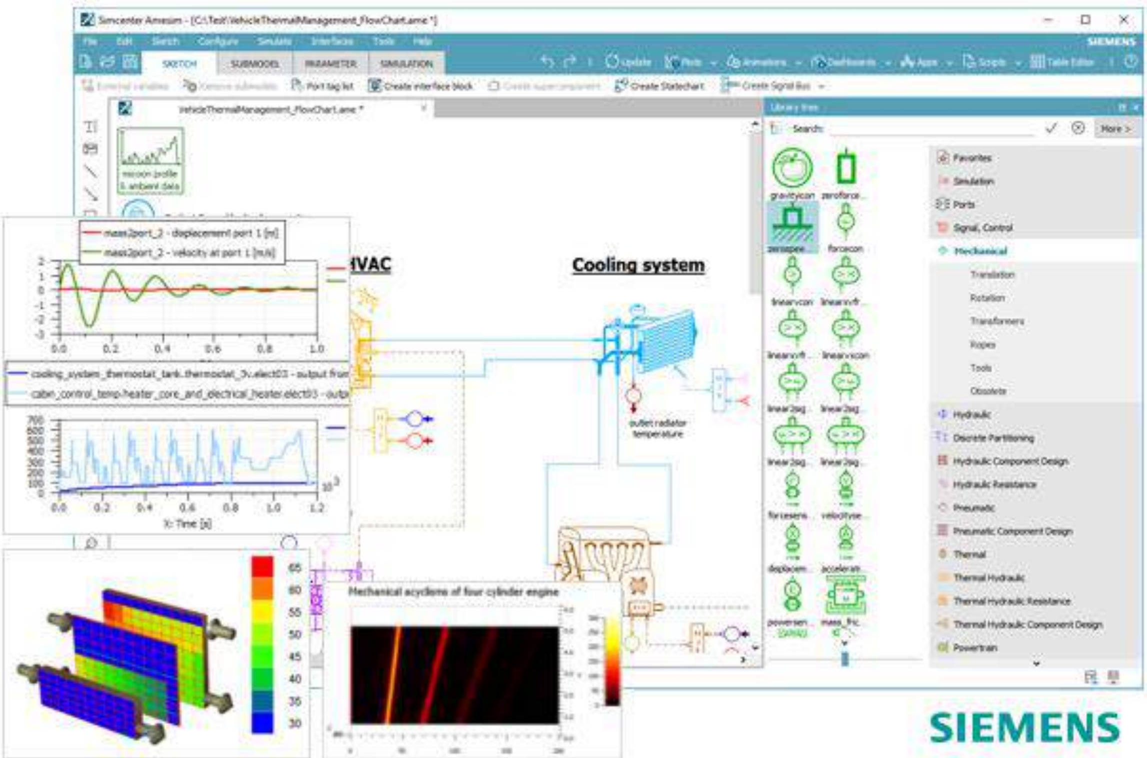


Figure 15: Modelling and simulation with Simcenter Amesim

The software package provides a 1D simulation suite to model and analyse multi-domain intelligent systems, and to predict their multi-disciplinary performance.

6.1.1. The Architecture of Simcenter Amesim

The architecture of Simcenter Amesim is shown in Figure 16. It offers powerful platform features so that any user can easily create a Simcenter Amesim model from the standard Simcenter Amesim libraries or from his own User libraries and run it to get interesting analysis results.
The Simcenter Amesim platform facilities ensure the easy use of the Simcenter Amesim models in day-to-day work, and they allow the integration of Simcenter Amesim in the design process to be used at most stages of the V-Cycle.
The Simcenter Amesim Platform facilities go from the "Simulator scripting" and "Simcenter Amesim customization" facilities up to the "MIL/SIL/HIL and Real-Time" or "1D/3D CAE".

[7] Computer-Aided Design

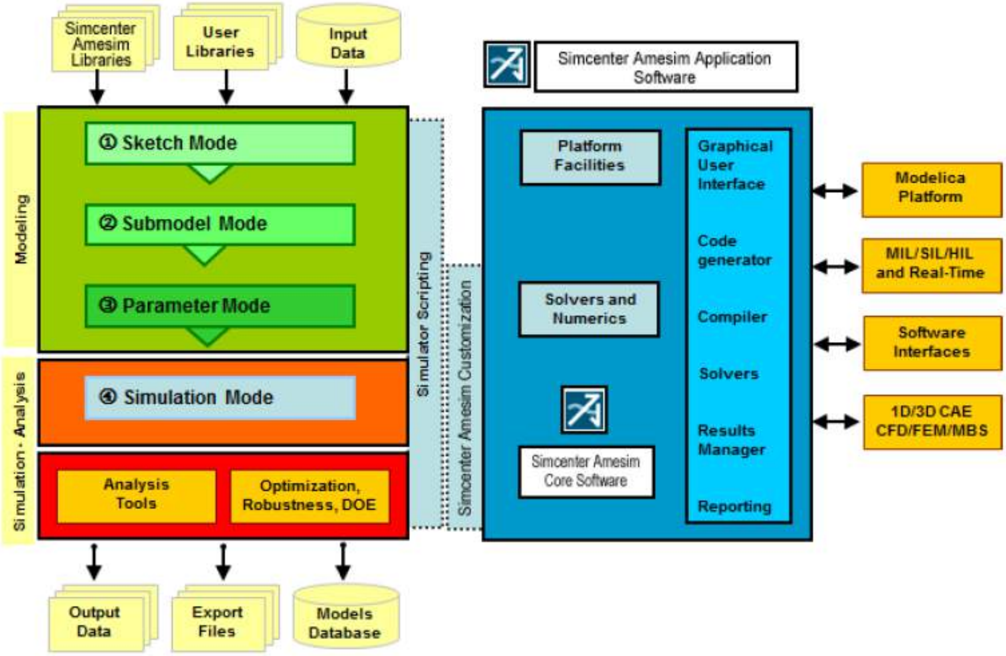


Figure 16: Architecture of Simcenter Amesim (simplified view)

6.1.2. Products overview

Simcenter Amesim software combines the multi-physical system simulation and application expertise in an integrated modelling and simulation platform for analysis of multi-domain, controlled systems. The software includes easy-to-use multi-port modelling of physical components (acausal and structural) as well as a block diagram approach (functional) for control systems and allows coupling them in a comprehensive workflow. Various scripting and customization capabilities enable seamless integration with existing design processes, (Figure 17).

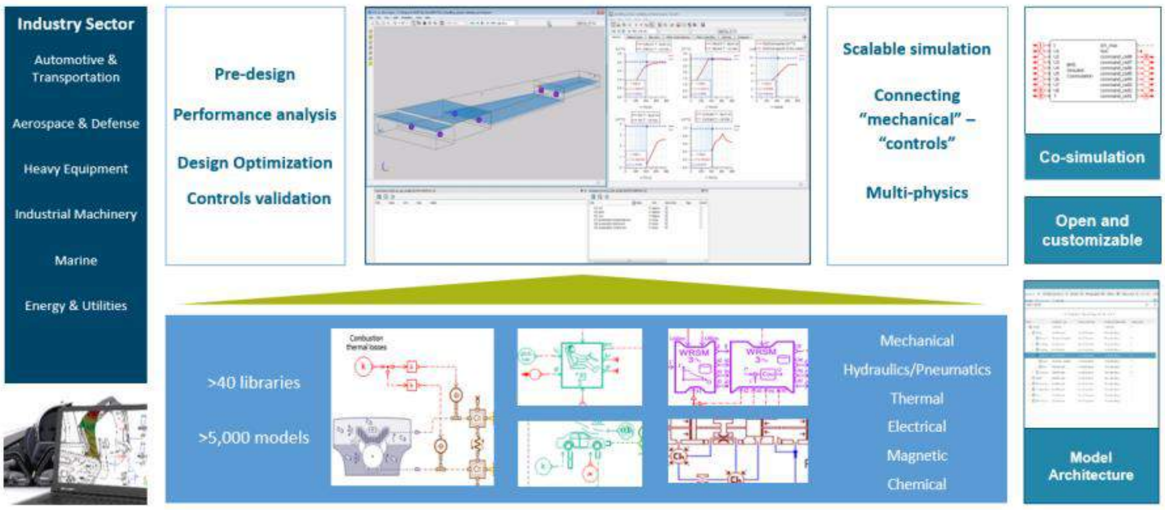


Figure 17: Simcenter Amesim system simulation solutions

Simcenter Amesim features a complete set of physical libraries containing hydraulics, pneumatics, thermal, electrical, mechanical and control signal components, as well as application libraries containing key engineering systems. These components contain years of know-how. Currently over 4000 validated physical models are embedded in the software libraries.

Based on these models, a full system description can be built to simulate the physical, dynamical behavior of complex engineering systems addressing specific industry applications, like vehicle dynamics, fuel systems modelling, hydraulic actuation, etc.
Typical usage for these models is the evaluation of design alternatives in the pre-design phase, system sizing & integration, performance balancing and controls validation.
Another important aspect is the ability to use these models within SiL (Software-in-the-loop), MiL (Model-in-the-Loop) and HiL (Hardware-in-the-Loop) processes for controls validation. Specific embedded tools allow model reduction to create real-time enabled models.

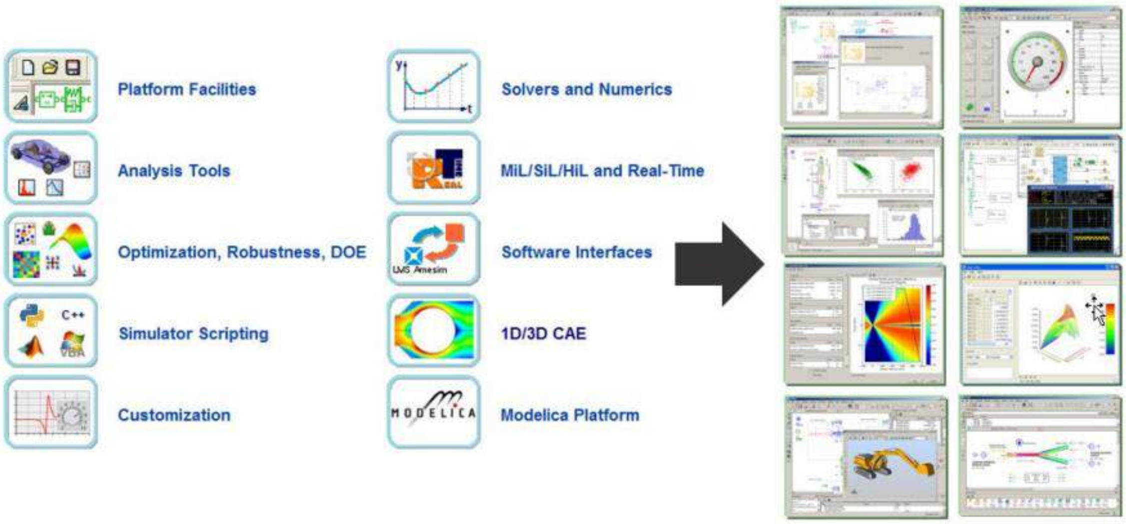


Figure 18: Overview of Simcenter Amesim platform features (partial list)

Simcenter Amesim offers a wide range of features that make it a complete platform for modelling and simulation. To get a fast overview of the Simcenter Amesim platform capabilities a first partial list is presented in Figure 18 where at right side are some snapshots of Platform features to illustrate few of the Platform capabilities in Simcenter Amesim.

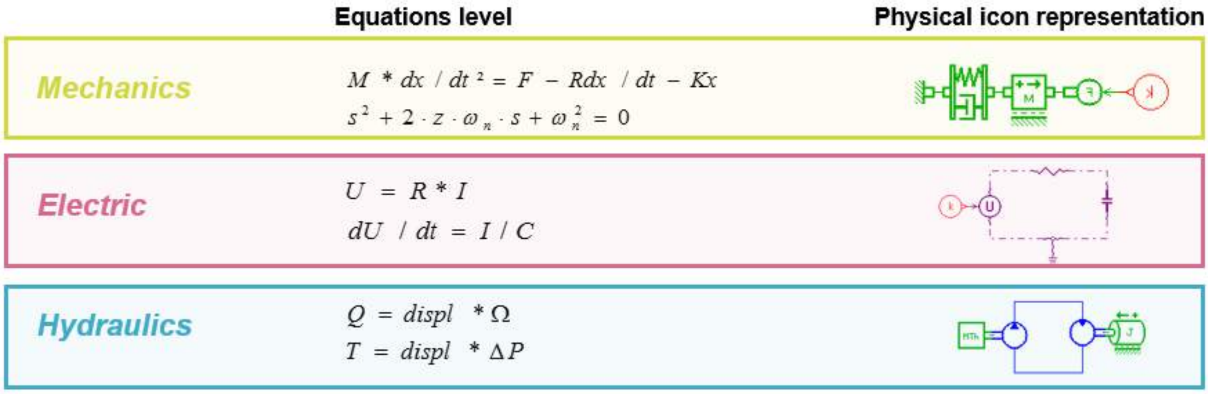
Highlights of the Simcenter Amesim software are:

- Simulation of physical multi-domain systems
- Broad range of application and physical domains
- Automotive, aerospace, and off-highway-specific solutions
- Steady-state and transient analysis
- Linear and non-linear systems
- Input/output analysis
- Parameter sensibility analyses
- Vibration and order analysis
- Time-domain and frequency-domain analysis
- Test systems with MIL/SIL/HIL and Real-Time
- Integration with CAE software tools (Computer-Aided Engineering)

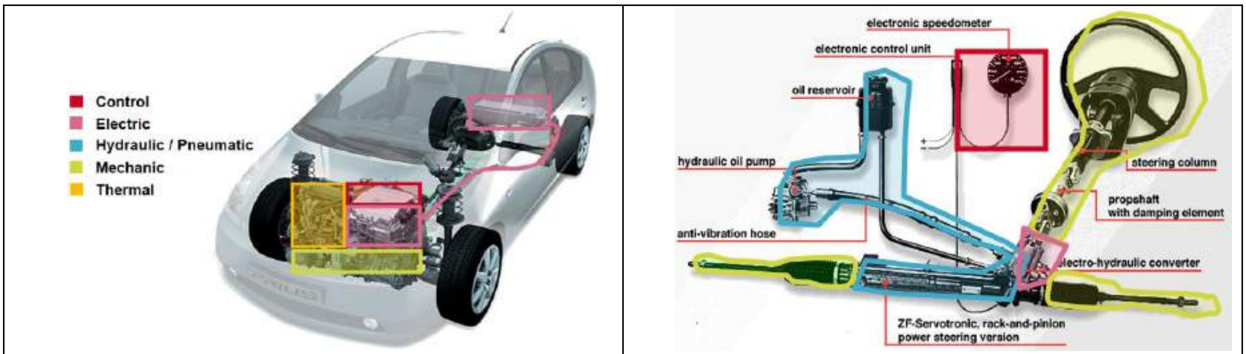
6.1.3. Mechatronics system example

Mechatronics is a multidisciplinary branch of engineering that focuses on the engineering of both electrical and mechanical systems, and also includes a combination of robotics, electronics, computer, telecommunications, systems, control, and product engineering.
One-dimensional computer aided engineering (1D CAE), also referred to as Mechatronic System Simulation, is multi-domain systems simulation in combination with controls.

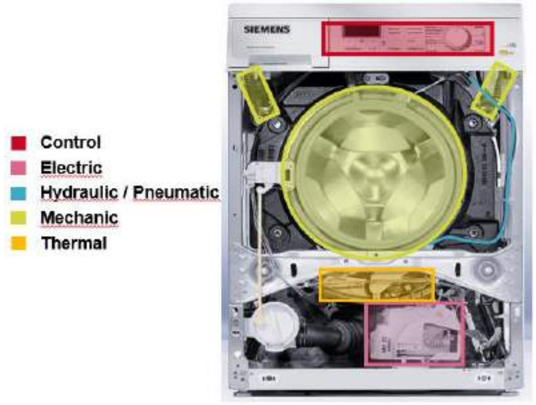
It is an approach to model and analyse multi-domain systems, and thus predicting their multi-disciplinary performance, by connecting validated analytical modelling blocks of electrical, hydraulic, pneumatic and mechanical subsystems into a comprehensive and schematic full-system model.
In a 1D mechatronic software the equations are usually written as **time dependent** with a focus on computing state variables to assess transient evolution and the physical equations of component behavior are represented by ***readable objects (icons).***



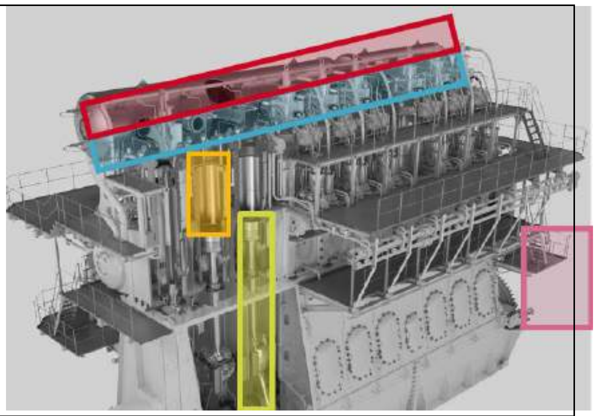
1D CAE calculations are **very efficient**. The components are **analytically defined**, and have input and output ports. Causality is created by connecting the inputs of a component to the output of another one (and vice-versa). That is why it is mainly an acausal tool.
The resulting mathematical system has a **very limited number of degrees of freedom** compared to 3D CAE. This solution **speed** the **openness** of 1D CAE software to different types of software codes and the **real-time** capabilities allow you to streamline the system development process.
1D CAE offers an open development approach, starting from **functional requirements** to **physical modeling and simulation**, enabling concurrent engineering of mechatronic systems in a **collaborative** design environment.
Typical Amesim mechatronics systems with different types of modelling blocks (control, electrical, hydraulic, pneumatic and mechanical subsystems) are presented in Figure 19.



a: Hybrid vehicle	*b: Electro-hydraulic power steering*



c: Washing machine



d: IC Engine

Figure 19: Amesim mechatronic systems

6.2. Application example

To get a better understanding of complex behaviors and for guidance through systems engineering concepts, a series of standard Simcenter Amesim automotive aplications have been developed. The applications cover a large hybrid and electrical range which comes with ready-to-use templates to assess consumption, range, cooling and drivability. These templates provide a good starting point for vehicle electrification projects by delivering parameter consistency and detailed internal combustion engine, transmission, electric drive, battery and cabin cooling subsystems models.

A typical electric Simcenter Amesim vehicle is presented in Figure 20. The driver model computes the braking pedal and accelerator pedal position signals in order to match the imposed velocity profile.

The control unit translates the acceleration demand into a motor torque demand and splits the braking demand into a regenerative braking generator torque demand and a mechanical braking demand.

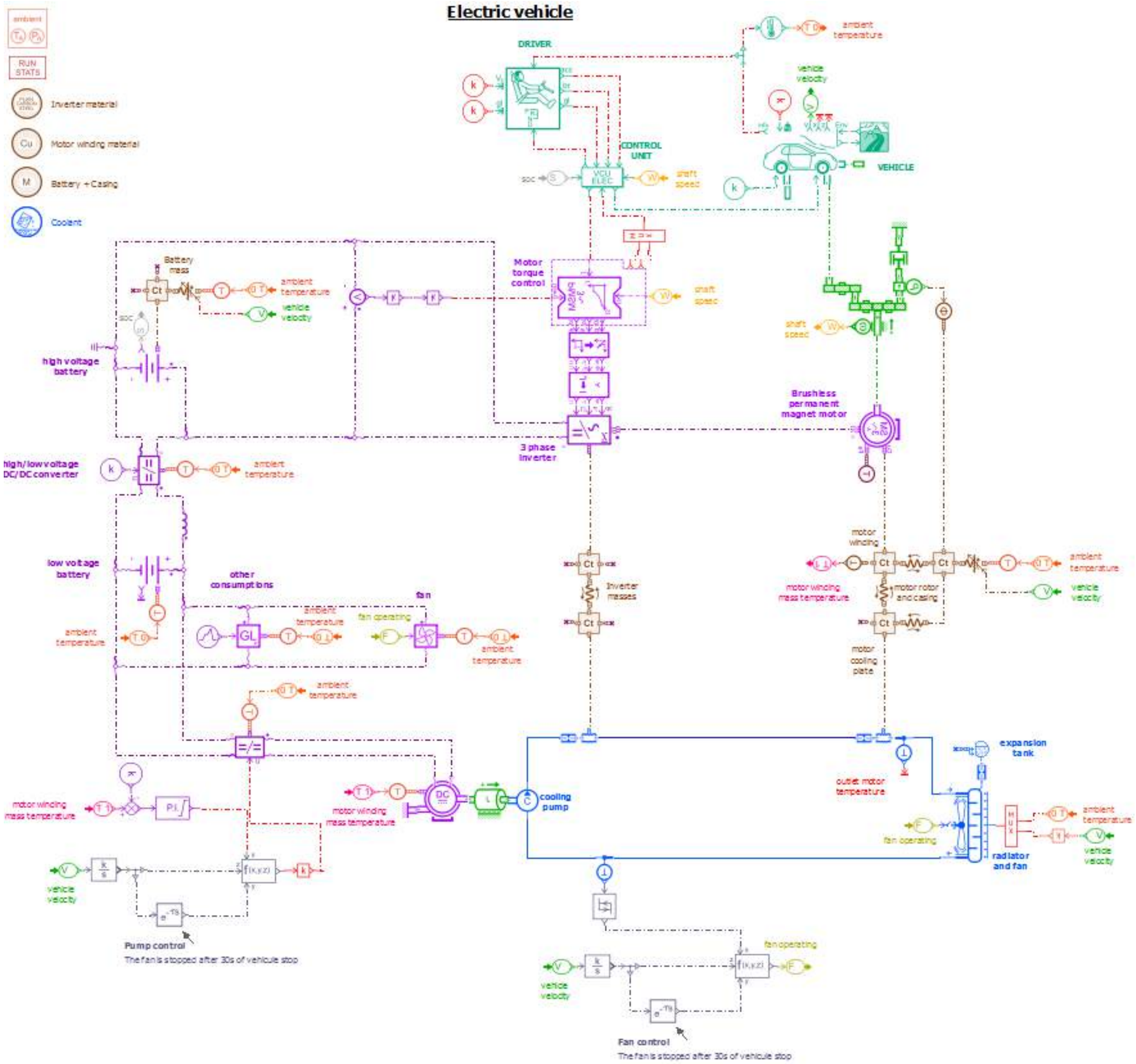


Figure 20: Simcenter Amesim Electric Vehicle

Such an example demonstrator is an efficient tool to study and analyze all phenomena that occur in an EV such as the power flow distribution, thermal management, electric drivetrain, cooling of the battery etc.

6.3. Simulation case study

The benefit of the modelling capabilities of Simcenter Amesim for system simulation solutions are used by many companies around the world.

Thanks to the multi-physics libraries, models and tools dedicated to their own applications, these Simcenter Amesim user's companies can build and validate their models for performing simulations very quickly.

One of the Simcenter Amesim case study simulation is the **Enhancing battery lifetime modeling using Simcenter Amesim** in collaboration with **IFP Energies Nouvelles** (Figure 21, Figure 22)[8]**.**

Main challenges:

- Develop battery aging simulation functionalities

[8] http://www.plm.automation.siemens.com/CaseStudyWeb/dispatch/viewResource.html?resourceId=37741

- Strengthen positioning of Simcenter Amesim as a best-in-class modelling and simulation platform

Keys to success

- Encapsulate fundamental physical phenomena
- Operate simulation platform efficiently
- Analyse electrochemical energy storage system behaviour

Results

- High-fidelity aging models easy-to-use
- Reliable aging simulation results
- Analyse 10 years of battery behaviour in a few hours

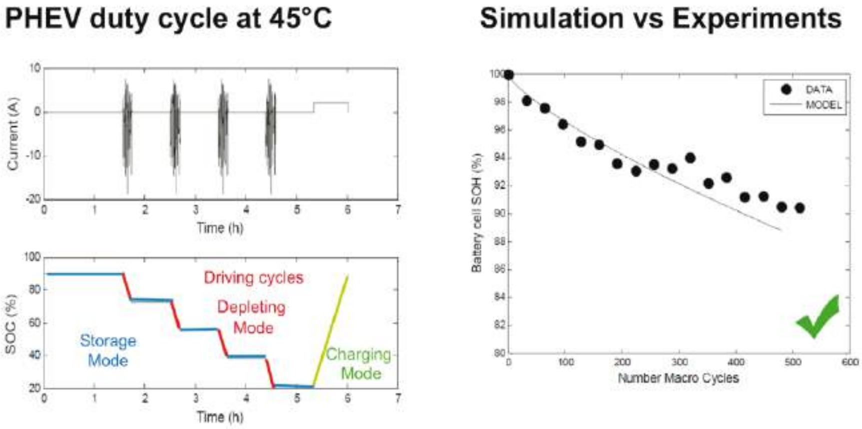


Figure 21: Validated PHEV battery model

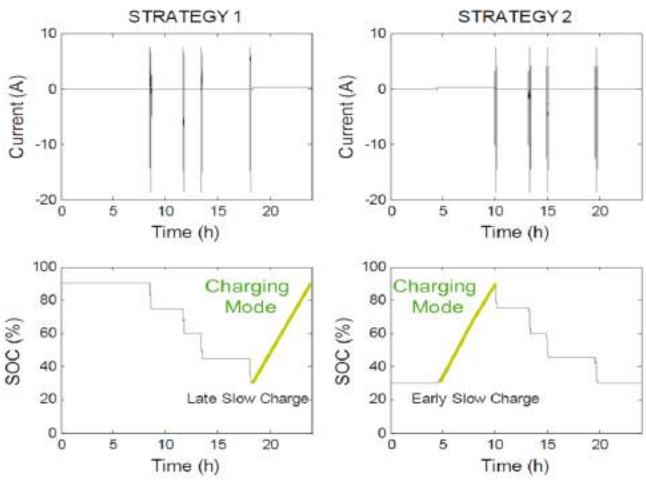


Figure 22: Charging strategy influence on battery life

6.4. Other Simulation Tools

The global 1D multidomain simulation is estimated to witness growth over the next period. Increasing product complexity and interdependence across different physical domains are among the main factors for this growing. This means that capability to develop more complex systems is one of the key factors to succeed both in research and product development.

Some of the most important 1D simulation players in the market are presented hereafter.
Siemens PLM Software and Dassault Systemes are PLM companies, while all other companies are specialized providers of 1D solutions or 1D plus Finite Element Analysis and/or test solutions. The 1D simulation tools produced by these companies are available to design and analyze multi-domain systems

with various types of vehicle solutions and architecture. These tools offer modeling capabilities, solvers and post-processing with a focus on the dynamics of the systems.

The most important 1D multidomain simulation tools on the market have been identified, summarized and compared. Typical 1D automotive applications analyzed include vehicle system analysis, electric vehicle, battery, fuel cell and hybrid powertrain modeling, energy and thermal management.
Simcenter Amesim has a good coverage for all solutions. It is mainly used in industry but has good connections to the Academics world.
GT-Suite, mainly present in Auto domain, was focus at the beginning on IC Engine vehicles but is starting to extend to hybrid & electric vehicle and thermal management solutions.
Dymola combined with Modelica libraries is a good tool for vehicle simulations while SimulationX and AVL Cruise efficiently models and simulates EV systems.

A non-exaustive list of simulation 1D tools is presented hereafter.

6.4.1. AVL CRUISE (AVL)

AVL CRUISE (https://www.avl.com/cruise) is the simulation package[9] that supports tasks in vehicle system and driveline analysis throughout all development phases, from concept planning, through to launch and beyond. Its application envelope covers all conventional vehicle powertrains through to highly-advanced HEV systems. The program offers the flexibility to build up a single system model, which can then be used to meet the requirements of diverse applications in the powertrain and driveline development. Starting with only a few inputs in the early phases, the model matures during the development process according to the continuously increasing simulation needs. CRUISE offers a streamlined workflow for all kinds of parameter optimization, component matching - guiding the user through to practical and attainable solutions. Due to its structured interfaces and advanced data management, AVL CRUISE has established itself as a data communication and integration tool for different teams (Figure 23).

AVL CRUISE application areas
AVL CRUISE is typically used in powertrain and engine development to optimize the vehicle system including cars, busses, trucks and hybrid vehicles, its components and control strategies with regard to:
• Fuel consumption and emissions for any driving cycle or profile.
• Driving performance for acceleration, hill climbing, traction forces, braking.

AVL CRUISE is also used for tasks like:
• Evaluation of new vehicle concepts such as hybrid powertrain systems.
• Analysis of standard and new gear box layouts like DCT and AMT.
• Analysis of torsional vibrations of elastic drivelines (under dynamic load).
• Drive quality assessment of transient events such as gear shifting and launching.
• Vehicle thermal management.
• Energy flow analysis, analysis of power splits and losses within components.

[9] https://www.avl.com/documents/10138/1108091/AVL+CRUISE+Product+Description.pdf

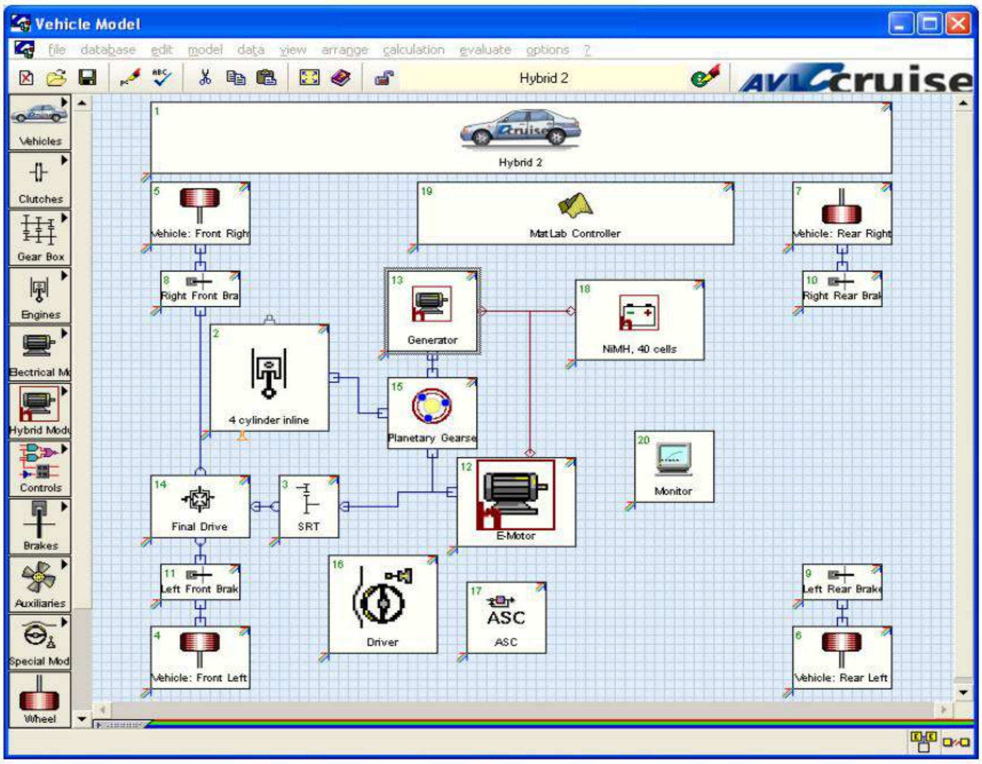


Figure 23: AVL CRUISE Vehicle model

6.4.2. DYMONAL System Engineering (Dassault Systemes)

DYMOLA System Engineering (https://www.3ds.com/products-services/catia/products/dymola/) is a Modelica compliant solution that efficiently models and simulates multi-physic dynamical systems. DYMOLA solves complex multi-disciplinary system modelling problems that can contain a combination of mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented characteristics and components.

DYMOLA has multi-engineering capabilities, which mean that models can consist of components from many engineering domains. Using the Modelica language, sub-systems are represented by interconnected components; at the lowest level dynamical behavior is described by mathematical equations or algorithms. Connections between components form additional equations. DYMOLA processes the complete system of equations in order to generate efficient simulation code.

DYMOLA application areas

Typical automotive applications are facilitated by Modelica automotive library. The engine and drive train are modeled using the Engines and Powertrain libraries. The flexibility of the open Modelica language is particularly suitable for modeling hybrid or alternative drive trains using the Battery, Brushless DC Drives and Electrified Powertrains libraries. Modal bodies or flexible shafts are available through the Flexible Bodies library. Engine and battery cooling is supported by the Cooling library, which can be combined with the HVAC library. The Human Comfort library adds models of occupant comfort for complete vehicle thermal modeling. Controller components are available in the Modelica Standard Library.

The hierarchically structured, open-source, Modelica models offer flexibility for multiple vehicle configurations while reusing common components (Figure 24).

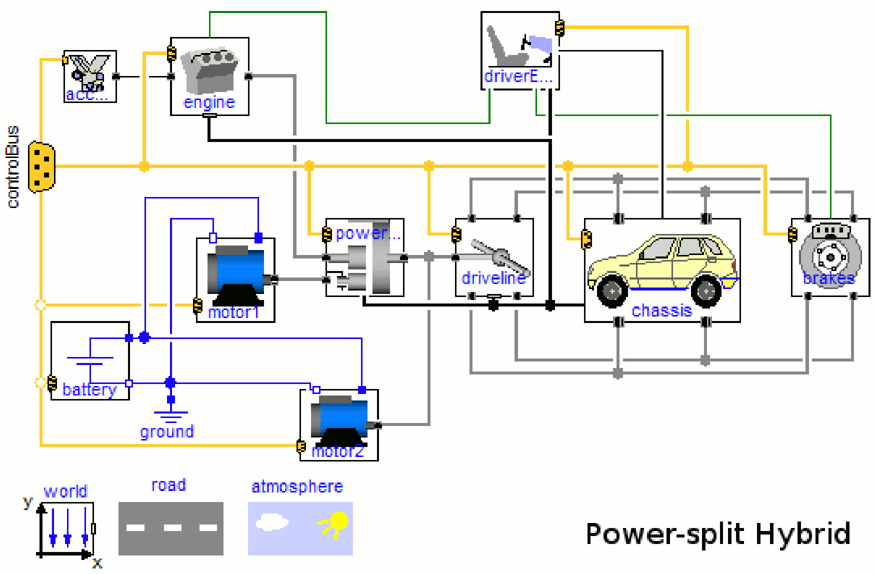


Figure 24: Dymola hybrid vehicle model

6.4.3. GT-SUITE (Gamma Technologies)

The GT-SUITE (https://www.gtisoft.com/) simulation consists of a set of simulation modeling libraries - tools for analyzing engine breathing, combustion, and acoustics, vehicle powertrains, engine cooling systems, engine fuel injection systems, valvetrains, crankshafts, and lubrication systems. The code can be used to investigate a wide range of issues, such as component design, vehicle emissions, and system interaction

GT-SUITE offers fast 1D/0D modeling solutions for real-time, HiL/SiL and control system simulations and supplies a comprehensive set of component libraries, which simulate the physics of fluid flow, thermal, mechanical, electrical, magnetic, chemistry, and controls.

GT-SUITE application areas

Models of almost any engineering system, including vehicles, engines, drivelines, transmissions, general powertrains and mechanical systems, hydraulics, lubrication and friction, thermal management, cooling, chemistry, after-treatment and much more can be developed in GT-SUITE.

With GT-SUITE's complete transmission library and object-oriented interface, any electrified vehicle architecture can be built and tested for fuel economy and performance.

After determining the vehicle architecture, GT-SUITE enables the easy integration of physical subsystems, including thermal management and after-treatment systems, allowing for the optimization of full-vehicle energy and thermal management strategies.

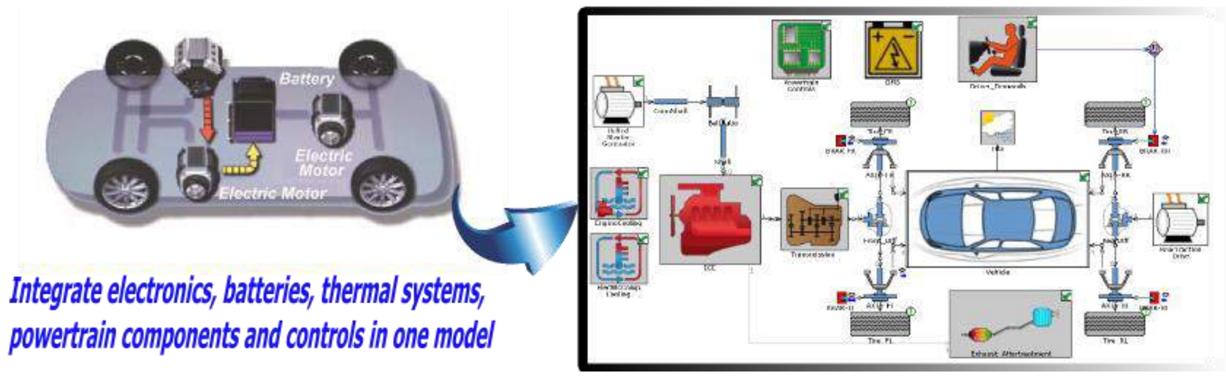


Figure 25: GT-SUITE electric vehicle model

6.4.4. MapleSim (MapleSoft)

MapleSim (https://www.maplesoft.com/products/maplesim/) is the system-level modeling solution based on the Maple mathematical engine and analysis environment to design and simulate multi-domain systems, plants and controls in one single environment. The schematic diagram interface enables rapid model development, thanks to the Maple symbolic computation foundation providing a numerically efficient model formulation.

MapleSim generates model equations, runs simulations, and performs analyses using the symbolic and numeric mathematical engine of Maple. Models are created by dragging-and-dropping components from a library into a central workspace, resulting in a model that represents the physical system in a graphical form.

The MapleSim library includes many components that can be connected together to model a system. These components are from areas of science and engineering such as electrical, mechanical, and thermal engineering fields. MapleSim also includes traditional signal flow components that can be combined with other physical components in the workspace. Thus, MapleSim is able to combine causal modeling methods with acausal techniques that do not require specification of signal flow direction between all components.

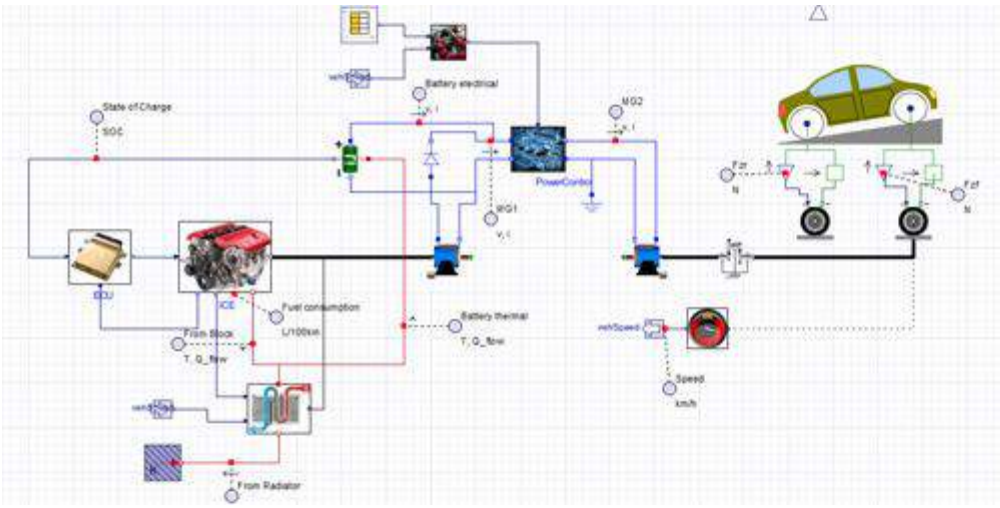


Figure 26: MapleSim vehicle model showing the Engine/Generator, Battery and Power Control, Electric Drive and Cooling System

6.4.5. SimulationX (ESI)

SimulationX (https://www.simulationx.com/) is an interdisciplinary, multi-domain simulation software for the design, analysis and optimization of complex systems on a single platform.

The software models the interaction of components from a multitude of domains including their mutual interaction and feedback on one platform. It is a CAE tool for modeling, simulating and analyzing physical effects - with ready-to-use model libraries for 1D mechanics, 3D multi-body systems, power transmission, hydraulics, pneumatics, thermodynamics, electrics, electrical drives, magnetic as well as controls - post-processing included. SimulationX fully supports Modelica language and offers a wide range of open, comprehensive CAx-interfaces (Figure 27).

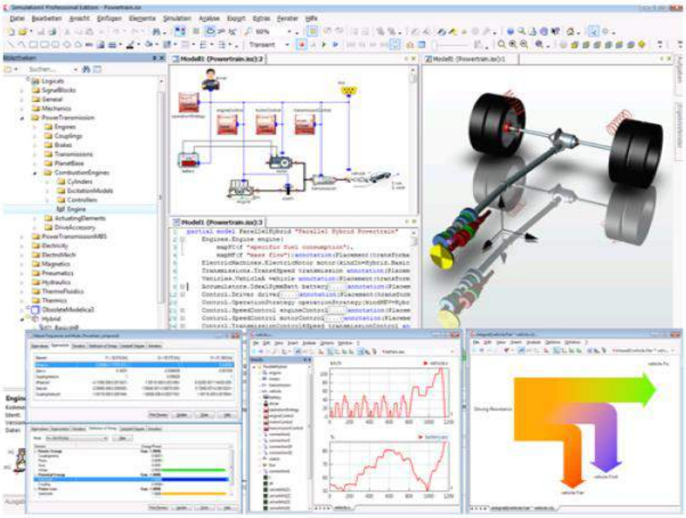


Figure 27: SimulationX Driveline: Analyse a Drive Cycle

6.4.6. SystemModeler (Wolfram)

System Modeler (http://www.wolfram.com/system-modeler/) is a platform for engineering as well as life-science modeling and simulation based on the Modelica language. It provides an interactive graphical modeling and simulation environment and a customizable set of component libraries.
The flexible environment supports automotive application as design and simulate vehicle dynamics, powertrain controllers, chassis and safety systems, and combine with Mathematica for control system design and optimization.

6.4.7. Simplorer (Ansys)

Simplorer (https://www.ansys.com/resource-library/brochure/ansys-simplorer) is a multi-physics circuit simulator, able to insert in a single schematic electric, mechanical, hydraulic, thermal component and mix them with mathematical operation described in terms of State Space, block diagram, State Machines and scripting algorithm. Simplorer offers the ideal environment for coupling Control drives (Power Electronics) and Electromagnetic devices (FEM Maxwell models).

6.4.8 CarMaker

Carmaker (https://ipg-automotive.com/) software solutions are specifically designes for the development and testing of passenger cars, light-duty vehicles, trucks and two-wheelers. The Matlab based software offers comprehensive tests in the field of ADAS and automated driving, power train and ehicle dynalics.
It claims increased efficiency thanks to seamless use throughout the entire development process (MIL, SIL, HIL, VIL) and the reusability of scenarios and test cases.

6.4.9. Analysis on Simulation Speeds

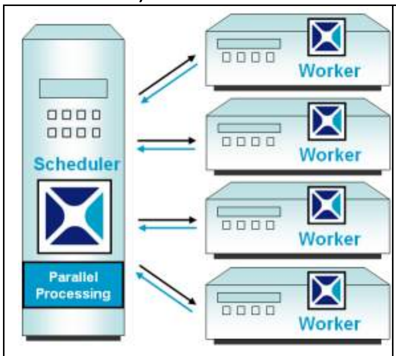
Providing fast running software solutions with a large area of capabilities is one of the keys of solving performance.

The total time taken by the solver to simulate the model depends on factors such as the complexity of the model and the solver characteristics including:

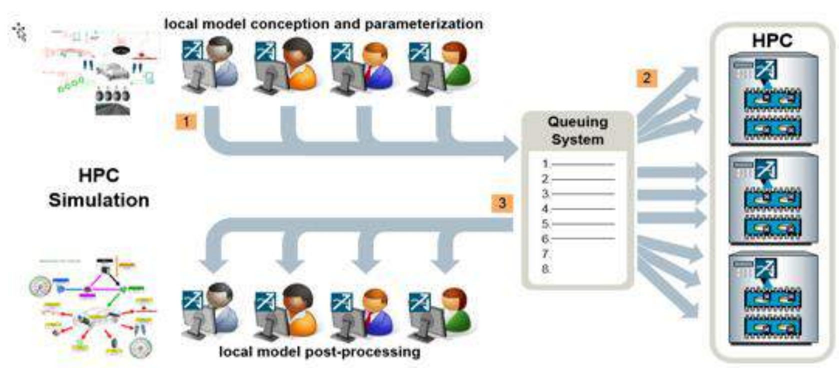
- Number and type of equations being solved.
- Number of discontinuities.
- Speed (or frequency) at which variables are varying in the model.

- Non-linearity of the equations.
- Solver settings, integration step size and accuracy.
- User submodels improperly coded.
- Hardware and network infrastructure including computer speed.
- Software configuration especially the compiler used to generate the model executable.

Thanks to new technologies appearing (multi-core computers, clusters, …) traditionally software packages (written for serial computation to be run on a single computer having a single Central Processing Unit) are improved. Better solutions as parallel computing and High-Performance Computing (HPC) provide huge computational power to solve complex problems that are difficult to address using personal computers within a reasonable timeframe. Parallel Processing can succeed in performing distributed computing which makes it possible to solve long-running and computationally intensive problems, especially when large independent data sets are involved which results in a significant speed-up of simulation runs. HPC can be seen as an extension of the Parallel Processing feature on a much larger scale where the goal is still primarily to perform multiple case studies on a single model (even if more complex cases, as co-simulation).



Parallel Processing with a distributed network



High Performance Computing with Simcenter Amesim

Figure 28: Contributions to calculation time

Different 1D tools offer the appropriate framework to get the analysis. A comparison between more aspects of a 1D software capabilities such as: cloud solutions, parallel computing, HPC, co-simulation, real-time, HiL and FMI interface have been checked on the basis of current published status (Table 4).

Table 4: Comparison of Simulation tools

Software solutions / Software capabilities	Simcenter Amesim	Matlab Simulink	AVL Cruise	Dymola	GT Suite	MapleSim	SimulationX	System Modeler	Simplorer
Cloud Solution	✓	✓	✗	✗	✓	✗	✓	✗	✗
HPC	✓	✓	✗	✗	✓	✗	✗	✓	✓
Parallel computing	✓	✓	✗	✗	✓	✗	✗	✓	✓
Co-simulation	✓	✓	✓	✓	✓	✓	✓	✗	✓
Real-Time	✓	✓	✓	✓	✓	✓	✓	✓	✗
HiL	✓	✓	✓	✓	✓	✓	✓	✗	✗
FMI Interface	✓	✓	✓	✓	✓	✓	✓	✓	✗

The tools, which cover all areas of the analysed software capabilities are Simcenter Amesim, Matlab Simulink and GT Suite, while for SimulationX information about parallel and HPC computing was not found. AVL Cruise, Dymola and MapleSim offer co-simulation, real-time and HiL solutions but they do not cover cloud, parallel and HPC simulations. As all software tools are constantly evolving Table 4 is presenting only a momentary overview.

7. Discussion and Conclusions

7.1. Discussion

The presented state-of-the-art report shows the necessity to clearly define modelling approaches in view of the later application. Most of actual simulation package are mainly based on a structural approach that enables an easy building of the studied system from component libraries. For an easy connection of the various components floating I/Os are thus used (acausal description). While such an approach leads to friendly use it can lead to a lack of understanding and an increase of the computation time. On the contrary, a functional and causal description will lead to better understanding of the system behaviour and also a reduced computation time. However, the component interconnections require pre-study to solve in advance conflict of association. This last point will definitively be a key issue for a large dissemination in industry. Nevertheless, when HIL testing will require high-fidelity model computed in real-time, this approach will be of high interest.
Therefore, this state-of-the-art report is an important document revealing the basic ideas and their effect on the system model. Hence, in the reminder of the WP1 Methods (Organisation methodology & testing scenarios) it is vital to stick to the given definitions and integrate the methods into this framework in order to create a maximum of benefits.

7.2. Conclusions

The presented report on state-of-the-art of modelling tools provides a detailed positioning of the project PANDA both with regard to existing H2020 projects and the representation approaches. After a positioning with regard to existing projects, the background of modelling approaches is presented based on dualities, pointing out the different philosophies and their consequences on the modelling. Thereafter, different representation tools are presented. Those representation tools allow the model organization and a special emphasis is put on the EMR representation that will be used in the context of the PANDA-project. Finally, an overview about simulation tools that are used in EV development is given. Here, a special emphasis is put on the introduction of Simcenter Amesim, which will be used in the project PANDA.
The objective of the PANDA project is to develop a dedicated functional causal library to enable the coupling of existing models with this disruptive organization. This will not replace actual simulation tools but provides a library of models organized such as to use the same real-time models for virtual or real testing. An extensive analysis of other H2020 projects on vehicle modelling showed that the use of the same functional causal library for both modelling and testing represents an original philosophy. Indeed, structural-based software packages are generally used, and co-simulation of this kinds of tools requires adaptation algorithms (such as FMI) that increase the global computation time. Once results are obtained in the project PANDA, it will be interesting to compare them to results obtained in in other H2020 projects.

8. Deviations from Annex 1

No deviations with respect to the description of work.

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Table 5: 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	IND	TUV	TUV SUD AG
8	UNIV	UBFC	Université Bourgogne Franche-Comté
9	SME	UNR	Uniresearch BV
10	IND	RTR	Renault Technologie Roumanie
11	SME	Bluways	BlueWays International bva

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Appendix A – Quality Assurance

As part of the quality assurance procedure:

- The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator);
- Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the EC.

NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	WP Leader	Peer reviewer 1	Peer reviewer 2	Technical Coordinator
	CHRENKO	IRIMIA	REYNOUARD	BOUSCAYROL
1. Do you accept this deliverable as it is?	Yes	Yes	Yes	Yes
2. Is the deliverable completely ready? If not, please indicate and motivate required changes.	Yes	Yes	Yes	Yes
3. Does this deliverable correspond to the DoW?	Yes)	Yes	Yes	Yes
4. Is the Deliverable in line with the PEMs4Nano objectives?	Yes	Yes	Yes	Yes
a. WP Objectives?	Yes	Yes	Yes	Yes
b. Task Objectives?	Yes	Yes	Yes	Yes
5. Is the technical quality sufficient?	Yes	Yes	Yes	Yes

Appendix B – Abbreviations / Nomenclature

Table 6 List of Abbreviations / Nomenclature

Symbol / Shortname	
BEV	Battery Electric Vehicle
CAE	Computer Aided Engineering
CAD	Computer Aided Design
EMR	Energetic Macroscopic Representation
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
HEV	Hybrid Electric Vehicle
HIL	Hardware in the Loop
HPC	High Performance Computing
MIL	Model in the Loop
PLM	Product Lifetime Management
P-HEV	Plug-In Hybrid Electric Vehicle