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ADEPT: "ADvanced Electric Powertrain Technology" – Virtual and Hardware Platforms

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Abstract — Alternative energy sources for traditional combustion engines (e.g. fuel cells, solar cells, batteries) in vehicles like motorbikes, cars, trucks, boats, planes will go hand in hand with a massive growth of the application of electric machines inside ('E-propulsion'). For automotive, marine, aerospace and other heavy duty transportation for traveling and transport of goods, the electric motor will replace- or supplement many alternative energy sources and traditional combustion engines. Design of high performance, low cost and clean propulsion systems requires international cooperation of multiple disciplines such as physics, mathematics, electrical engineering, mechanical engineering and specialisms like control engineering and safety. By cooperation of these disciplines in a structured way, the ADEPT program will provide a virtual research lab community from labs of European universities and industries. To stay on par with the competition there is an urgent need for European academic research communities to work in close cooperation with the European industry. After finishing the ADEPT project, the knowhow and expertise will also be open to other research organizations or industry that are not yet involved. This paper presents a review of trends within powertrain systems-level simulation as the context for the ADEPT program, before detailing the program itself.

I. SOCIETAL CHALLENGES

Although many fuel-saving technologies for travelling and transport are already commercially available and cost-effective, particularly when considered over their lifetime their market penetration is often low because of a range of political and technical barriers. Strong policies are needed to ensure that the full potential of these technologies and available high-tech know how in Europe is achieved over the next 10 to 20 years and the technical barriers can be removed by international research effort. Especially standardized designs and design methods, such as proposed in the ADEPT network, would significantly augment the acceptance of minimum energy performance standards.

Air pollution is a big issue e.g. in big cities like London, Paris, etc. and big countries like China (e.g. CO_2, NO_x, VOC_x, particulates etc.) About 25% of worldwide CO2 emissions are attributed to travelling and transport of goods. Cars and trucks represent the bulk of these emissions (about 75% worldwide), where aviation and shipping emissions are growing rapidly too. While energy use in transport could double by 2050, associated CO2 emissions must be cut dramatically as part of an overall strategy to cut energy-related CO2 emissions by 50%. The first priority should be to research technologies and practices that are cost effective. E-propulsion systems could enable this. Full or part E-propulsion solutions will enable a revolution in technology to move toward a truly low CO2 which will be built on some combination of electricity, hydrogen and biofuels.

In modern propulsion applications where both the environment and the user requirements are placing severe restrictions and demands on E-propulsions, it is critical to consider designs at a system integration level, taking into account the multiple domains that are interconnected. Therefore, fast but accurate modelling and simulation tools are essential in the early development phase for the analysis and assessment of different powertrain concepts. The ADEPT network enables a standardized fast design of efficient electric drives to minimize the time-to-market for electric powertrains that can be used by the European automotive industry.

II. RESEARCH TRENDS IN POWERTRAIN SIMULATION

Computer simulation is the discipline of designing a model of an actual or theoretical physical system, executing the model on a computer, and analysing the execution output. Within the overall task of simulation, there are three primary sub-fields: model design, execution and analysis. Within the development of information communication technology, system and control theory, communication technology, the simulation technology is changing also and has been widely accepted as a powerful tool in different fields of research, playing an important role (Figure 1). Moreover, the increasing role of monitoring and control software lead to so-called Cyber-Physical System developments, utilising various levels of virtualisation.

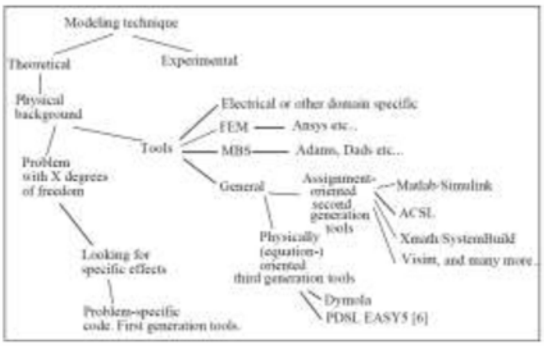

Fig. 1. Broad view of modelling techniques [1]

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III. SEPARATION OF USERS: ENGINEERS AND DEVELOPERS

The 'engineer' in this context applies to those wishing to build simulation models using data, whereas 'developer' describes those wishing to alter the software at anything lower than the application level. With the majority of the HEV simulation packages, the engineer's role becomes less well defined when the tool is needed to be used outside the very strict remit of operations offered by the GUI's. The limitation of the tools as presented at the application level mean that too frequently the engineer must take on the role of the developer to manipulate the models.

Simulation provides the means for evaluating designs without the cost of prototyping or practical assessment. Moreover it can be used to indicate how component parameters affect the performance of the vehicle. For the design of complex powertrains such as those found in hybrid or electric vehicles, simulation is essential as an initial and ongoing assessment of choices in the design process.

The simulation has a number of roles in the design process, and is integral to it. These roles and the scope of the simulation are summarised below:

- To provide a framework for evaluating the full vehicle configurations performance based on real or artificial drive cycle data.
- To provide analysis for the sizing of components of the vehicle and how they affect the vehicle's performance and behaviour.
- To provide a means to quickly evaluate different control strategies, and to optimise them for the typical drive cycle.

The simulation process is a means for evaluating various powertrain designs and to provide understanding and insight into their behaviour. The quality of the simulation output data is directly dependent on the quality of the simulation input data. For that reason, great care should be taken in collecting and setting up the simulation models.

The sophistication of the simulation tools used for hybrid powertrain simulation has been gradually increasing. The most significant work however is more recent, where there is an increasing need for highly robust and flexible simulation tools to help design hybrid vehicles. This is also driven by the advent of modern computers and improvements in programming and meta-programming platforms.

However both the area of hybrid electric powertrain research and the development of tools (particularly for co-simulation) are still relatively new, and the variety of advances in software techniques has not yet fully matured.

IV. POWERTRAIN SYSTEM SIMULATION

Simulation causality is a common theme between platforms, particularly those of system level simulation at powertrain level. Causality dictates that there is a common cause-and-effect relationship between the input and output variables of a simulated component. The principle of causality and its implication for powertrain simulation design is of fundamental importance [2]. There are two types of causality; integral and derivative [3].

In some cases, linear Differential Algebraic Equations (DAEs) may be reformulated to form Ordinary Differential Equations (ODEs) for which an analytical solution can be found. However, if the DAEs are nonlinear, an analytical solution may not be possible and a sequence of linear and/or nonlinear DAEs would need to be solved numerically.

Non-causal models (sometimes referred to as '*acausal*'), are defined in such a way that they do not inherently impose a calculation direction. Where non-causal models are made up from DAEs, they are required to be translated into a computational form prior to the simulation. The form of the translation is based on the nature of simulation required.

A. *Backward and Forward-Facing Methods*

A powertrain simulation is based on a network of component models that describe the individual behaviour of the vehicle parts, transcribed over discrete time steps. These components are modelled in terms of power input and output generally and take into account the load history as well as transient conditions.

Both simulations directions are based on the manipulation of DAEs into suitable forms.

Figure 2 gives an example schematic of the direction of simulation flow.

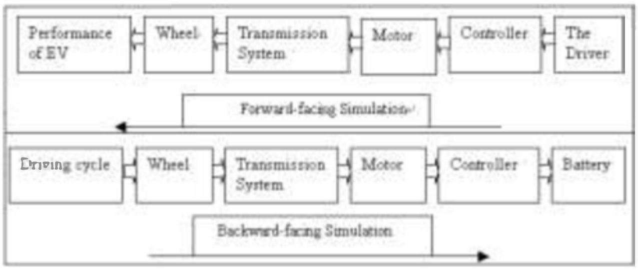

Fig. 2. Schematic showing forward-facing and backward-facing simulation methodologies [8]

1) *Generic Backward-Facing Approach*

Simulators using a backward-facing approach typically ensure the vehicle follows a speed-time trace. Starting from this trace, the simulation determines component by component, how each is required to perform. The backward-facing approach calculates the power input given the power output.

In such an approach, the control signal from the driver is not required explicitly, since the effects of the control system is determined before the cause.

The linear force required to drive the vehicle is then converted into the torque required at the wheels and likewise the linear speed of the vehicle is translated into rotational speed. By working though each component and its power losses, the amount of fuel or electric energy for the current time step is then determined.

Backward-facing simulation has several notable benefits for powertrain simulation:

- Component models which include efficiency or fuel consumption maps are normally defined in terms of the output speed and torque. This makes the maps readily compatible with this method.
- Evaluating and comparing vehicle performance is normally performed through vehicles following standard speed-time traces.
- Due to the majority of models being more readily defined by DAEs in the backward-facing direction, computation time for a vehicle able to follow a speed-time trace is reduced since simple integration routines (i.e. Euler's method) can be used with the relatively large time steps [6].

The approach also has some drawbacks:

- The backward-facing approach assumes that the speed-time trace is achieved by the vehicle. In cases where it is not, reliance on backward-facing models can lead to the need for increased computation.
- The approach cannot be used directly to calculate maximum acceleration, or best-performance calculations.
- Quasi-static backward-facing models derived from efficiency or fuel consumption maps do not inherently take into account dynamic effects. The approach also assumes that these maps are readily available for components.
- Since the simulated vehicle is not driven directly from control signals, direct modelling and development of control systems is not possible.

2) Generic Forward-facing Approach

Simulators using a forward-facing approach start from a control signals (throttle and brakes) from a driver model. If the vehicle is required to follow a speed-time trace, the driver model derives the required control signals, typically from a Proportional-Integral-Derivative (PID) controller.

The control signals are then used to determine the torque from the vehicle's Prime Move Unit (PMU) (typically either an ICE or EM). Forward-facing simulation has several benefits over backward-facing:

- Better for control system development - values calculated more directly model the vehicle, for actual rather than required.
- Dynamic models are more easily included.
- Maximum-speed, best-performance calculations are easier.

Forward-facing simulations have several drawbacks:

- The majority of powertrain models require that the component and vehicle states are known. Such an assumption requires numerical integration, which can lead to inaccuracies (without smaller time-steps) as well as more demanding computation.
- Most validated component models are defined as backward-facing only.

B. Vehicle Powertrain Simulation

Typically forward-facing simulation codes are most prevalent in areas of research focusing on models based on dynamic equations. Such research focuses on control aspects of the system, and its short-term behaviour. Areas of work such as driving simulators also use this approach.

Backward-facing simulation codes are more frequently applied to the assessment of the long-term performance of the vehicle (such interests as fuel consumption and emissions), from a given driving regime. The quasi-static, experimentally derived models are based on steady-state assumptions and therefore predict the longer-term behaviour of the components. To use dynamic equations to model longer term effects requires shorter time-steps in order to maintain the validity of the assumptions of each model.

The traditional methods of modelling components for hybrid powertrain simulation are from the backward-facing approach. Backward-facing simulation therefore becomes the most straight-forward computational approach, but as the literature shows even if the majority of the models used are backward-facing, the simulation method is not always limited to this approach.

1) NREL ADVISOR

Although many simulation tools existed prior, ADVISOR was the first widely used simulation tool for hybrid and electric powertrain modelling. Wipke at al. presented the Matlab/Simulink-based backward/forward powertrain simulation tool firstly in 1994 [6]. At this time, other simulation codes were not able to simulate parallel HEVs or conventional drivetrains [7]. The term 'backward/forward' is used since the tool utilises backwards methodology for solving, but incorporates forward models fed back into each component to determine power limitations.

The tool, Advanced Vehicle Simulator (ADVISOR), is designed for the simulation of conventional, electric, and hybrid vehicles with the intention of providing analysis for the performance and fuel economy (and emissions).

ADVISOR was one of the primary design tools used by the Partnership for a New Generation of Vehicles (PNGV), formed in 1993 [4]. Most models within ADVISOR are quasi-static based on experimentally measured steady-state data. The model includes analytical models for the dynamic elements not part of the quasi-static model, such as the effects of rotational inertia. A large amount of experimentally derived data was provided as part of the component models, from the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) testing facilities.

ADVISOR is the most widely used and probably the most refined simulation program in the field of hybrid vehicle powertrain simulation, and commonly accepted as the standard means for hybrid vehicle simulation. The choice of language of Matlab/Simulink was due to the wide acceptance of the language by academia/industry, combined with the self-documenting programming language which Simulink provides [7].

Wipke et al. suggested that forward-facing simulations were best suited to the simulation of maximum performance accelerations. They highlighted that the considerable drawback of such a simulation scheme was the considerable simulation time required. Powertrain simulations rely on knowing the states of the various components at a given instance. In forward simulation, these states are only calculated by numerical integration which requires relatively small time steps for reliable accuracy. Forward-facing is also better suited for the simulation of control signals, or the inclusion of dynamic models. Figure 3 shows an example configuration from ADVISOR.

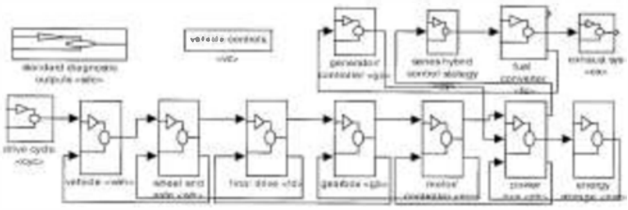

Fig. 3. ADVISOR's series-HEV top-level Simulink block diagram [6]

The proposed method compares the required values (backwards-facing results), with achievable values (forward-facing results) for each component in the powertrain. Typically, achievable values are governed by components further up the powertrain (i.e. closer to the power source).

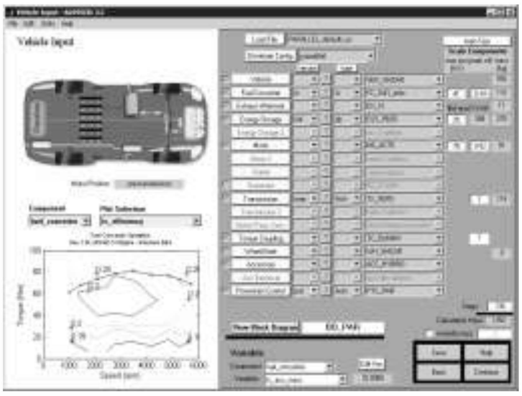

Fig. 4. ADVISOR Graphical User Interface (GUI)

This methodology is based on the two following assumptions [7]:

- No drivetrain component will require more torque or power from its upstream neighbour than it can provide.
- A component is performs the same in the forward facing calculations as it was computed to be in the backward-facing calculations.

Wipke et al. highlight the problems the tool has in terms of flexibility; that the program does not allow the user to develop new powertrain architectures themselves, and that re-programming of ADVISOR in Simulink is required for each new layout [7]. The interconnectivity of the models, and moreover the connections from control sub-systems means that the components lack modularity.

However, the GUI is limited to the selection of configurations from a menu, and the majority of component parameters can only be edited one value at time.

In 2002, ADVISOR was integrated with Ansoft's SIMPLORER to allow for co-simulation, allowing Simplorer to more accurately model the electrical parts of the vehicle. ADVISOR has also been shown to work in co-simulation with other products, as well as activities involving hardware-in-the-loop (HIL) simulations. HIL involves the incorporation of hardware components in simulated powertrains.

In 2003, AVL Powertrain Engineering, Inc. acquired a licence to commercialize ADVISOR. Although NREL retains a licence of previous versions of ADVISOR for continued free distribution and for use in DOE projects, AVL owns the rights to market future commercial versions. Since that time, AVL chose not to further develop ADVISOR, instead focusing on its own commercial tool, AVL CRUISE. Despite its age, the last version of ADVISOR is still used for research studies.

2) ANL PSAT and Autonomie

Rousseau et al. presented a simulation package written in Matlab/Simulink which adopts a full forward solution mechanism in 2001. The authors admitted this approach is much more computionally intensive than the backwards-facing approach [8]. However, the advantages of this method are that the powertrain model can be driven from control signals much as in a real vehicle. Such an approach aids best-performance simulations. Moreover this approach allows for the development of realistic control strategies from within the software.

The work emphasises the need for flexibility in modelling various powertrains, as well as standardising the input/output interfaces for the component models involved. The philosophy used to model the components is based on Bond Graph philosophy, and is claimed to be a generic approach to the component models and interfaces.

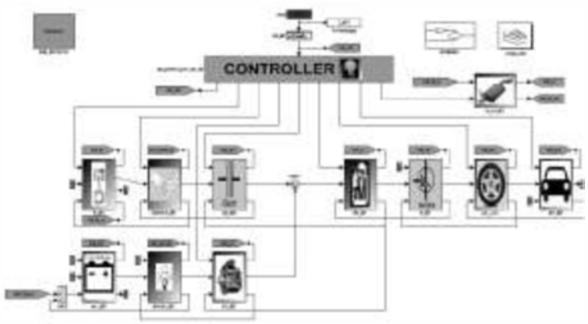

Fig. 5. PSAT Parallel Hybrid Simulink Top Level [8]

In addition, the models are governed by a centralised controller (PTC) which manages information flow between the component models. This allows for multiple instances of the same component model, where variables are kept as local to a component block. A 'GOTO-FROM' method of passing data to and from the blocks is then used when required. Figure 5 illustrates the Simulink layout for a typical vehicle.

The claims of flexibility extend only as far as that a large number of configurations are pre-defined within the tool. The tool in terms of appearance (as illustrated in Figure 5), and Simulink structure is very similar to ADVISOR. PSAT is now named Autonomie following a joint development with GM.

3) *TNO ADVANCE*

Van den Tillaart et al. presented the modular power train simulation and design tool and was used for the emissions analysis of both trucks, buses, and cars [10]. The program, ADVANCE, has been implemented in a Matlab/Simulink environment. The authors' emphasis on the design of this tool is for it to provide modular components. The components are connected via a central data bus which allows the sharing of information from the components. Figure 6 illustrates a top level view of the Simulink layout for a typical powertrain.

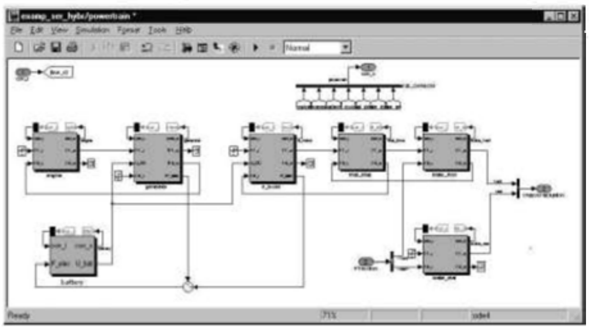

Fig. 6. ADVANCE block diagram [10]

In a similar way to PSAT, ADVANCE uses a 'GOTO-FROM' approach to communicating data with the central data bus.

4) *Modelica, OpenModelica and Dymola*

Modelica and OpenModelica were languages designed specifically for simulation. *Wallén* presents work modelling a conventional, series-HEV, parallel-HEV and combined-HEV in Modelica/Dymola [9]. Since Modelica is non-causal, the models do not rely on being explicitly defined as backward-facing or forward-facing. The equations are expressed in a neutral form and consideration of computational order as part of the model description is not necessary. The tool contains a translator for the equations within Modelica and the compiler generates C-code for the simulation. The code can also be exported to Simulink as required. This process is referred to as meta-programming. The component models are translated into a suitable form of DAEs as the simulation is run, and the simulation uses numerical integration to solve. This part of the process therefore represents a forward-facing simulation, although the definition of the model itself is not.

5) *MapleSim*

MapleSim is a relatively new-comer within powertrain simulation and boasts a symbolic environment much like Dymola. The advantages of this approach in terms of simulation time are a key aspect in its market promotion.

6) *LMS AMESim*

LMS AMESim is a systems-level and component simulation software able to couple several domains into a single platform. The software is largely actor-oriented where the user is able to drag and drop representative images of components to build up the powertrain under study.

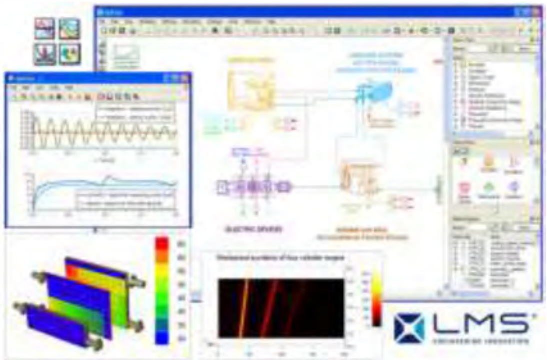

Fig. 7. LMS AMESim GUI

7) *Virtual Vehicle ICOS*

The Independent Co-Simulation (ICOS) environment produced by Virtual Vehicle in Austria is a framework for connecting simulation models from a range of different environments. Furthermore, the models can be distributed in different geographical locations remotely due to the network wrapper used. The approach is also attractive where industrial partners do not wish to distribute their models in open or closed form, whilst still allowing them to be used within powertrain simulations.

8) *AVL CRUISE, GT-SUITE, Ricardo Easy5 and others*

A number of other commercial tools are available for powertrain simulation and used by varying degrees within the market. This paper does not cover these in detail suffice to recognise that these are used both by industry and academia.

V. Functional Mock-up Interface (FMI)

The development of the Functional Mock-up Interface was initiated by partners within the ITEA2 project MODELISAR in 2008-2011 to standardise the exchange of models between simulation packages as well as co-simulation interfaces. The project was organised by Daimler AG, and coordinated by Dassault Systèmes, with a strong focus on the needs of the developing automotive sector from a modelling and simulation viewpoint. FMI is implemented for Functional Mock-up Units being models exported by one tool and imported into another [11].

The focus of FMI was to provide an open standard towards model exchange and the mechanism of coupling of two or more simulation tools. FMI v1.0 and v2.0 are supported by many mainstream software environments, although developments in this approach are still active.

A wide number of libraries have now been developed for FMI allowing commercial software vendors and research software to be developed to interface and exchange models with other standard packages. Progress has been slow but sure in the increased acceptance of FMI although there is still some way to go.

In particular with respect to ADEPT, FMI offers interfacing of more detailed component based tools with powertrain simulation and system level analyses [12].

VI. Models and Simulation in Certification

One area where models and simulation will play an increasingly important role in future is that of certification. Particularly in the case of heavy duty hybrid or electric vehicles, real-world performance is becoming increasingly difficult to assess. Within UN-ECE Heavy Duty Hybrid (HDH) Working Group is reviewing a HILS approach to the certification of future powertrains through the provision of a library for virtualisation of part of the powertrain. Similar approaches may be considered for electric vehicles such as buses in regard to auxiliary systems considered via UITP. Tools such as VECTO are already being developed so assist with CO_2 impact assessment and further developments in this area are expected to involve transparent tools towards certification.

VII. Future Requirements Towards Open Simulation

This research area is still expanding and the literature conveys that there is no fixed theme for approaches in R&D. Backward-facing, forward-facing, and various combinations of methods have been employed for the simulation of hybrid powertrains with varying degrees of success, as well as languages allowing greater degrees of flexibility. There are several factors that have driven this to being the more suitable system of solution, namely that:

- The majority of models of the major contributors to power loss and power limits within the powertrains, are based on data defined in terms of the components output. These models include ICEs, EMs, and batteries.
- The evaluation and comparison of hybrid vehicles is typically performed starting from known drive-cycles. Best-effect performance evaluations are not considered a primary measure and/or comparison of a xEV's performance.
- There is less work in modelling the dynamic behaviours of hybrid electric powertrains in this field than in traditional vehicle powertrain simulations. The reason for this is that one of the more general philosophies of hybrid technology is to smooth the operation of the ICE, and therefore the backward-facing steady-state model becomes largely more valid, than perhaps would be true of a conventional powertrain. Additionally, the timescales of simulations are sufficiently large that the time-steps frequently used are too large to be able to model dynamic effects.

Since the turn of the century, the quality of research has gradually improved in presenting generalised methodologies for the simulation of hybrid and electric vehicles. This is partly due to the area of research being new, and partly because of the nature of the software and control techniques being used have become more prevalent.

The first step for many interested in the simulation of hybrid vehicles is still often to develop their own component and system models. Although there is some incremental research on the technical details of the models being used, from the software viewpoint, there is little open domain re-use. Indeed, the lack of an open source successor to ADVISOR is still missing, particularly in the research domain. The limited amount of incremental research of simulation techniques in this field is mainly due to existing simulation packages relying on closed or incompatible approaches. This is heavily dependent on the languages being used to model the systems, but also in the manner in which they have been programmed, as well as commercial limitations. The most common language being used in research is still Matlab/Simulink, but it is only more recently that it is possible to be programmed in a way to allow for greater modularity, standardisation, and interchange.

Although recent developments such as FMI have greatly improved open approaches towards modelling and simulation within automotive, much work remains in further expanding functionality and best practices.

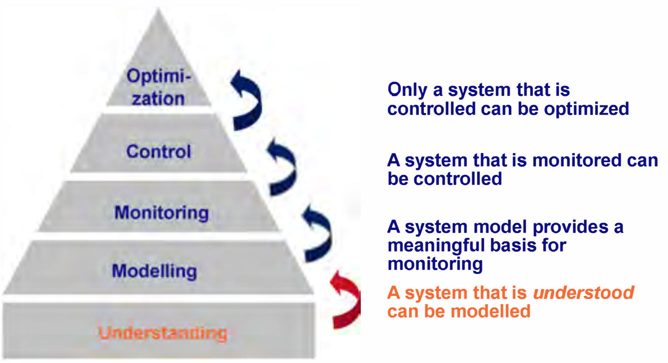

Fig. 8. Hierarchy of Roles from Modelling to System Optimisation

The role of model-based control development is prevalent in many parts of automotive research and development, and is expected to continue to grow further in future generations of vehicles, particularly alongside control (Figure 8). The role of modelling towards control governs both offline development and online implementation of control, wherein reduced-order models are selected for efficient and robust approaches to topics such as energy management and driveline control. Areas such as model predictive control, and state estimation represent well known examples of model-based approaches, particularly in environments with high degrees of freedom.

With increasing developments in ECU capabilities, as well as external sources of information, the level of sophistication of control algorithms is able to expand further. Model-based monitoring approaches to On-Board Diagnostics is expected to support the reliability and robustness of complex systems, as well as remote assessment/monitoring. Additionally, model-based control lends itself to development of virtual sensors where the inclusion of real sensors is either not possible or undesired. Advances in standards for interfacing, implementation and integration, and the use of such approaches are anticipated in parallel with the model-based approaches themselves.

Coupled with optimal control theory, model-based control development offers a route for system and subsystem optimization within the field of applied automotive research. Functional testing, robustness and safety underpin development strategies for such methods.

Research priorities:

- Multi-scale and coupled domain simulation approaches
- Model-based optimization strategies for predictive and adaptive algorithm development; including methodologies for HIL assessment and certification
- Algorithm developments for use in next generation ECUs, particularly consideration for combinations of vehicle functions within multicore environments and information-rich external data sources
- Model-based approaches for On-Board Diagnostics, together with new approaches to system identification and interfacing for model exchange for virtual sensor development
- Standardised testing and model identification for automotive components

VIII. ADEPT Concept and Motivation

ADEPT unites the efforts of an interdisciplinary network of European research groups with a strong industrial participation. The consortium will tackle the most challenging problems faced in the field with a total of 14 fellows. It focuses on concepts, methods and (virtual) design tools or future E-propulsion systems. Fellows receive comprehensive inter-domain training through local measures, and network wide activities on topics including electrical engineering, mechanical engineering and computer engineering, and a course on environmental impact. Each fellow will conduct at least two secondments to industry, ensuring that education includes a strong industrial link and the researcher can develop vital application expertise. A number of measures, including the establishment of ERASMUS partnerships, and formal recognition of training elements towards long term joint Ph.D. programs will ensure that ADEPT leads to long lasting collaborations and benefits for the involved institutions. The goal of the whole ADEPT program is to produce a virtual development environment for E-propulsion systems and to train and to establish a multi-disciplinary research network. The whole training and research program will raise the profile and to improve career perspectives for 12 ESRs, and 2 ERs, offering a high-quality structured consortium providing personalized training opportunities in E-propulsion systems and in complementary skills (i.e. entrepreneurship). An intimate involvement in all aspects of the collaboration (research, knowledge transfer, secondments, workshops) along with an extensive training program in a wide range of fields (electromagnetics, thermal, mechanical, vibro-acoustic, control, vehicle integration of E-propulsion) will allow early-stage and experienced researchers to develop the technical proficiency and complementary skills required to make significant contributions to their professional careers.

Through industry-academia partnerships, ADEPT will facilitate the uptake of scientific results in E-propulsion and industrial products and solutions. Specifically, ADEPT addresses the following targets:

- Scientific target: ADEPT guidelines on low-cost and scalable E-propulsion system architectures and design methodologies will be summarised in a textbook and released at the network's conclusion.
- Training target: ADEPT facilitates successful training of 14 fellows in multidisciplinary skills and enable training collaborations between the network partners beyond ADEPT.
- Industry involvement target: ADEPT enables all industrial full partners to report at least one technically successful product development pre-study utilizing the ADEPT design and validation best practices before the final year.

ADEPT will address a substantial breakthrough in the utilization of E-propulsion systems through research and training activities covering the full spectrum of Societal Challenges (SC) and Technological Challenges (TC)

IX. Technological Challenges

A. *Create cleaner, safer, more robust and affordable electric drives*

Many factors and constraints are to be taken into account at the design stage of a low cost E-propulsion solution. As such, the powertrain imposes important boundary conditions on several technical and behavioural aspects, requiring a multi-attribute optimization. Alternative power trains will change the means for traveling and transport of goods and the industry worldwide: users will ask for them and the industry will make “big business” with clean machines in the world market [13].

B. *Enable high degree of electrification in all types of powertrain*

E-propulsion systems need to provide sufficient power and torque, and the industry needs models which make clear how torque and power characteristics relate to propulsion performance. Additionally, boundary conditions imposed by the energy source should be taken into account, as this will impact range, efficiency, robustness and safety [14]. All components will produce heat or conversely may need heating, therefore thermal management is a key concern. Additionally how will the motor cooperate with a high voltage AC system? How can the motor sound be taken into account during the design of the electric motor? How can E-propulsion be fully integrated, i.e. where should the various components be placed most effectively?

C. *Internet based tools for open source modelling and simulation*

Early Stage Researchers (ESRs) will address multi-physics, system integration and multi-criteria system level technological challenges. They will create a virtual powertrain library containing new E-propulsion concepts, tested within a realistic powertrain (simulation) environment, with the aim of being (re)used, shared and developed. After integration of E-propulsion, they will be able to simulate and test new concepts in realistic operational environments. Design methods and tools will be remotely accessible by all partners via internet, providing a virtual research environment which is at the heart of the ADEPT program.

X. Research Lines

The research lines of the ADEPT program follow the development cycle of any electric drive for E-propulsion solutions, by taking into account all important attributes and helping to resolve multiple, often contradictory, constraints. This involves various domains next to the core technology development for E-propulsion. The research network itself is composed of academic and industrial (private) institutions in the area of ADvanced Electric Powertrain Technology (ADEPT). Moreover, OEMs complement the network as associated partners with their application expertise. All projects contribute to one or more research lines.

The consistency of the project contributions to the RL's is supervised by the leading universities of the research lines:

1) *RL1: New E-propulsion technology:*

The integration of the appropriate Advanced PM-less E-machine (P1) and Advanced E-power electronics (P2) components for E-propulsion applications, together with both Control strategies for E-propulsion (P3) and New E-propulsion configurations (e.g. Electronic gear) (P4) is important. The choice of the most suitable standardized E-propulsion technology depends on factors like driver expectation, vehicle constraints, safety requirements, energy source, etc. There are several Advanced E-machine (P1) and new E-propulsion configurations (P4), so defining the overall operating point and selecting the most cost effective E-propulsion is a challenging task requiring co-ordination throughout the Projects

2) *RL2: Component-level design and modelling tools:*

The Component-level design and modelling tools will be supported by theoretical and numerical analysis and simulation, which will be fine-tuned and validated on real-world examples and through experiment. There is a comprehensive need for research to facilitate the selection of preferred Advanced Electromagnetic Materials (P5) for Advanced E-machines (P1) [15]. The performance of a propulsion system, combining P1, P2 and P3, changes markedly with temperature, hence the need for Thermal analysis and losses for E-propulsion (P6) in order to predict accurate functioning under transient loading whilst ensuring that insulation, semiconductor and magnetic materials are not degraded, and coupling the temperature dependence of materials to their electromagnetic performance (P5). Many of the design guidelines which have been established for machines operating in less aggressive environments have very limited utility. This will be thoroughly researched in Mechanical/Vibroacoustic E-propulsion (P7) for various propulsion applications.

3) *RL3: E-propulsion system level integration:*

System level integration is started by electromagnetic design (P1), coupled with thermal calculations (P6) and selection of power electronics devices (P2) taking into account the DC bus voltage, maximum current and required switching frequency and the loop is closed by selection of the control paradigm (P3) and E-propulsion configuration (P4). The selected materials (P04) and modelling tools (P5, P6, P7) must not only guarantee the E-propulsion operation with sufficient response to the reference signals, but also optimize the efficiency and safety of the entire electric drive. This is preferably performed using Multi-physics optimal design of E-propulsion (P8) and Multi-criteria optimal design (P9). The operator expectation on an E-propulsion puts particular requirements regarding safety, reliability and fault-tolerance. Therefore, improved multi-physics and multi-criteria design and modelling need to be developed and verified. E-propulsion contains a multi-disciplinary design project (P8), i.e. electromagnetic, thermal, electrical, mechanics and acoustics, supported by a multi-domain focus on physical modelling (P9) where different physical components and signal-flow can be modelled together to create model diagrams that intuitively map onto any real-world propulsion applications.

4) *RL4: Powertrain virtual development platform:*

Real-world applications will be tested using so called 'Hardware-in-the-Loop (HiL) analysis', enabled by the research on a Flexible E-propulsion testing (P10) platform that is used (a practical combination of hardware and software and theoretical models in one simulated system) to test the control system with real inputs and outputs, where the rest of the system and processes are simulated in real-time. The HiL shall be augmented by Module integration (P11) technology to enable a qualitative and quantitative approach to develop and/or to test E-propulsion components since a highly realistic simulation of the component in a new combination of hardware, software and high level models in system is supported by a Virtual powertrain library development environment (P12). The integrated hardware/software platform (P10, P11, P12), will be researched both for use on prototype propulsion applications and for hardware-in-the-loop test purposes. This flexible prototyping platform, which beside the P1 motor can also support all kind of other motor types, will be developed along with high level modelling (based on MATLAB-Simulink) to support it. As such, modern embedded systems with digital logic control technologies on FPGA will be employed, which represents the most flexible implementation of the reprogrammable part hardware part of the platform (P10). Each of the ER's and ESR's is dedicated to one of the twelve projects, which will be their main theme of research supervised by the host organization for the ESRs or ERs.

XI. Training within the ADEPT Programme

The ADEPT training program covers scientific training, personal skills and industrial orientation, see Figure 9. The fellows will be responsible to continuously monitor their TO success criteria and report regularly on their achievement in personal training progress report. Final responsibility to achieve the training goals is with the fellow's advisory committees, which assess their progress based on progress reports.

Fig. 9. Training program organized in scientific, personal and complementary sections

TO1: S&T Training. Advanced multi-physics design (electromagnetic, mechanical, vibro-acoustic and thermal), modelling and testing of electrical machines and drives; E-propulsion noise-harshness-vibration optimization (NVH) design; optimized integration of all required components in the drivetrain, including controllers and sensors, supported by electromagnetic design, acoustic design, NVH and very high levels of safety and reliability; using and interconnecting different modelling and simulation environments (Flux 2D/3D, JMAG Designer, MOTOR-CAD, SPEED, Matlab-Simulink, Dymola/Modelica, Lab Amesim, Virtual Lab, Star-CCM+, etc) for model-based design of electric powertrain subsystems and components; extending the existing modelling and simulation environments by creating new models; create new virtual, open-source training and research environment which will enable early integration of powertrain modelling, testing and simulation at different abstraction levels from the early design phases towards integration of all (multidisciplinary mechatronic) components. Theoretical and practical S&T training will be provided through the training activities

TO2: Communication. Effectively use and decide on appropriate forms and levels of communication, depending on the type of the event (conference, workshop, public talks, scientific papers, articles in newspapers, etc), as well as communicate and explain research in a comprehensive way to diverse audiences (supervisor, specialists, school/university students, general public, jury, etc) are vital elements of academic work, but also of R&D activity. ADEPT will provide fellows with fundamental skills in research communication and continuous training through individual and collaborative dissemination activities.

TO3: Ethics and social understanding. Understanding and applying principles of ethical conduct of research (integrity, collaboration, peer-review) are important issues to be addressed. Moreover ADEPT will educate fellows in understanding the relevance of research which will enable the development of clean and efficient vehicles for future sustainable transport and how the strategic orientation of transportation R&D in Europe reflects the Industry's mission to integrate sustainability into all future activities directly from the outset, creating a competitive advantage for the European economy, contributing to social welfare and protecting the environment.

TO4: Personal training. Personal training, as part of the PCDP developed together with the supervisor(s), will include personal career counselling and local training activities, such as courses on research topics specifically relevant for the fellow's participation in ADEPT, language courses, and training on further interests of the fellow.

TO5: Personal development and team-working. Personal effectiveness /development and Career management are essential skills for independent research work of fellows during the project and for their future career. Moreover, the fellows should be aware of their own working style, that of others, and how they interact in a process highly disciplined with regular gateways (check-points) and targets set to measure how efficiently the different disciplines (electromagnetic, mechanical, NVH, etc) are working together. ADEPT will support them to be able to identify appropriate and realistic goals for achieving the objective of the individual research program of; to work together with the supervisor(s) on the personal training and research plan; to operate in an independent and self-directed manner, showing initiative to accomplish the defined goals of the work plan; to communicate effectively with the supervisor(s) and with other researchers (if necessary) for achieving these goals; to manage time and resources so as to achieve goals; to handle difficulties in research and other professional activities in an appropriate way; to critically reflect on experiences and act on such in a cycle of self-improvement.

TO6: Entrepreneurship and innovation. ADEPT will encourage further development of its fellows in industry and academia by training them in developing a start-up plan and in grant proposal writing. Moreover, the collaboration with industrial partners will make them aware of the industrial innovation processes (organizational structures, product life cycle, development process, intellectual property rights) representing integral elements of leading roles in industrial R&D and industry-academia collaborations.

XII. CONCLUSION

The future application field for traveling and transport of goods on the road, off the road, over water or in the air, is constantly changing and improving due to the technologically driven nature of the alternative powertrains in combination with advanced e-propulsion technologies

This paper presented the ADEPT project, which is setting a first important step to enable an open-source environment (ADEPT platform) for design, modelling and testing of electrical drives for electric powertrains. This environment will provide design, analysis models and testing facilities for electrical machines, power electronics and control, for a quick route to market of new and innovative electrical powertrain solutions. The combination of both high-qualified academia and experienced industrial partners in this project ensures a secure and solid basis for this open-source platform.

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