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Review of Optimal Design Strategies for Hybrid Electric Vehicles

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Abstract: In this last decade, the industry headed in multiple transportation sectors towards hybridization and electrification of powertrains. This trend can be particularly observed in the automotive industry (passenger vehicles, commercial and construction vehicles), as well as, in water and air transportation systems. This change was a clear result of multiple environmental or market driven objectives as high fuel economy, pollution or limited resources. The electrification of transportation has brought an increase in the design complexity of the powertrain; and, in the same time a challenge for the research institutes and original equipment manufacturers (OEMs). Multiple hybrid electric architectures have been developed under a continuous struggle to find the best solution with respect to various objectives and constraints. To find the optimal design of, for example, a hybrid electric vehicle (HEV), is a complex optimization problem that can be addressed through various methods. Prior to the choice of a suitable algorithm for the optimization of this design problem, there is a need of in-depth understanding of the current state of knowledge in architecture choices and optimization algorithms. This paper presents an overview of the existing approaches and algorithms used for optimal design of hybrid electric vehicles (HEV). It also includes an introduction in various hybrid topologies and examples from different transportation sectors.

Keywords: optimal design, hybrid configurations, powertrain simulation, topology and size optimization, integrated framework, hybrid electric vehicles(HEV), hybrid electric submarines (HES), hybrid electric boats (HEB).

1. INTRODUCTION

In recent years, when the future of automotive power trains is discussed, the emphasis on reducing the CO₂ emissions is significant. This is enabled by the usage of other energy sources and leads directly to reduced air pollution. After Toyota Prius was lunched for the Japanese market in 1997, Audi was the first European car manufacturer that released a hybrid passengers car. Nowadays hybrids are offered or planned by Ford, General Motors, Honda, Nissan, GM, Daimler Chrysler, PSA Peugeot Citron, Mercedes-Benz, Hyundai and others. As they have proven their beneficial aspects, hybrid concepts have entered other markets as well. We can find now, hybrid commercial vehicles (as for example buses, Trigui et al. (2009), or trucks, Kadri et al. (2006)), hybrid construction machineries (as forklifts, Minav et al. (2010)), hybrid boats (see for applications Bolognani et al. (2008), Pizzo et al. (2010), Tang et al. (2006)), hybrid submarines, Skinner et al. (2009), or hybrid aircrafts, Rajashekara et al. (2008).

When a hybrid system is designed particular choices need to be done for each component of the drive line, and each of these choices are influencing the performance of the vehicle, e.g., fuel consumption, emissions, drivability or others. Finding the optimal design of a power train implies that the optimal solution for each design parameter has been found such that the propulsion is conducted at the optimal overall efficiency. Due to the complexity of the problem this has not been solved so far in an integrated way. In Guzzella and Sciarretta (2007), three different existing layers of optimization have been defined as: (i) structural optimization, where the objective is defined in terms of the powertrain structure (topology), (ii) parametric optimization, where the objective is defined in terms of the parameters of the fixed structure (size and type of components) and, (iii) control system optimization, where the objective is to find the best energy management system (EMS). Various methods address these optimization problems, yet until now there is no systematic optimization methodology that simultaneously considers all these layers. The broad design space to be searched and the multiple possible cases makes this problem non-trivial. As a follow-up of these complex requirements the HEV design needs to be addressed with a strongly interdisciplinary approach, Moore (1997). The papers that have addressed this (or, part of) problem for power train optimal design analysis are considered in the following sections.

Hybrid vehicles are characterized by two, or more power sources to produce, store and deliver power, and this usually refers to an engine and an electric motor (EM). This configuration for hybrid electric (HE) systems, engine and an EM, will also be considered here as default unless stated otherwise. This hybridization brings along a wide variety of possible topologies (architectures) when building the powertrain, yet, more generally, all these topologies can be split into three categories: series, parallel and series-parallel topologies, Ehsani et al. (2007).

Since, series drive trains, as depicted in Figure 1, perform best in stop-and-go driving, they are primarily being considered for buses and other urban work vehicles, Emadi et al. (2005). If the series hybrid topology is not used in city driving, then high powers need to be transmitted to the wheels from the EM, hence large electrical machines are required for high vehicle speeds. The features of the traction motor are deducted from the vehicle dynamic required performance, therefore the remaining
variables that can be optimized with respect to size are the battery pack size and the generating group (engine/generator) power. While in series topologies there is more flexibility in positioning the components, in parallel topologies, as depicted in Figure 1, the energy losses are smaller due to the mechanical connection.

The larger battery and motor, along with the generator in a series configurations makes these more expensive than the parallel hybrids. When compared with other topologies a disadvantage of the series topology is at high vehicle loads relatively low transmission efficiencies are achieved, Hofman (2007).

The third category of hybrid topologies, series-parallel combine the benefits and drawbacks from both series and parallel architectures. For a wide variety of applications, these can bring reduced fuel consumption, Xiong and Yin (2009). The efficiency of any hybrid topology varies according to the conditions under which they are driven and the design choice of one or another architecture depends on the mission of the vehicle and the trade-off between cost and performance.

Intensive research has been conducted on hybrid components technologies and storage devices for different applications. The particular requirements of each application define the technology that is chosen for usage as well as the sizes. This paper provides an overview of the state of the art of design algorithms that can include also topology, technology or size optimization. In this paper the problem of real time implementable EMS is not addressed. Instead paper focuses on the overall design of both topology and EM in the design phase of the powertrain. Section 2 discusses the optimal design problem, it offers an overview of existing algorithms used and their results for various applications. Para-

\[
\text{minimize...} \quad f(x) = \{\text{fuel consumption, emissions, costs,}...,\} \\
\text{with respect to...} \quad x = \{\text{engine size, motor position, battery size, motor size,...}\} \quad (1) \\
\text{subject to...} \quad 0 - 60 \text{ km/h} \quad \leq \quad ... \quad (\ldots),
\]

where the desired objectives, parameters and constraints can be defined by the user. All the parameters/choices of this optimization problem together with the desired targets/constraints and the given application can be summarized as in Figure 2. One approach in solving this problem, target cascading, was proposed in Kim et al. (2003) and used in Hofman and van Druten (2004), where the objectives of reducing the fuel, emissions or the costs, can be cascaded down to subsystem level and further on to component level, which shows the direct coupling between components, subsystems and design objectives (see Figure 2). The advantage with this approach is that the original problem is split into hierarchical set of subproblems, and “local” optimizations can be defined and solved for each subproblem.

Fig. 1. Topologies for hybrid electric vehicles: (a) Series topology and (b) parallel topology

The third category of hybrid topologies, series-parallel combine the benefits and drawbacks from both series and parallel architectures. For a wide variety of applications, there is an obvious advantage when using series-parallel hybrid electric vehicles. The most obvious advantage of series-parallel hybrid electric vehicles is the possibility of finding the global optimum solution (as for example dynamic programming (DP)) and the possibility of real time implementation, reusability, complexity and so on. A study on the EMS strategies for HEV with the emphasis on those that consider the look-ahead road situation and trajectory information can be found in Ganji and Kouzani (2010).

In this paper optimal design algorithms which have been used for topology/technology/size and control optimization are discussed together with their results for various applications. Parametric optimization, with emphasis on sizing, of powertrain components have proven to be beneficial with respect to fuel
consumption, emissions, costs and dynamic performance of the transportation system. Finding the optimal size of some powertrain components can be found in Murgovski et al. (2011), Gao and Porandla (2005), Trigui et al. (2009), Sundstrom et al. (2010c), Sundstrom (2009), Rousseau et al. (2008), Hofman et al. (2005), Gao et al. (2007), Pizzo et al. (2010), Skinner et al. (2009) and others. Variation in the type of technology for the second storage device can be found in Williamson et al. (2005), and for the type of transmission and size in Hofman et al. (2008). Variation of topologies can be found in Skinner et al. (2009) and Murgovski et al. (2011).

2.1 Parametric and structural design optimization examples

In recent years, beside control system optimization, parametric and structural design optimization problems have been addressed in multiple application areas. In Figure 4 a split of the reference papers, involved in optimal design of hybrid electric (HE) transport systems, is done between different applications and the types of topologies they analyzed. The fastest growing automotive research area is represented by passenger cars, where multiple manufacturers are heading towards HEV/EV or Plug-in HEV(PHEV). Examples will start, as depicted in Figure 4 with passenger cars and will continue with increasing in load applications, from trucks and busses to boats and submarines; furthermore, the algorithms used for optimal design are categorized and analyzed in the end of this section.

Optimal sizing is discussed for passenger vehicles with parallel topologies in Fellini et al. (1999), Rousseau et al. (2008), Sundstrom et al. (2010a), Gao and Porandla (2005), Hofman et al. (2005) and Gao et al. (2007). The solution is to define the application (given HEV and the driving cycle) and decide what are the parameters to be varied (e.g. internal combustion engine (ICE), battery (BAT) or EM size, minimum and maximum allowed state of charge (SOC) of the BAT). Accordingly, the fuel consumption has been analyzed by comparing the results of existing optimization algorithms (DIRECT, DP, Sequential Quadratic Programming (SQP), Genetic Algorithms (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), Equivalent Consumption Minimization Strategy (ECMS)) or Rule Based (RB) algorithms on the defined optimal design problem.

In Fellini et al. (1999), a parallel topology of a Chevrolet Lumina MidSize Sedan was analyzed. The simulations studies were done in ADVISOR where Turbo Diesel Engine Simulation (TDDES) program was integrated. This integration is motivated following the need of a more modular object oriented software for vehicle simulation. The simulated model contains a 1.45 L diesel engine, a 55 kW EM and a 65 kW BAT, resulting in a fuel economy of 43.41 m.p.g. 5 optimization algorithms are discussed here (SQP, Trajectory, Complex, DIRECT and Sequential Metamodel Optimization (SMO)) and from these, motivated by the presence of numerical noise, two derivative-free optimization algorithms, namely DIRECT and Complex, were chosen to solve the parametric optimization problem. The resulted fuel economy of 12% was a consequence of a smaller engine, motor and battery obtained from the optimization algorithm. For the particular problem DIRECT algorithm was more efficient then the Complex algorithm, both as fuel economy and as total number of function calls until convergence (here, whenever Complex algorithm got stuck in infeasible regions, a re-starting of the simulation was required).

A second parametric optimization example for passenger cars with parallel topologies can be found in Gao and Porandla (2005). Here, a topology with a 33 kW EM, a 88 kW Gasoline Engine, a 240 cells BAT with capacity 6.5 Ah and a 4 speed manual gearbox with final drive ratio of 3.63 is used for simulations. This configuration leads to a fuel consumption of 35.1 mpg, which, using 3 different algorithm is improved with 5 mpg. The drive cycle is composed out of a city driveway (FTP-75 cycle) and highway driving (HWFET cycle). DIRECT, SA and GA are used to optimize 6 design variables of the HEV given some bounds, were the resulting values are presented in Table 1. A comparison of the initial values of the design parameters and the optimum design variables show that SA and DIRECT find almost the same optimum point, while GA was assumed that it got stuck in a local minimum point. For a fair comparison here all algorithms are restricted to the same maximum number of evaluation functions. All three methods lead to a decrees in the mass of the vehicle, reduced fuel consumption and improved vehicle performance. Motivated by the slow convergence of the DIRECT algorithm a new hybrid optimization algorithm results by combining DIRECT with SQP. The results of applying this algorithm to the Rosenbrooks’s Banana function are compared with the results obtained with DIRECT and the hybrid algorithm manages to find the optimum function with a much smaller number of function evaluations.

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Initial Value</th>
<th>DIRECT</th>
<th>SA</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel converter power rating</td>
<td>86 kW</td>
<td>83.1 kW</td>
<td>82.4 kW</td>
<td>53.8 kW</td>
</tr>
<tr>
<td>Motor controller power rating</td>
<td>10 kW</td>
<td>20.2 kW</td>
<td>21.9 kW</td>
<td>65.4 kW</td>
</tr>
<tr>
<td>Battery number of cells</td>
<td>240</td>
<td>245</td>
<td>311</td>
<td>220</td>
</tr>
<tr>
<td>Min. allowed SOC</td>
<td>0</td>
<td>0.25</td>
<td>0.22</td>
<td>0.21</td>
</tr>
<tr>
<td>Max. allowed SOC</td>
<td>1</td>
<td>0.84</td>
<td>0.78</td>
<td>0.83</td>
</tr>
<tr>
<td>Final drive ration</td>
<td>3.63</td>
<td>3.9</td>
<td>4.0</td>
<td>3.49</td>
</tr>
</tbody>
</table>

Table 1. Final design variables values

A mid-sized to large family car, with a parallel topology, is analyzed in Sundstrom et al. (2010b). The optimal sizing of the powertrain components (ICE, BAT and EM) is discussed. First the sizing is analyzed by using DP; and, then, a sizing rule for the hybrid vehicle is developed that can find the optimal hybridization ratio with very little computational effort. Various...
parameters are varied and based on their influence on the design variables rules are constructed. The proposed method for sizing the vehicle finds the optimal point within 3.2% of the global optimum point for all 8 cycles. For most of the cycles, the method performs with less than 1% error. The method is robust to different variations and it performs slightly worse in the highway cycle because the SOC boundary is reached and the proposed algorithm needs to be modified, while DP can handle and overcome this problem. The advantage with this approach is the removed computational burden had by DP when solving the optimal control problem.

In Rousseau et al. (2008) a parallel gasoline Citroën vehicle is analyzed, which has the EM located near the wheels. Size variations for different powertrain components are discussed using DP and using a real time approach, e Equivalent Consumption Minimization Strategy (ECMS). Using AMESim as a software tool for validation, Matlab/Simlink for optimization and NEDC as input driving cycle, the optimal power split is found with DP. Starting from the initial design, where the fuel consumption of the HEV is 3.76 l/100 km (conventional vehicle 4.76 l/100 km), the following have been concluded: (i) by changing the BAT capacity (with the same weight), will cause the engine to change its operating point and it will not influence the fuel consumption as long as the SOC remains in its bounds without touching them; (ii) variation of BAT weight will influence the fuel consumption since the weight of the vehicle will also vary; (iii) the variations of the maximum and minimum EM power may change the fuel consumption (but not significant), but it will also change the state of charge trajectory. The results with DP in AMESim are compared, and only a small difference can be observed.

Two models, Honda Civic and Toyota Prius, are discussed in Hofman et al. (2005) and their parameters are varied to observe the influence on fuel economy. For this analysis 2 transmission types are considered, the CVT from the IMA and the E-CVT from the Prius, 3 combustion cycles (Otto, Diesel and Atkinson) and 3 vehicles, the two initial ones and an average between them. The influence of the transmission and different engines are done in the conventional case, with the use of DP to compute the optimal power split. The main conclusion with respect to transmission and engine type, when a NEDC drive cycle is used, are: (i) the V-belt CVT results in a 4% higher fuel consumption, (ii) downsizing the engine results in a better fuel consumption and changing the combustion cycle from Otto to Diesel and from Otto to Atkinson saves about 13% and 16% respectively.

In Gao et al. (2007), the optimization of 6 design variables of a parallel topology are used to compare 4 optimization algorithms using a composite driving cycle. The results, summarized in Figure 5, show that a significant improvement can be observed in fuel economy, power rating of, especially, the EM and dynamic performance after optimization. Here the results have been normalized to 100% such that the difference between the value before optimization and the values after optimization is easily understandable. The mass of the vehicle increases slightly for GA and PSO and descreses for DIRECT and SA. The load has a direct influence on the fuel consumption, hence GA and PSO have worse performance than DIRECT and SA, with SA offering the biggest fuel economy. We observe a significant decrees, approximately of 70% from the initial value, of the power rating of the motor for all algorithms, an increase of the power rating of the ICE in case of GA with 11%

The results presented here from a limited number of papers show the importance of optimization in design, and more, the difficulty brought by the big dimensions of the search space. By widening the analysis to multiple transportation sectors, it can be concluded that these research questions (in general , the search of optimal design parameters) are acknowledged, but not yet addressed or developed properly in an integrated way, also see Chan et al. (2010). When looking at heavier transport applications, trucks, boats, submarines or airplanes, the dependency of the powertrain design on the particular type of applications is maintained. Some work can be found for city hybrid electric busses, hybrid electric submarines (HES) or hybrid electric boats (HEB). Environmental, energy and cost issues have driven also the construction equipment industry to develop more energy-saving and efficient machines. The potential of hybridization of machines as forklifts trucks, loaders, excavators is discussed in Jo and Kwak (2011). Here the emphasis is done on the uniqueness of each equipment’s powertrain and the challenges that this brings when the design step is done, see for example the hybrid topology of an excavator in Figure 6. By capturing kinetic energy from the swing body and potential energy from its boom, the energy storage
Fig. 5. Performance assessment and final design variables values after optimization of a parallel HEV - 4 different algorithms, see also [Gao et al. (April 2007)]

system can be recharged for later usage. By hybridization, in different commercial available applications can reduce fuel as much as about 20% without any degradation of performance of drivability.

Fig. 6. Series topology of a hybrid excavator

In Williamson et al. (2006), a structural analysis is done for a heavy-duty diesel electric city transit bus. Here the parallel topology with an integrated starter-alternator is concluded to be more suitable for typical stop and go type diesel HEV transit busses. This, when compared with a series and a parallel topology. From various analysis, the series topology has resulted as being the less desired for the analyzed kind of application. The main disadvantage of series architecture is that the overall vehicle weight is 1 ton greater then in the other two cases, leading inherently to bigger fuel consumption and higher emissions. Worth to here mention is that the overall efficiency of the series topology reduces radically with time making this case not suitable for long drive distances.

In Murgovski et al. (2011), the optimization of component sizing is discussed for a PHEV city bus. The battery and the power generation unit sizes are discussed and results from convex optimization are compared with results from DP for two cases: a parallel and a series topology. Taking into consideration some assumptions, as the gear and the engine on/off state which are determined prior to the optimization, and making some approximations, the original problem is translated into a convex optimization problem. These approximations are necessary because some components yield inequality constraints which are not convex and equality constraints which are not affine, making the problem not solvable trough convex optimization. The optimization, subject to both time dependent and time invariant variables, is solved both with convex optimization approach and with DP. The results show that the vehicle with the parallel powertrain consumes 19.27 l/100 km while the series consumes 16.88 l/100 km. This is strongly connected with the bigger size of the BAT resulted for the parallel powertrain, 489 cells compared with 394 cells resulted for the series powertrain configuration. When the results from convex optimization are compared with the results from dynamic programming it is concluded that the error due to the approximations used for convexifying is small while the improvement in computation time and the number of variables used is significant.

The optimal sizing for the battery and the combustion engine is analyzed in Trigui et al. (2009) for a PHEV city microbus. The vehicle has a series topology and a predefined bus line to follow, a loop of 5.7 km long with nearly 3 stops per km, repeated 21 times per day. First DP is used to find the optimal SOC trajectory for the EMS, and next, the sizing process for the BAT pack and the engine. The most favorable case is when the largest battery is used at the highest depth of discharge. For the European average the CO₂ reduction is less then 15% in the best case. A trade off must be made between the cost of the vehicle and the CO₂ emissions.

The flexibility that a series topology gives to the designer has made this topology to be more used in boats and ships sector, where space and positioning flexibility is important, for examples see Pizzo et al. (2010), Bolognani et al. (2008). Similar to the automotive design challenges for HEV, in a hybrid submarine the mechanical propulsion can be used for high propulsive loads and electric propulsion for low propulsive loads, improving the efficiency points at which the power suppliers are functioning. In Skinner et al. (2009) three topologies of a next-generation SSN (nuclear powered attack submarine) submarine, as in Figure 8, are analyzed (direct electric drive, geared-electric drive and hybrid electrical/mechanical drive) and compared with the conventional mechanical drive using 4 driving cycles. The design optimization approach used in Guzzella and Sciarretta (2007), where multiple devices are considered simultaneous for the optimization is used here to show which topology and which sizes will find the best combination of cost, risk and mission effectiveness. An evolutionary multiobjective optimization (EMOO) approach, namely a multiobjective genetic algorithm (MOGA) as described in Konaka et al. (2006), is used to optimize 9 design variables (EM size, propeller diameter, number of EM, EM gear ratio, steam turbine rated load-propulsion, steam turbine rated load-electrical, power split ratio, number of AC generator pole pair and AC scaling factor). 5 objective functions are defined and each of these objective
functions are evaluated for each of the 4 scenarios resulting in 20 objective function in total. Each evaluation is performed in Matlab/Simulink and SQP is used to select the optimal power split method. From this analysis, it is concluded that the hybrid configuration brings the best results by resulting, in average, in an improvement of 8% in the energy consumption.

Fig. 7. (a) Direct electric drive architecture, (b) Hybrid electrical/mechanical drive architecture, (c) Geared-electric drive architecture

Size optimization for a series hybrid boat is addressed in Pizzo et al. (2010) and for a series-parallel one in Dupriez-Robin et al. (2009). The HEB, with the topology depicted in Figure 8 is a convectional bus boat used by the Venetian Transport Consortium Company, with 23 m length and 4.22 m width, propelled by a single 140 kW ICE that is able to develop all the power required in each operating conditions. Two cases are discussed: (1) when the engine is at fixed speed and power (around 80% of its maximum power, where ICE usually have their maximum) and (2) when the engine is functioning at variable speed and power, both in a series drive train framework. Case 1 leads to an increased ICE but a good efficiency functional point. Case 2 leads to a lower overall efficiency but also a reduced weight for the storage system. From a cost point of view this represents a clear benefit. Given a particular driving cycle, based on the power requirements of the system, the authors of this paper are analyzing (manually) different sizes. In the second paper where a parallel HEB is analyzed, Dupriez-Robin et al. (2009), the importance of the "driving cycle" defined for the boat is emphasized since defining this can be more difficult then for HEV. In all designed cases the fuel consumption changes with the capacity of the battery, and it is not significant if regenerative braking is not allowed.

2.2 Trends in optimal design strategies

A decade ago the realization of HEV was acknowledged as possible and analyzed as functionality, see Chan (2002). This area has emerged and, as a subsequent effect, the control algorithms for HEV have been developed to improve fuel consumption and performance and decrease emissions and costs, Chan (2007). Nowadays the challenge has changed towards how can we extract the best result given the real functionality and requirements of the transportation mean.

From these analyzed cases it can be concluded that finding the optimal design is a complex problem, where multiple parameters and cases need to be analyzed. Trade-offs between performance, cost, fuel consumption, computation time exist and they depend strongly on the application. From Figures 4 and 9, which summarizes found topologies for various applications, it can be concluded that there is no best, predefined, topology for any application. Hence, in future research the choice of topology has to be addressed and integrated with the choices of sizes, technologies and control.

Depending on the usage of the transportation system and the loads that this has to carry we can observe a trend in using different types of topologies as depicted in Figure 9. All transportation systems that are possible to drive on a "highway type" of cycle will, most likely, not have a series topology, while transportation systems that will work in a stop and go manner will most likely not have a parallel topology.

The importance of the assumptions and the approximations that are made during the optimization and their influence on the final result needs to be stressed here. For example, many of the optimization algorithms assume that the battery SOC will not hit the bounds, which in practice can become a problem (as for example in plug-in HEV) if not explicitly treated by the energy management system. In plug-in HEV the objective is to discharge the battery as much as possible before plugging the vehicle in the electric grid, Serrao et al. (2011). The questions to answer is if these algorithms can cope with this, how and what is the effect on the objective of the optimization when these bounds are reached or violated.

Regardless on the topology, it is noted that the efficiency improvement is fairly dependent on the overall efficiency of the energy storage system, which is usually limited by the overall weight of the supplementary drive train components. The requirements that energy storage systems need to meet for heavy-duty applications is different then for light duty applications. A comparison of different energy storage devices is presented in Ehsani et al. (2007) and the trends towards combined chemical batteries and ultracapacitors is mentioned as being the most promising way to meet the energy power demands within future compact and lightweight structures. In Williamson et al. (2005) the secondary storage device for heavy-duty hybrid vehicles is analyzed. The performances of lead-acid (PBA), lithium-ion (LiIon), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), and nickel-zinc (Ni-Zn) batteries, as well as ultra-capacitors (UC) are investigated over city and highway.
driving schedules for a heavy-duty diesel-parallel hybrid transit bus application. Pros and cons for all these are presented and recommendations are given towards their possible use within HEV. Not addressed here but with a clear contribution on the result are the simulation software environments. These need to be sufficiently sophisticated such that accurate analysis can be made. Gao et al. (2007) presents an overview of these tools, their applicability depending on the application and examples.

Another important factor when implementing these algorithms is their complexity and the computation time required when implemented. As stated (and used) in Fellini et al. (1999), the computational time can be substantially decreased if the simulation is performed on distributed workstations. For the algorithms used in this paper the advantage was the non-dependency on computing the gradient. Nevertheless, a disadvantage is that the global convergence comes at the expense of a large and exhaustive search over the domain, hence an increase of the simulation time. Figure 10 classifies the algorithms found in Section 2.1 for optimal vehicle design. This classification is done to create a clear picture of the reasons of why one or another algorithm has been used. As stated in the introduction of this paper here, the real time implementable optimization it is not included, since it is outside of the scope of this paper.

For example, this challenge is solved in Skinner et al. (2009) with the use of a multiple-objective genetic algorithm, but for most of the algorithms found here there exist versions where this is possible (which come with an increase of computation time). From the analysis done here it can be observed that algorithms which can search the global solution are preferred. This is often the case since when stuck into a local minimum, the optimization fails to reach the OEMs desire, i.e. the “best” solution. For this reason, DP is a widely used algorithm, but its long computation time represents an important drawback when more than two variables are used in the optimization problem. Sometimes, see Sundstrom et al. (2010c), DP is used in prior studies and rule-based algorithms are developed based on this analysis. So-called, “hybrid” algorithms are proposed to overcome drawbacks, offer faster computations and (near, or) global optimum solutions to the design optimization problem. SA and DIRECT offer in several papers good results. More extensive steps towards the vehicle design problem have been made in the work of Sundstrom (2009) and Murgovski (2012), where the focus is made on the sizing and control layers. So far there is no automated method to be found in literature to solve all the optimization layers within the design problem at once.

3. CONCLUSIONS

This paper presents an overview, examples and trends that can be found in solving the optimal design of a hybrid powertrain problem, with specific emphasis on size, technology and topology optimization. From given examples the spread of hybrid technologies can be observed in all transportation areas, and in all of them the optimum power train design solution is desired for fuel consumption minimization, emissions and dynamic performance. Future work of this research involves the analysis and development of a tool that can offer integrated optimal design for commercial vehicles under given work conditions.

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