Title: Towards smart vehicular DC networks in the automotive industry

Subtitle: Process, computational tools and trends in the design and simulation of electrical distribution systems (EDS) of vehicles

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The automotive industry is experiencing unprecedent requirements to fulfill higher expectations from customers and include new functionalities in vehicles such as driving assistance, gadget connectivity, sharing capabilities and electrified traction. In this regard, the electrical network is nowadays one of the most challenging on-board systems to be designed and prototyped considering the aforementioned demands added to its intrinsic complexity. For instance, a single vehicle contains tens of Electronic Control Units (ECUs), hundreds of power consumers and more than a thousand wires having an aggregate length of more than 3 km and a weight above 50 kg [1]. As a consequence, there may be up to 10^{10} possible wiring architectures that translates in a great logistics effort to integrate disperse and vast data from manufacturers and suppliers. In this regard, it is crucial the development of software platforms to suitably visualize, analyze and simulate these intricate vehicular electrical networks in multiple possible configurations and scenarios. Only by means of versatile power flow simulation, prompt detection of failures in the electrical distribution system (EDS) can be done, such as unwanted voltage drops or erroneous components sizing. Hence, those configurations not complying with operational and safety requirements could be dismissed in an early project stage. Indeed, with a simulation phase evaluating a wide amount of architectures within the EDS design, the prototyping stage would simply permit to endorse the results previously attained with numerical methods, where obviously, a wide amount of architectures has been already evaluated. Therefore, time-to-market may be shortened as the required number of prototypes could be potentially reduced.

To enhance the flexibility and reliability in virtual experimentation, the inclusion of thermal constraints, hardware in-the-loop (HiL) and power traction networks is of great significance. Additionally, these simulation platforms should also assist the analytical reasoning of designers by means of interactive interfaces. To do so, it is crucial for these tools to include perspectives from visual analytics (VA). The latter is a multidisciplinary field that has gained significant attention in the last years as it facilitates human-information interaction and intuitive understanding of complex systems having large datasets, as in the case of EDS of vehicles.

In this context, to provide the reader with a satisfactory understanding of the design, simulation and trends of on-board EDS, this paper is organized as follows. Next section describes key related concepts employed in the automotive industry and details the wiring process. Then, the authors expose some of the features of the existing computational tools able to design and simulate vehicular EDS. Later, a tailored power flow simulation is proposed to attain smart vehicular electrical networks. A case study is described and analyzed. After that, some noteworthy trends and future research areas in this field are mentioned. Here, the importance of thermal studies, hardware in-the-loop and visual analytics among other aspects is highlighted. Finally, conclusions are inferred.

2 The wiring design process in vehicles

For a particular car model, most manufacturers are nowadays offering selectable functionalities to customers even if the logistics complexity in the development process is highly increased. To allow this customization while ensuring proper electrical operation in all the configurations, a modularity strategy is held. This approach lies in the use of families and modules. A family consists in a group of elements able to perform a specific function. This function can be, for instance, the sound system which is made up of different components such as the radio, front loudspeakers, back loudspeakers, touch screen, etc. The components are in turn organized inside modules. With this approach, a family can be formed by different modules, where each of them is composed by predefined components and might represent a different level of complexity of the required functionality (Figure 1). Following the example of the sound system family, the possible configurations might include Modules A and B. Module A could represent a higher equipped sound system compared to Module B.

The elements in a specific family are not only electrical as fuses, wires, relays, connectors and loads (such as the loudspeakers in the example) but also fixing and protective parts such as clips and tapes. As a general rule, for each family in the vehicle, only one module can be chosen as the final client can select just one of the various possible configurations (modules) for a given functionality. Once a specific module has been selected for each family, a detailed description of a specific and unique wiring harness configuration is built. Depending on the previous, the complete EDS of a vehicle can be composed by a set of different wire harnesses (like the one depicted in Figure 2). For instance, a harness for the interior which transports energy to most of the consumers, but also smaller harnesses such as those for the doors or bumper. The type of loads included in the harness has a significant impact on the selection of its wiring cross-section and electrical protections. The final product of this stage is the complete wiring harnesses description as they would be installed inside the vehicle, maintaining the modularity information all along. Figure 3 shows the scheme of all the wiring harnesses present in a car for a given user-defined configuration and vehicle model.

Next, the process continues with the design of the wiring schematics (WS) containing diagrams with logical connections among all the components inside the full on-board EDS. The WS exhibit the electrical power distribution from the battery to the last of the consumers, indicating the connections through fuses, relays and other electrical elements. Cross-references between WS files are also included. Later on in what are referred as wiring plans (WP), numbering of the cables, wiring cross-sections, couplings and other physical characteristics are added to the WS. Simultaneously to the development of the WS and WP files, the elaboration of the routing files for the wires also takes place. Here, all the wire paths between components are designed considering mechanical constraints and then traced into 3D CAD files. Similarly to the case of the WS and WP, there is a database containing the graphical information of every component. After this, the WP are combined with the routing diagrams to generate a full graphical description of the wiring harness containing also the cables length information. From this merge, a file (referred as KBL) having an Extensible Markup Language extension (.XML) is created. The KBL file embeds all the required manufacturing information of a wiring harness and also contains 3D information that can be later represented into elaborated 2D wiring schematic layouts known as full wiring drawings (FWD). There is a KBL file for each harness in a vehicle. The hitherto explained process can be visualized in Figure 4.

To end the databases creation process, two excel files are automatically generated from the KBL file; these are the Wirelist (WL) and the Bill of Materials (BOM). The WL includes a numbered list of all the wires present in the harness, along with information such as identification tag, origin and destination node with pin information, total length, cross-section, color, insulation type, and others; all together with the family and module to which each cable belongs. This list is critical as it contains all the connections performed with wires. On the other hand, the BOM file lists electrical components which are not wires, such as fuses, relays, but also elements from the wire harness that have only mechanical purposes such as fixings, wire-guides, etc, specifying also the module and family for each one.

3 Computational tools for the simulation of on-board EDS

The use of simulation in the automotive engineering branch was firstly extended in domains of aerodynamics, vehicle collision and engine multibody dynamics. In the last years, sustained efforts have also taken place in areas like artificial vision, virtual reality, network communications, energy balance, electrical traction and charging systems. However, as a consequence of the large-disperse factory information and sharp intricacy of the vehicular EDS, only few commercial platforms and even less academic efforts have proposed computational tools able to perform a detailed simulation of these systems considering the necessary manufacturing data pre-processing, the complex wiring and the different electrical components forming the harnesses. In this regard, commercial tools such as EBCable, Vesys and Eplan Harness proD permit only design duties but are not suited for simulation. Meanwhile, platforms such as Power Net Simulation by Bosch and Simulink from Matlab mainly allow to simulate the overall energy balance employing general models for the battery, alternator and loads; all operating under selected scenarios and driving conditions. Finally, software tools like Harness Studio, Siemens Solid Edge and Saber RD have typically assisted in the harnesses design but in the last years have also included specific add-ons intended for simulation of the EDS. However, not much information is available regarding the features, models and methodology employed by those add-ons, which in most cases remain unknown by the user and thus do not allow to establish a benchmarking between them. In consideration of the above, next section details an entire procedure to successfully perform a reliable power flow simulation for on-board EDS taking into account the available automotive factory data formats.

4 Tailored power flow simulation for smart vehicular electrical networks

Data pre-processing

The data containers including the greatest amount of electrical details from the harnesses are the WL and BOM files which in turn were formed from the KBL files as previously explained. However, as those files were primarily structured for exchanging manufacturing information, they are not conceived for electrical simulation. Besides, they neither contain all the necessary data such as time-current characteristics of fuses, temperature class of each cable, pin-out information of the consumers, among others. Therefore, to create a proper data container intended for power flow studies, besides including the WL and BOM archives as inputs, a customized multi-dimensional data structure has been created and referred as QT. The latter is an excel file having condensed information from the automatically generated BOM and WL but complemented with the aforementioned missing data which has been taken from other disperse databases.

As the XML files were originally designed to contain all the possible modules that exist for a given family within a car model, the newly generated data container provides by default the full modules information. In practice, a specific vehicle is described by a selection of only one module per family, thus its simulation requires filtering of the data container. The way to achieve this is to allow the user the introduction of a list of modules (one per family) in the form of a table, corresponding to the car configuration under study. Once this table is introduced together with the data container, a pre-processing algorithm removes the unnecessary information. Finally, the filtered data is forward used as input for the power flow solver. Figure 5 sketches the overall data pre-processing process.

Tailored power flow simulation

Traditionally, the most used algorithm for solving power flow studies in conventional electrical systems relies in the Newton-Raphson criteria. Nonetheless, the algorithm chosen to face the vehicular EDS features is the method known as Backward/Forward Sweep (BFS). This method uses the Kirchhoff's current and voltage laws (KCL and KVL) iteratively. This approach has been mainly selected for some reasons:

- The formulation for this specific case of application is simpler.
- The convergence speed of these BFS methods have been proved to be better than the Newton-based tactics in radial or slightly meshed systems [2].

To provide some insights on the tailored developed algorithm to perform power flow simulation for the vehicular EDS, below are listed its main highlights and procedure:

1) Classification of the network components as consumers or source according to the type and number associated to their pins.
2) Determination of the interface between the positive and the negative grid. The on-board EDS has been considered as a two-fold grid, having a positive and a negative grid. The first one refers to all the nodes and segments connecting the positive terminal of the battery to components and between them, while the latter refers to the nodes and segments that connect to the negative terminal of the battery. The strategy of studying the vehicular EDS as two separated networks relies on the fact that in such systems the path to ground (negative grid) represents an intricate network itself as it commonly passes through current splices and sequential ground bolts before reaching the main ground bolts in the vehicle body. Additionally, it has been verified that this approach benefits the accuracy of the model.
3) Formation of the incidence matrix providing the connections data, where each row represents a branch of the system and each column a node. The cut and non-cut branches are also defined.
4) Obtention of the branch resistances matrix by employing the information of wire length between nodes and conductor resistivity given in the customized created data container. The calculated resistance considers the effects of temperature variation by means of the linear classical equations.
5) Calculation of all the Thevenin resistances of the cut-branches using a unitary current sequential injection method. To do so, the loads are seen as current injections to the nodes where they are connected. A related nodal current injection for each of the grids, the positive and the negative, is defined. In the case of components classified as Electronic Control Units (ECUs) the procedure is exactly the other way around: the current associated to a ground pin is split among its associated input pins.
6) Removal of the branches which define loops in both the positive and the negative grid by analyzing the incidence matrix. Hence, a compensation technique will afterwards be included in order to estimate the currents in the cut branches. This adjustment uses the Thevenin equivalent resistance in the cut branches.
7) Once the system is radial as a consequence of the previous step, the BFS iterative process is launched including the compensation algorithm.
8) The branch currents in the non-cut branches are calculated. This calculation is direct from the nodal currents already assigned by means of the incidence matrix.

9) The voltages of all nodes (except the slack one) can be obtained making use of the branch currents and the resistances of the non-cut branches. At this stage, the voltage drop in the cut branches can be calculated using two different methods.
10) In the first method, since we have all voltages in the network, we can use them to obtain the voltage drop directly in the cut branches
11) By the second manner, the branch currents and the resistance of the cut branches are used to calculate the voltage drop.
12) Analyze if the calculated voltage drops are consistent, this is if the voltage drop error is lower than a predefined threshold.
13) Both previous approaches must match when the algorithm convergence is achieved. If not, the second approach is used to update the branch currents as in Step 8) and a new iteration is launched. For the interested reader, a detailed explanation of the entire previous methodology can be found in reference [3].

Case of study

The aforementioned methodology is quite simple but still robust and efficient to tackle the challenges involved in the EDS of vehicles as this section corroborates with a case of study. In this example, a specific modularity list (for a given car model) has been added by the user by means of a previously referred QT file. The sample network in Figure 6 contains a 14 V battery connected to the vehicle ground as the feeder. The node A1 represents a connection to a metal plate which distributes energy to the network through different fuses (elements having prefix “F”). The nodes identified with the prefix “Sp” are splices nodes. Splices represent ultrasonic soldered connections of multiple wires. On the other hand, consumers have been named with the prefix “C” while couplings and ECUs have the prefix “K” and “E” correspondingly. The reason the numeration is not exactly consecutive is to represent the fact that given the modules selected, certain components have been filtered out.

Component E1 is an electronic control unit, therefore classified as 'Source'. It has 4 pins where pin 1 and 4 are power inputs and pin 3 is a power output. Pin 2 is a signal pin and thus neglected. The numbered grounds represent bolt ground points located in different places of the vehicle body and connected through the vehicle body itself. The battery ground or negative terminal is identified with the code gr00.1. Figure 6 exhibits the different node voltages as well as the branch currents. Voltage drops are encountered in the lines as a result of the calculated lines resistances given their physical characteristics. Nominal node voltages decrease following the power flow as expected. In addition, the voltage drop in fuses is dependent on their type and the calculated branch currents are consistent all along the circuit.

5 Future research and trends towards smart EDS

Proper results were attained in the case of study described in the previous section given a simplified network. Nonetheless, the proposed simulation strategy is able to individually analyze the different harnesses in the on-board EDS. In addition, the described methodology may also serve as a referential framework to include more functionalities and ongoing trends procuring the development of smart vehicular EDS, among these we have:

Thermal studies

The inclusion of heat thermal analysis is of high relevance. This may allow to study the thermal behavior of automobile cable harnesses in steady state and transient regime given certain environmental and driving conditions. As a result, more trustworthy electrical simulations would be achieved as the wiring physical properties would be updated according to the pre-defined scenarios. On this regard, some advancements have been proposed in [4] where the modeling is limited to the simulation of single wires or bundles but not applied to the entire EDS, however.

Hardware in-the-loop

Nowadays, the role of Hardware in-the-loop (HiL) is becoming more and more significant in the automotive industry as it provides an efficient alternative to perform trustworthy simulations and develop robust control strategies for complex and challenging applications such as autonomous driving [5] or electrical-mechanical traction shift in hybrid electric vehicles (HEV) [6]. For the case of on-board EDS, the use of HiL would permit to develop accurate dynamic models and analyze the real-time transient and steady-state response of the electrical network when including actual loads, ECUs, sensors and actuators under different driving scenarios. Hence, the outcomes of the power flow and thermal off-line simulations will be enhanced to exhibit accurate results. This will provide EDS designers with the sufficient industrial reliability to promptly endorse or discard different network topologies and configurations on an early stage.

Automobile high voltage networks, power converters and smart energy systems

As the electric and hybrid vehicles sales is exponentially growing, for reliability purposes it is decisive to enhance the interaction of the high-voltage (HV) power conversion stage with the low-voltage (LV) EDS. Despite the fact that both systems are now intended to exchange energy in normal operation modes [7]-[8], under extreme conditions the on-board EDS should be resilient and flexible enough to receive energy from the HV battery in order to maintain the proper supply of critical loads. Besides, the EDS could be designed for being able to provide the user with warnings and messages related to early fault detections and the status of the ongoing performance of the system.

Visual analytics

Visual Analytics (VA) has emerged as a promising multidisciplinary field that encompasses different research areas such as visualization, data analysis, data mining, human-computer interaction, and others. It has been employed by different disciplines to gain knowledge, amplify cognition and get insights from large and complex datasets. In electrical systems, some contributions have been done by means of VA. However, all of them focused only in power systems, but not on extensive, weakly-meshed and structurally complex low-voltage DC distribution networks as in the case of vehicles. In this regard, the inclusion of the VA precepts and tools in on-board EDS simulation platforms would be of high significance as this may permit to develop aesthetic yet functional interfaces, enhance intrinsic knowledge from designers, improve the visualization of electrical parameters, determine risky or unsuitable electrical configurations, perform batch simulation and data mining, among others [9]. In this regard, a bunch of possibilities appear only by including some interactive techniques such as color contouring, animation, data aggregation and automatic layout generation. Figure 7 exemplifies the use of those techniques in networks of other ambits (noise monitoring, social, transportation and energy production). However, it may permit the reader to infer an idea of the possibilities in the use of VA practices to handle the needs of the intricated EDS of vehicles.

Conclusions:

The design of vehicular electrical networks is a highly challenging stage in the automotive industry as a consequence of the complex, large and disperse electrical data from manufacturers and suppliers. Indeed, for a particular car model, there are a huge amount of possible wiring paths, configurations and components. This translates in a great logistic and engineering effort to suitably accomplish customization and the newly required functionalities. On this subject, the development of interactive and robust software platforms able to visualize and simulate the on-board EDS has been justified in the present work. These computational tools can be of great significance to assist engineers in studying the network under various conditions and topologies prior to a prototyping stage. Therefore, inappropriate configurations may be promptly discarded and thus shortening the design process.

In order to perform numerical simulation in the on-board EDS, a data pre-processing stage is firstly needed to collect the required electrical information from different manufacturing data files. To perform a power flow analysis, the Backward/Forward Sweep (BFS) method has been employed by virtue of its practicality, high convergence speed and adaptability to slightly meshed topologies as in the case of vehicular networks. Some remarks and results on the custom developed power flow algorithm have been exposed. The proposed case of study exhibits consistency in the attained voltage drops and branch currents throughout all the elements.

As part of future work and research, the inclusion of the mentioned new functionalities will become more relevant in coming years as vehicular EDS will be requested to become smarter to robustly support driving assistance, flexible gadget connectivity and extended electrified traction.

References

[1] SEAT S.A. 2 km of wiring weighing 42 kg – the neurons and arteries of the SEAT Ateca. Accessed on 18-09-2019. [Online]. Available: https://bit.ly/2kQGpqw

[2] P. Arboleya, B. Mohamed, C. Gonzalez-Moran, and I. El-Sayed, “BFS algorithm for voltage-constrained meshed DC traction networks with nonsmooth voltage-dependent loads and generators,” IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1526–1536, March 2016.

[3] Paola Mantilla-Perez et al., “Simulation of Electrical Power Flow in the DC Distribution System of Modern Vehicles”, IEEE Transactions on Vehicular Technology Systems. Under Review.

[4] A. Rius, “A novel optimization methodology of modular wiring harnesses in modern vehicles: weight reduction and safe operation,” Ph.D. dissertation, Universitat Politecnica de Catalunya, Spain, 2017.

[5] C. Brogle, C. Zhang, K. L. Lim and T. Bräunl, "Hardware-in-the-Loop Autonomous Driving Simulation Without Real-Time Constraints," in IEEE Transactions on Intelligent Vehicles, vol. 4, no. 3, pp. 375-384, Sept. 2019.

[6] H. Zhang, Y. Zhang and C. Yin, "Hardware-in-the-Loop Simulation of Robust Mode Transition Control for a Series–Parallel Hybrid Electric Vehicle," in IEEE Transactions on Vehicular Technology, vol. 65, no. 3, pp. 1059-1069, March 2016.

[7] H. V. Nguyen, D. To and D. Lee, "Onboard Battery Chargers for Plug-in Electric Vehicles with Dual Functional Circuit for Low-Voltage Battery Charging and Active Power Decoupling," in IEEE Access, vol. 6, pp. 70212-70222, 2018.

[8] J. G. Pinto, V. Monteiro, H. Gonçalves and J. L. Afonso, "Onboard Reconfigurable Battery Charger for Electric Vehicles with Traction-to-Auxiliary Mode," in IEEE Transactions on Vehicular Technology, vol. 63, no. 3, pp. 1104-1116, March 2014.

[9] Xavier Dominguez et al., “Visual Analytics-Based Computational Tool for Electrical Distribution Systems of Vehicles”, IEEE VPP Conference, Vietnam, October 2019.

Short Bios:

Xavier Dominguez (uo233585@uniovi.es) received the Engineering Degree in Electronics and Control at the Escuela Politecnica Nacional-Ecuador in 2010. Thanks to an Ecuadorian scholarship (Senescyt), in 2014 he attained a M.Sc. degree in Electrical Energy Conversion and Power Systems at the University of Oviedo-Spain, where he is nowadays pursuing an industrial Ph.D. in Energy and Process Control related to a research project sponsored by the automotive Spanish manufacturer SEAT S.A. His current research areas are modeling, simulation and visualization of on-board electrical networks of vehicles, smartgrids and renewable energy integration.

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Figures:

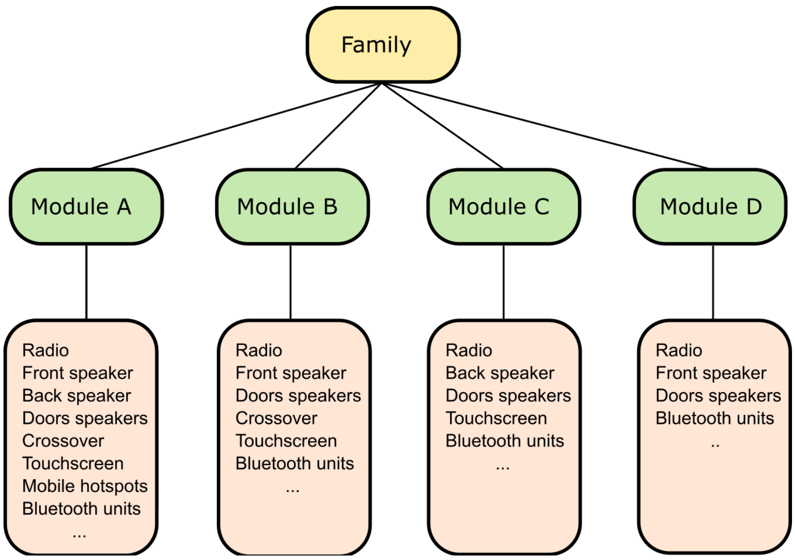


Fig. 1

Fig. 2

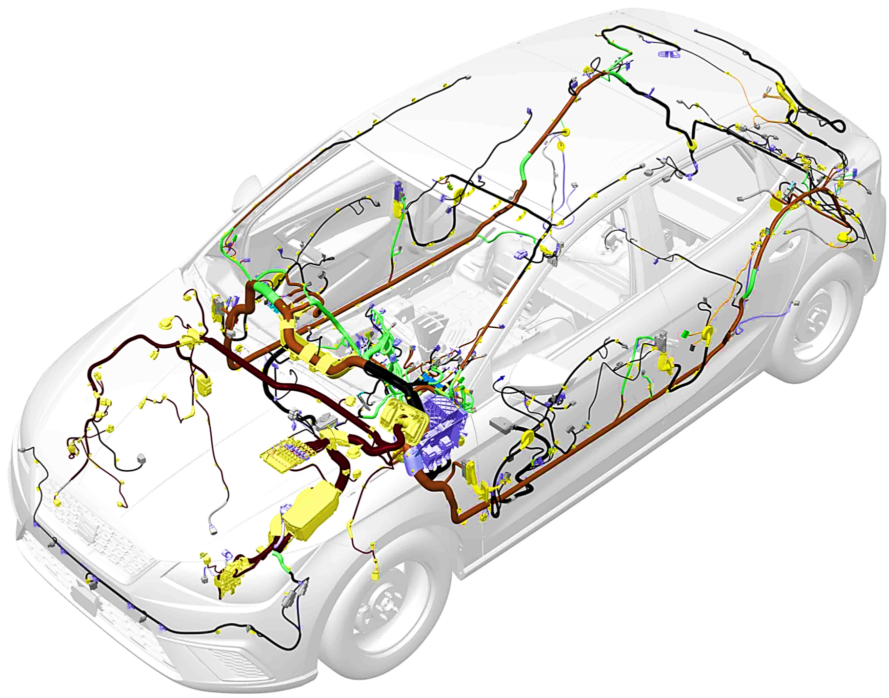
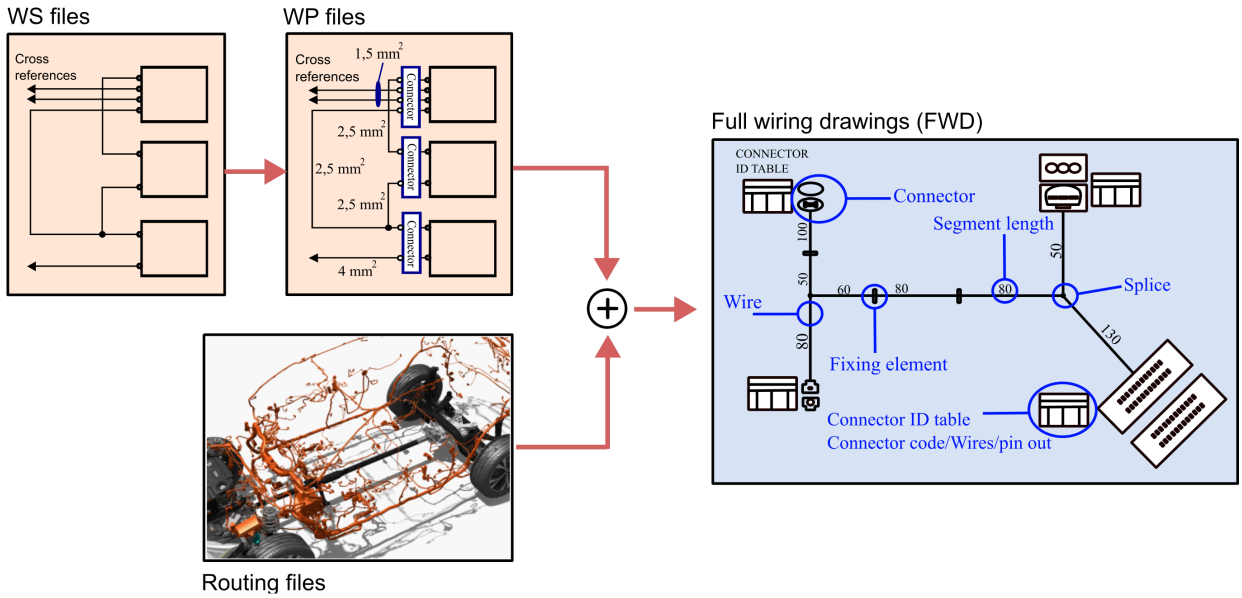


Fig. 3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Cross references
WP files
Cross references
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Connector
Connector
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Routing files
Full wiring drawings (FWD)
CONNECTOR ID TABLE
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Segment length
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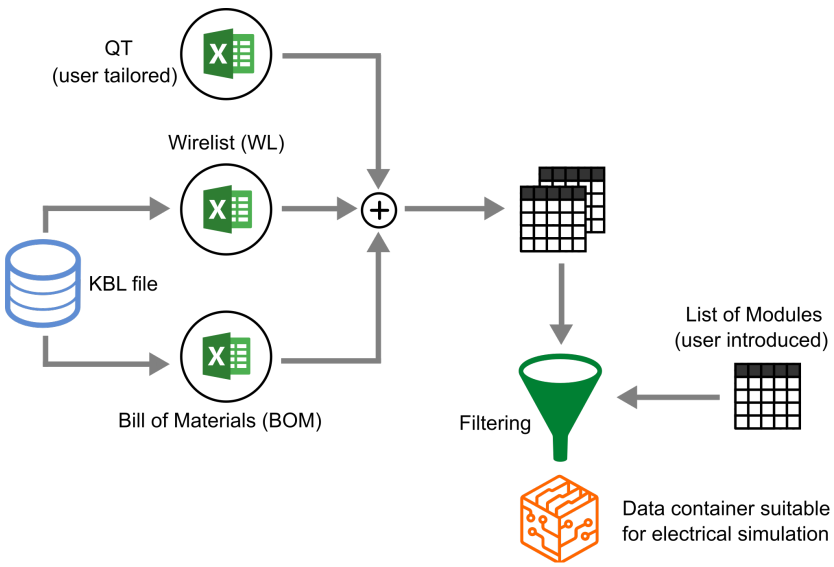
Fig. 4


QT
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List of Modules
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Filtering
Data container suitable
for electrical simulation

Fig. 5

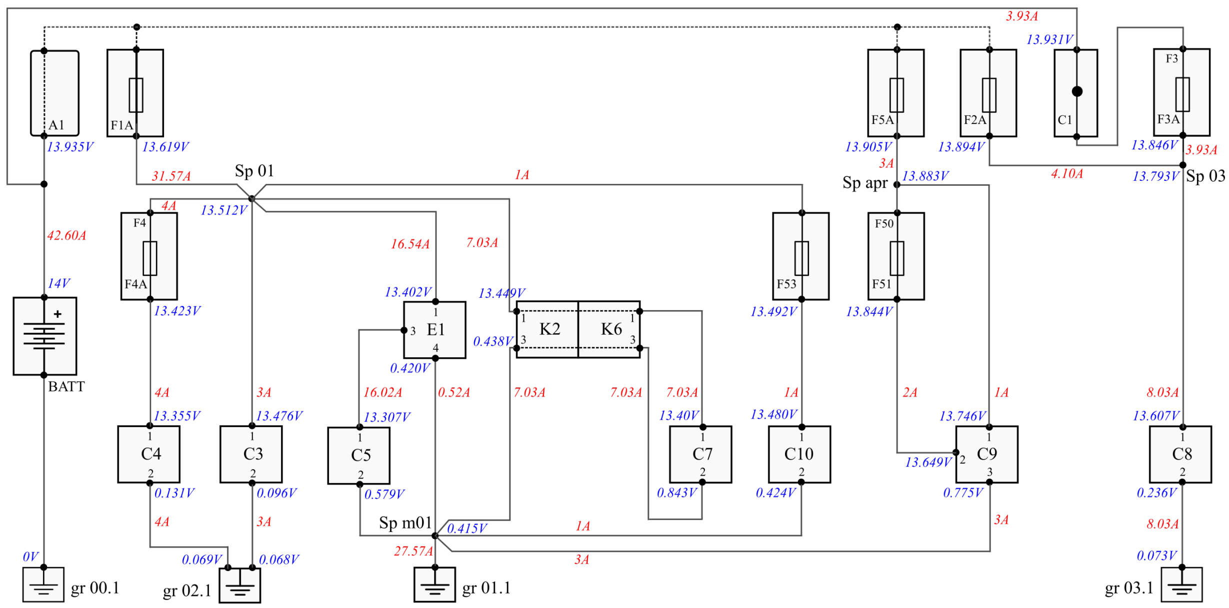
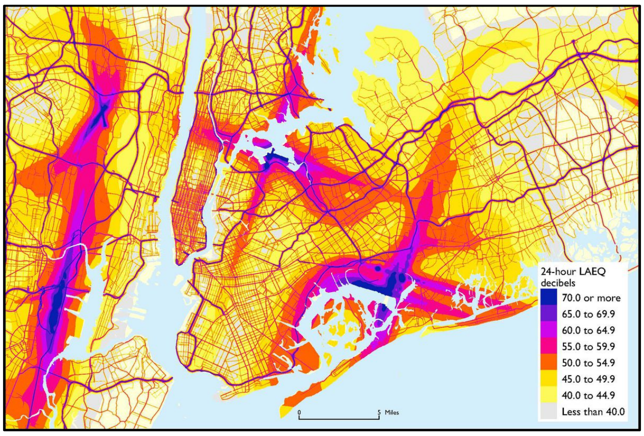


Fig. 6



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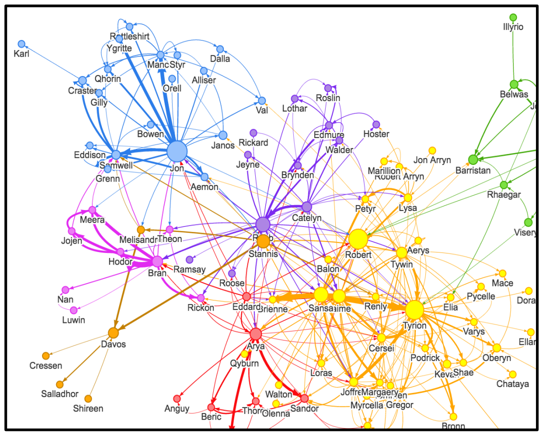

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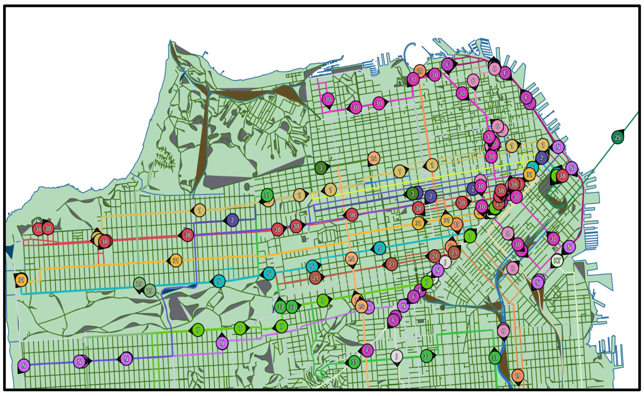

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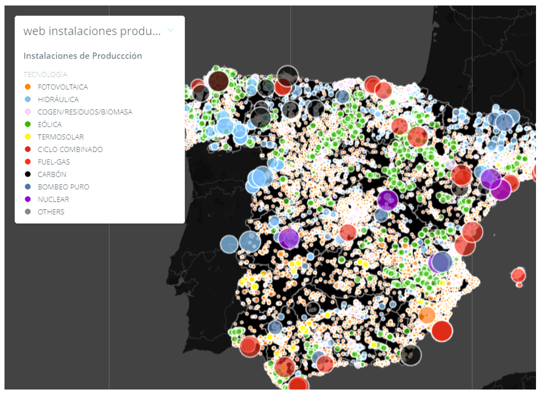

(d)

Fig. 7

(a) Taken from https://bit.ly/2lhudiN

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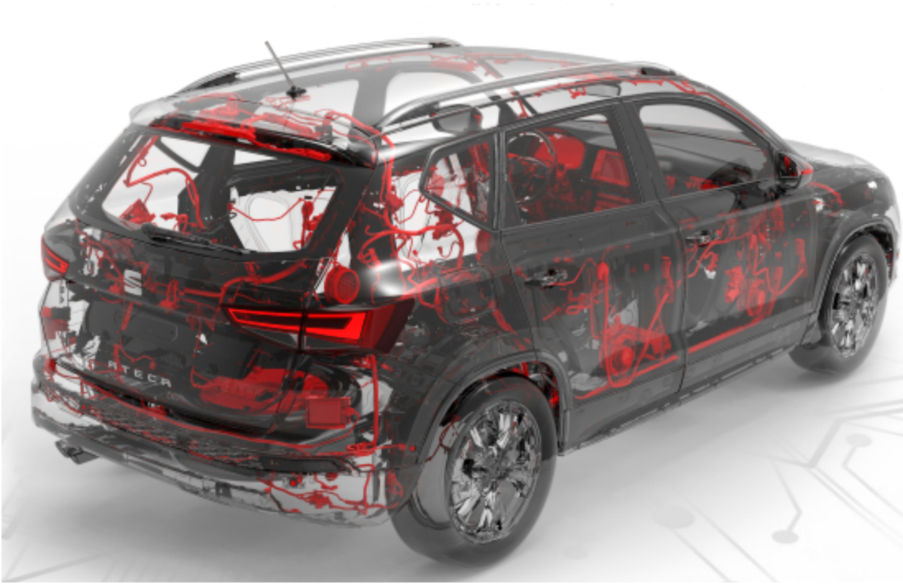

Fig. Tentative

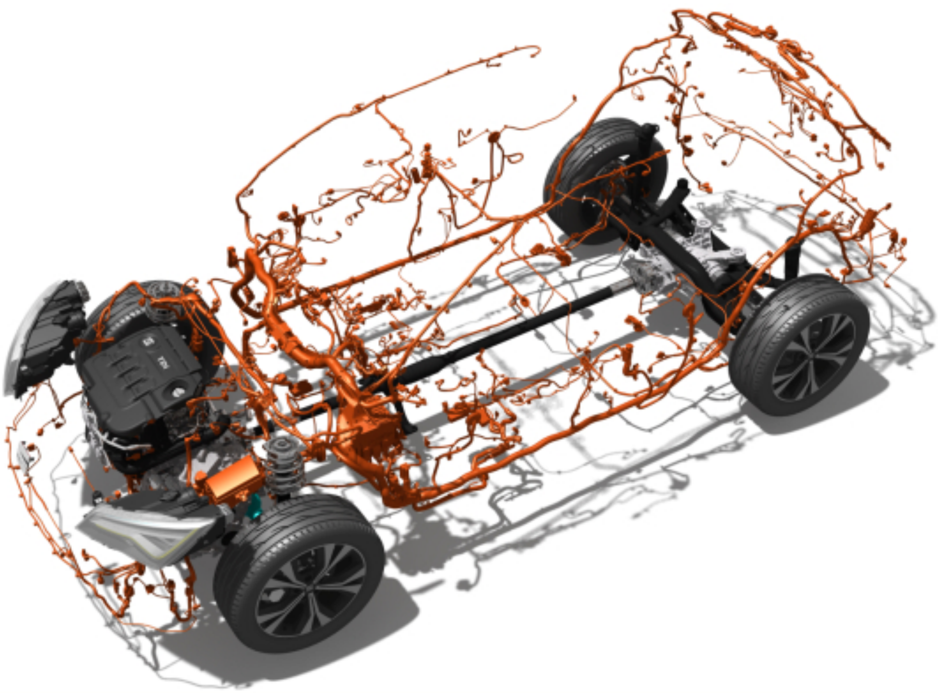

Fig. Tentative