Universidad de Oviedo

Department of Electrical, Electronics, Communications and Systems Engineering

PhD Thesis

Analysis of on-board electrical networks of vehicles with visual analytics and simulation tools

by

Edwin Xavier Domínguez Gavilanes

PhD Program in Energy and Process Control
Electrical Energy Conversion and Power Systems Research Line

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Dissertation submitted in fulfillment of the requirements for the degree of Doctor of Philosophy in the Energy and Process Control PhD program at the University of Oviedo

Supervisor: PhD. Prof. Pablo Arboleya Arboleya.
Co-Supervisor: PhD. Prof. Islam El-Sayed.

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Departamento de Ingeniería Eléctrica, Electrónica, de
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Tesis Doctoral

Análisis de redes eléctricas de vehículos con herramientas de analítica visual y simulación

Edwin Xavier Domínguez Gavilanes

Tesis presentada en cumplimiento de los requisitos para la
obtención del grado de Doctor en el programa de Doctorado en
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Supervisor: PhD. Prof. Pablo Arboleya Arboleya.
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To the Source that nurtures all that Is . . .

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grown sons and daughters make us want to give back to life all the grace we have received. To my brothers, Darío, Diego and Daniel; I'm proud to see the men you have become. To my beautiful sisters, Anahí and Valentina; you represent the kindness and freshness in our family. Endless thanks to my grandparents, Plutarco, Esther, Lucila and Maximiliano; for being the solid nurturing roots of our tree. To Luis and Carmen, for your appreciation, support and for making me feel as one of your sons.

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Resumen (Spanish)

La complejidad de los Sistemas de Distribución Eléctrica de Vehículos (VEDS) ha aumentado significativamente en los últimos años debido al uso de nuevos dispositivos y sensores electrónicos, funcionalidades de seguridad avanzadas, mayores necesidades de los usuarios, demandas de eficiencia superiores y la electrificación de las funciones mecánicas tradicionales, incluida la inserción de sistemas de tracción eléctricos. Por otro lado, para garantizar la fiabilidad, los cables de los automóviles suelen estar sobredimensionados para evitar incrementos de temperatura, de modo que se mantenga la integridad del aislamiento y se garantice una resistencia mecánica aceptable para soportar el proceso de fabricación. Además, los VEDS en sí mismos son sistemas intrincados ya que en un solo vehículo, normalmente abarcan miles de cables y uniones eléctricas, cientos de consumidores de energía y decenas de Unidades de Control Electrónico (ECU) y elementos de protección que están todos interconectados con configuraciones intrincadas de ruta de cableado.

Para superar estas demandas, el uso de plataformas de software en la etapa de diseño para visualizar, simular y analizar adecuadamente los VEDS es crucial. A este respecto, existe una variedad de entornos informáticos pensados para la mayoría de otros sistemas vehiculares modernos como chasis, aire acondicionado, motor, tren de tracción y propulsión eléctrica. El uso de herramientas de simulación en la etapa de diseño mejora la productividad y reduce los costos de creación de prototipos en estos sistemas. Sin embargo, este no es el caso de VEDS, donde en la mayoría de casos se emplean prototipos reales y registro manual de datos en las primeras etapas de diseño, lo que ralentiza el tiempo de comercialización del automóvil. De hecho, las pocas herramientas de software comerciales de la industria centradas en VEDS están destinadas principalmente al diseño de diagramas eléctricos y para intercambiar información de VEDS desde un punto de vista de fabricación.

Además, las pocas plataformas que últimamente han afirmado ser capaces de realizar simulaciones de flujo de potencia, no proporcionan información específica sobre su modelado y métodos numéricos. De ahí que el desarrollo y reporte de la implementación de software a medida para este fin, como el que se presenta en este documento, representa un aporte significativo en este ámbito de investigación.

Con el fin de superar los desafíos antes mencionados, dar soporte a las tareas de diseño y disminuir la necesidad de prototipos físicos, esta tesis presenta una metodología para implementar una herramienta web orientada a la industria y destinada a la visualización y simulación de VEDS. En este sentido, se destaca la relevancia de las estrategias de Analítica Visual (VA) para amplificar la cognición y la comprensión del usuario de estas redes al utilizar software informático. Las tendencias de investigación y las perspectivas futuras relacionadas con VEDS también se identifican y discuten para obtener suficiente contexto y enfrentar los desafíos de estos sistemas automotrices. La metodología expuesta favorece la creación y mantenimiento rápido de software basándose en seis pilares clave: preprocesamiento de datos a medida, apropiada simulación de flujo de potencia, desarrollo de software ágil, uso exclusivo de herramientas de código abierto, marco de software basado en web e incorporación de diferentes técnicas basadas en VA. Entre estas últimas estrategias, se incluye la generación automática de esquemas eléctricos amplios y detallados para favorecer la interacción y la comprensión intuitiva de la red. La practicidad y versatilidad de la arquitectura propuesta hace que la plataforma exhibida sea fácilmente escalable a otros entornos de ingeniería basados en la web que requieren simulación por computadora. Además, las funcionalidades descritas se ejemplifican y validan considerando como casos de estudio los mazos eléctricos principales de vehículos comerciales. Se exponen paso a paso flujos de trabajo de simulación completos para proporcionar información detallada sobre la implementación de este tipo de herramienta informática.

Abstract

The complexity in Vehicle Electrical Distribution Systems (VEDS) has significantly increased in the last years due to the use of new electronic devices and sensors, advanced safety functionalities, higher user needs, superior efficiency demands and the continuous electrification of traditional mechanical functions including the insertion of electrically-powered traction systems. Moreover, to ensure reliability, wires in automobiles are often oversized to avoid temperature increase so that insulation integrity is maintained, and also to warrant an acceptable mechanical resistance to withstand the manufacturing process. In addition, VEDS by themselves are intricate systems as in a single vehicle, they normally encompass thousands of wires and electrical joints, hundreds of power consumers and tens of Electronic Control Units (ECUs) and protection elements that are all interconnected with intricate wiring path configurations.

To rise above these augmented demands, the use of software platforms at the design stage to suitably visualize, simulate and analyze in-car VEDS is crucial. In this respect, a variety of computer environments exist for the majority of other systems in modern vehicles like chassis, air conditioning, engine, power train or electrical drive. The use of simulation tools at the design stage enhances productivity and reduces prototyping costs in these systems. However, this is not the case of VEDS in automobiles where in most cases real prototyping and manual data registry exist at early design stages which slows down time-to-market. Indeed, the few commercial software tools in the industry focused on VEDS are mostly intended to design electrical layouts and exchange VEDS information from a manufacturing point of view. In addition, the few platforms that lately have claimed to perform power flow simulations, do not provide specific information about their modelling and numerical methods. Hence, the development and reporting of tailored software

for this aim, as the one presented in this document, represents a significant contribution in this research ambit.

In order to address the aforesaid challenges, support the design duties and diminish the need for physical prototyping resources, this thesis reports a methodology to deploy an industry-oriented web-based computer environment intended for the visualization and simulation of VEDS. In this respect, the relevance of Visual Analytics (VA) strategies is highlighted to amplify user cognition and understanding of these networks when using computer software. Ongoing research trends and future perspectives related to VEDS are also identified and discussed to gain sufficient context and meet the challenges of these automotive systems. The exhibited methodology favors rapid software prototyping and maintenance and is based in six key pillars: tailored data pre-processing, convenient power flow simulation, agile software development, sole use of open-source tools, web-based software framework and incorporation of different VA-based techniques. Among the latter strategies, the automatic generation of broad and detailed-level electrical layouts is included to favor interaction and an intuitive comprehension of the network. The practicality and versatility of the proposed architecture makes the exhibited platform readily scalable to other engineering web-based environments that require computer simulation. Moreover, the described functionalities are exemplified and validated considering as case studies the main wire harnesses from commercial vehicles. Full simulation workflows are exposed in a step-by-step manner to provide further insights about the deployment of this type of computer platform.

Acronyms

AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
ANN	Artificial Neural Networks.
BDA	Big Data Analytics
BFS	Backward/Forward Sweep
BMS	Battery Management System
BOM	Bill Of Materials
CAD	Computer-Aided Design
CSV	Comma-Separated Values
CI	Current Injection
DA	Data Analytics
DER	Distributed Energy Resource
DM	Data Mining
DSO	Distribution System Operator
DT	Decision Trees
EV	Electric Vehicle
EPIoT	Electric Power Internet of Things
GIS	Geographic Information System
HEV	Hybrid Electric Vehicle
HiL	Hardware in the Loop
ICEV	Internal Combustion Engine Vehicle
IoV	Internet of Vehicles
KBL	Kabel Baum Liste (Cable Tree List)

MDS	Multi-Dimensional Scaling
MHEV	Mild Hybrid Electric Vehicle
MN – BFS	Meshed Network- Backward/Forward Sweep
ML	Machine Learning
OEM	Original Equipment Manufacturer
PCA	Principal Components Analysis
PCP	Parallel Coordinate Plots
PHEV	Plug-in Hybrid Electric Vehicle
PMU	Phasor Measurement Unit
SCADA	Supervisory Control And Data Acquisition
SOC	State Of Charge
SOH	State Of Health
tSNE	t-Distributed Stochastic Neighbor Embedding
TSO	Transmission System Operator
URL	Uniform Resource Locator (Web address)
VEDS	Vehicle Electrical Distribution Systems
WL	Wiring List
WP	Wiring Plans
WS	Wiring Schematics
XML	eXtensible Markup Language

Contents

”Starting a business and building a product are not for the faint of heart. You have to learn to not let little disappointments get you down and to stay focused on the big picture.”

Gillian Tans - Dutch businesswoman, 2019

Chapter 1

Introduction

1.1 Background and motivation

The complexity in Vehicle Electrical Distribution Systems (VEDS) has significantly increased in the last years due to the use of new electronic devices and sensors, advanced safety functionalities, higher user needs, superior efficiency demands and the continuous electrification of traditional mechanical functions including the insertion of electrically-powered traction systems. Moreover, to ensure reliability, wires in automobiles are usually oversized to avoid temperature increase so that insulation integrity is maintained, and also to warrant an acceptable mechanical resistance to withstand the manufacturing process [1].

For these reasons, more and bigger power supplies, Electronic Control Units (ECUs) and wires are required. This raise in system intricacy and weight provokes more time spending and energy in the manufacturing process as well as efficiency reduction in daily fuel or battery consumption [2]. On the other hand, the amount of information that planning engineers must handle is huge as today’s vehicles may contain hundreds of power consumers, up to ten thousand possible wiring combinations and more than a thousand wires having a total extension close to 3 km and a weight above 50 kg [3, 4]. Consequently, these networks (See Fig. 1.1) demand an enormous amount of protections, wire harnesses, ECUs, splices and joints to properly transmit signals or power supply to the different components. Every wire harness, hereafter in this document only referred as harness for simplicity, is basically an assembly of bundled cables protected by tapes, fittings and plastic coatings capable to maintain safe electrical operation of the network for the demanding conditions that may exist in the surroundings. Independently of the type of vehicle (e.g., Internal Combustion Engine (ICE) propelled, hybrid, electric or other), on-board VEDS are deployed in a similar manner. This is interconnecting different harnesses intended to supply energy to the different consumers within a vehicle, except by those related with electrified traction (e.g., inverter), which in turn are fed by a separate higher-voltage network having its own battery. Therefore, the approach proposed in this thesis to analyze in-car electrical networks can be applied to all kind of vehicle. Owing to assembling requirements, the entire VEDS are typically formed by a primary harness which delivers, through couplings, power supply as well as communication and control signals to different secondary harnesses such as those related with the bumpers, doors, seats or engine.

Despite the aforementioned requirements, these electrical networks are not only intended to be flexible and robust, but also they are expected to be aligned to fulfill efficiency standards [5, 6], design challenges [7] and emerging environmental policies on greenhouse gases reduction [8]. To satisfy these augmented demands, the use of software platforms at the design stage to suitably analyze, visualize and model the great amount of electrical information is crucial. In this respect, specialized visualization and simulation tools exist for the majority of other systems in modern vehicles like chassis, air conditioning, engine, power train or electrical drive. The use of simulation tools at the design stage enhances productivity and reduces prototyping costs in these systems. However, this is not the case of VEDS in automobiles, where in most cases real prototyping exists at early stages and thus increasing time-to-market. This is

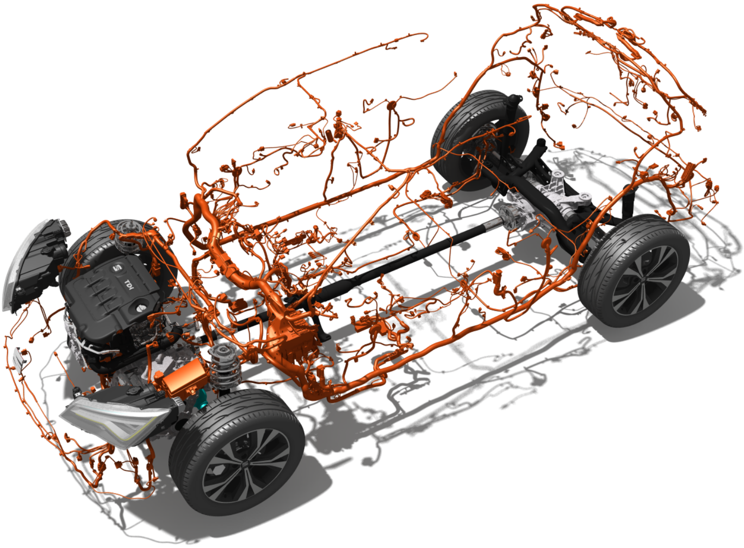


Figure 1.1: Wire harnesses in a vehicle

a consequence of the massive amount of wiring harnesses groups, paths and configurations as well as large complexity on integrating disperse and vast data from automotive manufacturers and their components suppliers. Besides, the pursue of Original Equipment Manufacturers (OEMs) to add augmented comfort and customized options to consumers has provoked a significant increase in assembly logistics due to the great amount of possible harnesses architectures [9].

Considering all the aforesaid, the design and prototyping of vehicular electrical networks represent a highly defiant stage in a car model development process. To face these challenges and permit vehicle design engineers an early detection of unsuitable configurations, such as those leading to undesired voltage drops, excessive temperatures or mistaken components sizing, the development of software platforms that simultaneously include Visual Analytics (VA) precepts and computer simulation is compelling.

In fact, VA has been successfully employed to gain knowledge, amplify cognition and get insights from large and complex datasets in electrical systems as discussed in next chapter. However, all the related contributions focused only in power systems, but not on extensive, weakly-meshed and intricate low-voltage DC distribution networks as in the case of vehicles. Despite this increasing interest on VA in the last years in the academic environment, VA is not consistently adopted when developing industrial applications as observed almost a decade ago [10]. Unfortunately, as the literature reports, this situation still persists to these days in some engineering fields as in the case at hand. Moreover, as Chapter 4 will elaborate, the existing commercial software devoted to VEDS is mostly focused in design and data manufacturing exchange and is not intended to incorporate VA strategies. In addition, the few computer tools that lately have claimed to perform power flow simulations in VEDS, do not provide specific information about their modelling approaches. For this reason, the development and reporting of a tailored computational platform for this aim, as the one presented in this document, represents a significant contribution in this research ambit.

1.2 Thesis objectives and contributions

To cope the challenges from the previous context, the objectives and contributions derived from this thesis are summarized below:

- Provide a grounding understanding about the benefits and challenges related to the incorporation of visual and data analytics for the particular concern of electrical networks and the automotive industry. A systematic literature review exhibited a significant utilization of Visual Analytics (VA) in electrical systems, however, all the literature works were in the context of power systems. Additionally, a survey on the use of VA in the automotive industry revealed the lack of software platforms permitting a suitable visualization and simulation of Vehicle Electrical Distribution Systems (VEDS) considering their inherent factory characteristics and components. The aforementioned research was of high relevance to infer the challenges and benefits of VA in those broader related domains to then extrapolate those approaches and good practices to the particular needs of VEDS. This contribution led to a conference article presented at the 2019 IEEE Vehicular Power and Propulsion Conference (VPPC). Similarly, to anticipate forthcoming insights and challenges related to the inclusion of Data Analytics (DA) in VEDS when sufficient electrical observability conditions exist, a review of the ongoing DA unfolding was conducted within the domains of other vehicle applications and also for power electrical networks. This has led to an article submitted to the Electric Power Systems Research (EPSR) Journal which is currently under review.

- Identify and study the impact of research trends and future perspectives related to VEDS. The automotive sector is experiencing deep transformations that will substantially change the way in which on-boar vehicle networks and their related systems are developed. Beyond the inclusion of VA and custom-made versatile power flow simulation methods in VEDS, to provide researchers plentiful insights about other ongoing technological trends that will play a significant role in the deployment of forthcoming electrical systems in automobiles, different topics were identified and discussed. Among these we have data analytics, advanced thermal analysis, new electric/electronic architectures, electronic-fuses, mild hybrid power trains, hardware in the loop and vehicle high voltage networks and power converters. This analysis has been exposed in sections of a journal paper published in the IET Electrical Systems in Transportation Journal and in an article in the IEEE Electrification Magazine.

- Develop of a methodology to deploy an industry-oriented web-based computer platform intended for the visualization and simulation of VEDS. Contrary to other in-car engineering systems where the use of simulation tools is highly extended prior to a prototyping stage, so far the simulation of VEDS is not still a common practice as manufacturers so far have mainly relied on laborious empirical procedures for technical validation. Hence, to provide flexibility in VEDS design and procure faster endorsement, this thesis has exhibited specific guidelines and experiences to develop a web-based software platform that encompasses custom-made electrical simulation of VEDS with Visual Analytics precepts. This approach facilitated users an increased understanding of the network under different scenarios as the outcomes of the electrical data modelling were leveraged by means of aesthetic yet interactive visual representations of the system. This kind of computer tool and approach represent a novelty contribution for the automotive sector. Only open-source software development tools have been employed. Moreover, due to its scalability, the proposed software scheme can be readily extended to other industry web-based simulation environments. The work done in these aspects has led to a publication in the Energies Journal.

- Validate the functionality of the deployed software tool considering real wire harnesses from commercial vehicles. The industrial doctorate project related to this thesis was beyond academic research efforts as it was oriented to provide an applicable computer platform that supports automotive engineers in the design and validation duties of VEDS. Hence, the deployed software tool was endorsed with the analysis of real electrical harnesses from commercial vehicles from the Spanish manufacturer SEAT S.A. This validation of the software tool, along with full simulation workflows to provide meaningful insights on this matter, were also reported in the Energies Journal publication. Being this project the first of its kind, it paves the way for further research and development of simulation platforms for on-boar electrical networks of vehicles.

1.3 Thesis publications

1.3.1 Journal papers

- Dominguez, X.; Mantilla-Pérez, P.; Gimenez, N.; El-Sayed, I.; Díaz Millán, M.A.; Arboleya, P. Web-Based Simulation Environment for Vehicular Electrical Networks. Energies 2021, 14, 6087, `https://doi.org/10.3390/en14196087`

- Dominguez, X., Mantilla-Perez, P., Gimenez, N., El-Sayed, I., Díaz Millán, M.A. and Arboleya, P. (2020), Development of a Computer Platform for Visualisation and Simulation of Vehicular Distribution Systems. IET Electr. Syst. Transp., 10: 341-350, `https://doi.org/10.1049/iet-est.2020.0047`

- X. Dominguez, P. Mantilla-Perez and P. Arboleya, ”Toward Smart Vehicular DC Networks in the Automotive Industry: Process, computational tools, and trends in the design and simulation of vehicle electrical distribution systems,” in IEEE Electrification Magazine, vol. 8, no. 1, pp. 61-68, March 2020, `https://doi.org/10.1109/MELE.2019.2962890`.

- P. Mantilla-Pérez, X. Domínguez, N. Gimenez, B. Mohamed, M. A. D. Millán and P. Arboleya, ”Vehicular Electrical Distribution System Simulation Employing a Current-Injection Algorithm,” in IEEE Transactions on Transportation Electrification, vol. 7, no. 4, pp. 2453-2463, Dec. 2021, `https://doi.org/10.1109/TTE.2021.3068569`

- P. Mantilla-Pérez, J. Pérez-Rúa, M. A. D. Millán, X. Domínguez and P. Arboleya, ”Power Flow Simulation in the Product Development Process of Modern Vehicular DC Distribution Systems,” in IEEE Transactions on Vehicular Technology, vol. 69, no. 5, pp. 5025-5040, May 2020, `https://doi.org/10.1109/TVT.2020.2983288`

- Dominguez, X., Prado, A., Tersija, V. and P. Arboleya, ”Evolution of Knowledge Mining from Data in Power Systems: the Big Data Analytics Breakthrough,” Electric Power Systems Research Journal, (Under review)

1.3.2 Conference paper

- X. Dominguez, P. Arboleya, P. Mantilla-Perez, I. El-Sayed, N. Gimenez and M. A. D. Millan, ”Visual Analytics-Based Computational Tool for Electrical Distribution Systems of Vehicles,” 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), 2019, pp. 1-5, `https://doi.org/10.1109/VPPC46532.2019.8952440`.

1.4 Thesis outline

This thesis is organized is six chapters as follows:

- **Chapter 1** has introduced the research scope, exposing the objectives, contributions and derived publications.

- **Chapter 2** presents a comprehensive background about Visual Analytics (VA) and deepens on its literature review for the case of vehicle applications and electrical networks. For those ambits, Data Analytics employment is also revised to infer potential challenges that may eventually arise in VEDS in the mid-term.

- **Chapter 3** describes the characteristics of Vehicle Electrical Distribution Systems (VEDS) and their context within the product development process of the automotive industry. The required VEDS factory data pre-processing is commented to then elaborate on the techniques to perform power flow analysis of these in-car networks. Lastly, research trends that will play a significant role in future VEDS are exhibited.

- **Chapter 4** starts exposing the role of computer simulation in the automotive industry, particularizing for the case of VEDS. Then, it is explained the key foundations that have been considered to implement the presented computational tool for VEDS visualization and simulation.

- **Chapter 5** presents full user workflows to perform the visualization and simulation of VEDS, considering as case studies real main-harnesses from commercial vehicles. The benefits of the deployed software environment are exemplified and evidenced along this process.

- **Chapter 5** summarizes the conclusions and results achieved during the development of this thesis. Future work is also commented.

- The **Appendix** contains the journal and conference publications derived from this research.

> ”The ability to take data—to be able to understand it, to process it, to extract value from it, to visualize it, to communicate it—that’s going to be a hugely important skill in the next decades.”
>
> Hal Varian - Google Chief Economist, 2016

Chapter 2

Visual Analytics Background

2.1 Introduction

This chapter firstly presents an introduction about Visual Analytics (VA) to provide the reader a comprehensive understanding of this framework. Its concepts, process, applications and categorization are discussed. Since there are no prior attempts in the literature to use VA for the particular case of Vehicle Electrical Distribution Systems (VEDS), the state of the art review is addressed considering the employment of VA in applications related to vehicle technology and electrical networks. By doing so, those approaches and methods have been inferred and later scaled to cope the punctual needs of VEDS as future chapters will exhibit. Also for those ambits, a review of data analytics deployment is performed to provide sufficient insights about the context and challenges that future data analysis in VEDS will encounter, given the data explosion phenomenon we are witnessing automotive applications.

2.2 Visual Analytics (VA)

We are living in a data-abundant era where the management and analysis of data is becoming increasingly difficult due to its rising volumes, constant generation and high variety of sources and formats. In this context, Visual Data Analytics, hereafter just referred as Visual Analytics (VA), emerged enclosing effective approaches to better understand and evaluate large datasets in order to discover insights in data that may conduct to advantageous innovations in businesses and organizations.

Despite the fact that highly sophisticated data analysis tools have been developed, a reliable fully-automated search, filtering and analysis can only be ensured in well-defined deeply-understood problems [11]. However, this automated methods often fail when a dynamic adaptation of the algorithms is needed and they also miscarry when trying to communicate the outcomes and the nature of the analytical processes they include [12]. The visualisation of those processes themselves will permit the examining of their dynamics to then favor greater user cognition which in turn translates into better decision making. Moreover, even the same problems can be more efficiently tackled with a combination of visual and automated methods that working together can achieve more reliable and precise results [13]. With this understanding, we could say that VA represents the commonplace where humans and computers collaborate merging their best strengths (see Fig. 2.1). This approach is commonly referred as human in-the-loop [14]. Indeed, VA aims to ease the analytical reasoning course by means of interactive computing tools that boost human capabilities to gain awareness, discern and recognize entangled dynamics relying on data.

From a historical perspective, the demarcation of VA was not straightforward given the broad spectrum of disciplines and tools it encompasses. The early definitions denoted the purpose of VA as “facilitating analytical reasoning by interactive visual interfaces” [12] and highlighted the relevance of interaction [15]. As the foregoing delimitation was vague, a more explicit demarcation was proposed settling VA as the merge of “automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and

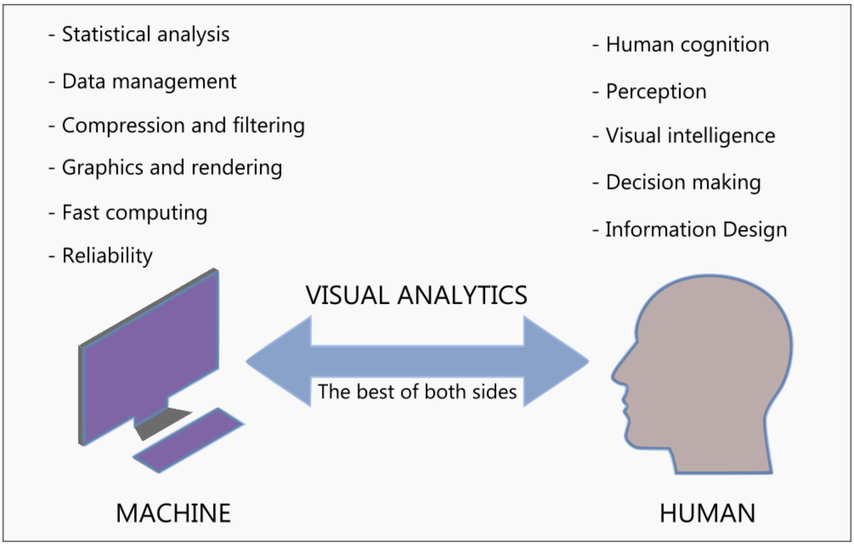


Figure 2.1: Visual analytics pursue to combine the strengths of humans and machines. Adapted from [13].

complex datasets" [16]. Nevertheless, in the last years VA has been conceived as a highly multidisciplinary field that merges different research areas such as visualisation, computer simulation, data analysis, data mining, human-computer interaction, data processing, geo-spatial analytics, statistics and others [17].

2.2.1 The VA process

As exhibited in Fig. 2.2, the usual VA workflow can be seen as a 6-steps process:

1. Pre-processing: Raw heterogeneous datasets must be converted to well-organized data formats by means of cleaning, filtering, transformation, integration and/or computer simulation.
2. Analysis: Data algorithms are applied to procure knowledge acquisition from data. Nonetheless, depending on the volume and complexity of data

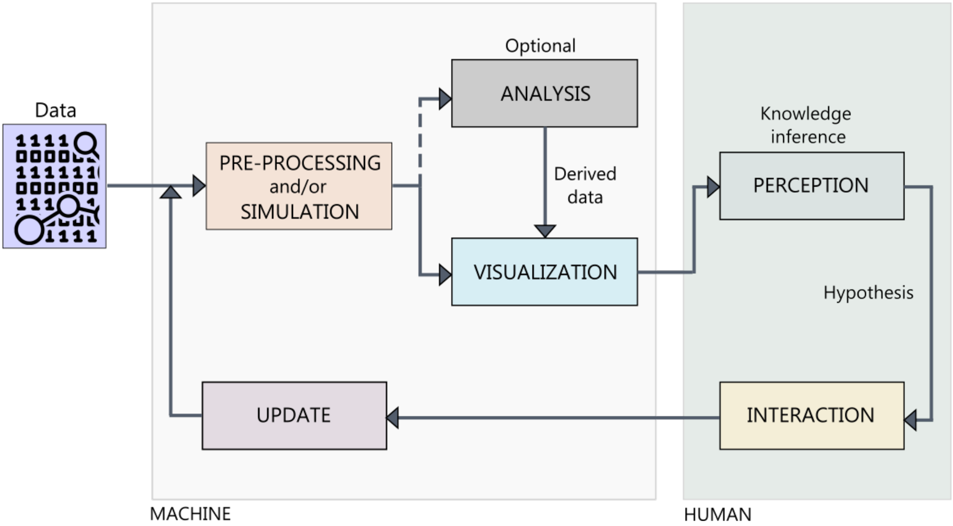


Figure 2.2: Visual analytics sense-making process. Adapted from [18]

as well as the nature of the problem, this stage can be included or not in the overall process.

3. Visualization: Data is mapped with specific visual forms (geometry, shape) and attributes (color, size, position).

4. Perception: Human cognition and reasoning takes place so that representative knowledge, awareness and hypothesis are generated.

5. Interaction: Here we can mention two levels of interaction. The base-level interaction includes functionalities such navigation, panning, zooming, dragging, parameters modification and others. These favor the user to reconstruct the information so that new understandings are integrated into the process. The high-level interaction is intended to corroborate user hypothesis. It consists on allowing the user to explore, under different scenarios, the approximate behavior and responses of a mathematical model that represents a real-world system. This can be achieved in synergy with computer simulation.

6. Update: The process enters into a loop where the user can modify the

visualization to further explore the data to then draw faster and better insights and conclusions.

2.2.2 VA applications

A great variety of disciplines have benefited from VA, such as imaging science, telecommunications, cybernetics, astronomy, physics, environmental sciences, medical informatics, education, biology, engineering among others. To exemplify, Fig. 2.3 exposes some VA applications from different fields.

Considering the dimensionality of visualization and the type of interaction [18], VA applications can be categorized as follows:

1. Visualization-based classification:

   (1a) 2D-to-2D: Here users attain insights from data by means of analytical reasoning on 2D data that is naturally mapped in 2D coordinate system visualizations (see Fig. 2.4a). It is worth to recall that in this category, 2D not only refers to XY space positioning but to any kind of data having two attributes, for instance a specific epidemiology parameter versus time as in [19].

   (1b) Multi-dimensional-reduction-2D: In multi-attribute datasets, algorithmic methods are employed to reduce the dimensionality of data to two dimensions for later visualization (see Fig. 2.4b). Among the most common multi-dimensional reduction algorithms, we have Principal Components Analysis (PCA), t-Distributed Stochastic Neighbor Embedding (tSNE) or Multi-Dimensional Scaling (MDS).

   (1c) Multi-dimensional-to-2D: In this case, multi-dimensional data is transformed and mapped in 2D visualizations, to do so however, the dimension of data is not reduced with algorithmic approaches as in the previous case. Here, data is encoded for complementary representations. For instance, using the Parallel Coordinate Plots (PCP) technique, data samples in an orthogonal coordinate system are projected onto parallel axes [20]. This transforms these points to polygonal lines and permits different data dimensions to be displayed simultaneously (see Fig. 2.4c). Another extended approach in this category is the Coordinated Multiple Views (CMV) tactic where two or more distinct views support users to better understand their data by means of different representations [21]. This is the case of Fig. 2.4b.

- (1d) Multi-dimensional-to-3D: Multi-dimensional data is now transformed and mapped in 3D visualizations to improve the illustration of data (See Fig. 2.4d).

2. Interactive-based classification:
   - (2a) Exploratory-oriented: This applies when user interactions (zoom, encoding, filtering, sorting, simulation, etc) are designed to observe how the data reacts to a given parameter manipulation or request.
   - (2b) Expressive-oriented: In this category, user interactions are able to change the algorithms for rendering the visualization or the underlying models performing data analysis.

It should be noted that both types of interactions mentioned above can be simultaneously present in a given application.

Considering that so far general concepts and applications have been presented, it is appropriate to make a review on the particular use of VA in VEDS. However, no former works exist in the literature using VA in this specific research line. Bearing this in mind, it is now conducted a review on the use of VA in vehicular technology and also for the case of electrical networks. This will permit to later extrapolate to VEDS the approaches and good practices from these areas that support the scope of this thesis.

2.2.3 VA in vehicle applications

In automotive vehicle applications, a few attempts to use VA in varying depth exist. So far they have been mostly engaged in the domain of computed-aided-design [31], artificial vision [32], vehicle collision [33,34], engine multibody dynamics [35], virtual reality [36], aerodynamics [37], sensor data [38] and electric charging analysis [39]. Additionally to the previous references, it is worth to highlight the contributions performed in [10] regarding the systematic deployment of visualisation systems for vehicle communication networks in a large automotive company. From the previous work, some tools were derived to study communication processes correlations in sequence diagrams [40], connect multimedia components from large datasets [41] and detect errors in masses of trace data [42] among others.

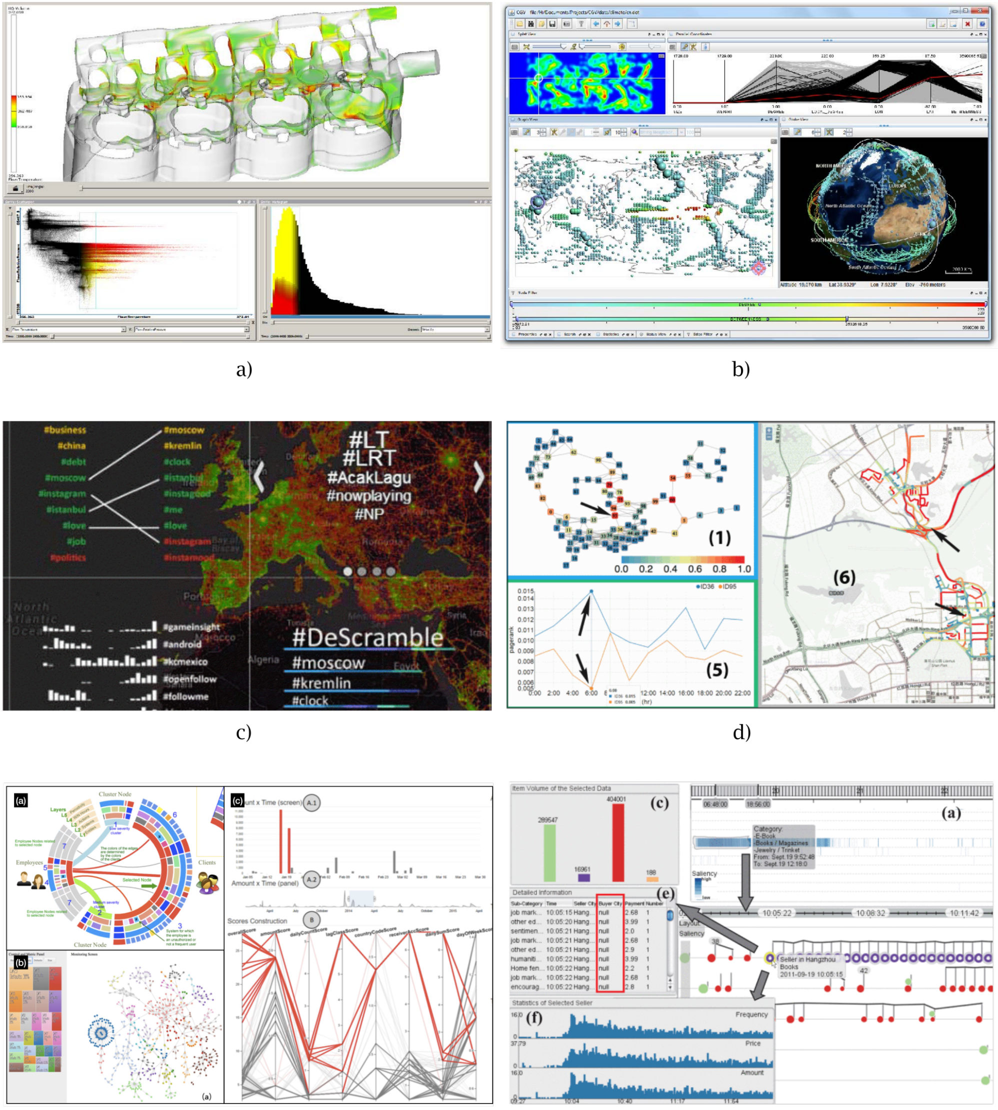
As Section 4 will discuss in more depth, a few commercial software tools are commonly employed in the automotive industry for VEDS visualization and design purposes. However, they do not permit the evaluation of electrical data by means of tailored VA interfaces with high-level interaction such as electrical simulation, which is in turn an aim of this thesis. In this respect, they do not permit a realistic power flow simulation of the on-board network based on available factory information. This exclusion of the specific features of vehicle harnesses and its wires, fuses, ECUs and loads is a significant limitation of those computer platforms.

2.2.4 VA in electrical networks

The first significant contributions of VA in electrical engineering came about the early 2000's. They were oriented to power systems and focused on showing data in aesthetic representations that included features such as color countouring [43], data aggregation, animations and 3d visualizations [44]. The usability of these representations were also evaluated [45]. Later on, the spotlight was on taking advantage of those representations in simple contingency [46] and power market scenarios [47]. Then, some years passed without relevant contributions taking place. A decade ago, the literature commenced again to enrich with efforts concerned on including electrical meaningfulness [48] to develop "weighted" graphs to highlight the physics of power systems and not only structural or geographic information [49, 50]. For these kind of applications, where the geographic or coordinate position of buses is not compulsory for visualizing and understanding the network, the use of force directed graphs [51] to avoid overlapping of lines or the adoption of multi-dimensional scaling with "electrical distances" [52] to infer electrical connectivity, exhibited as valid alternatives.

It is also worth mentioning the attempt in [53] to propose metrics to assess the quality of network layouts for these purposes. As single-line diagrams are still broadly used by field and design engineers, some efforts have been made to develop algorithms to arbitrarily layout those diagrams. A ruled-based approach suitable for radial and small-size meshed distribution networks was suggested [54]. The performance of this last proposal was improved in [55] by means of a branch and bound technique. A particle swarm optimization method to include the depiction of substations and transmission lines was also proposed [56]. To encompass strongly meshed networks, an algorithm based on physical laws and enhanced by geospatial data was then exposed [57]. Efforts to include substations' geographic and space constraints [58] as well as rules to construct diagrams for SCADA screens [59] have also been presented. Regardless of the diversity in the aforesaid research, it is important to note that all the reports focused VA only in the domain of power systems, but not on scenarios of intricate low-voltage DC distribution networks like in modern vehicles.

Bearing in mind that VA techniques favor the user to obtain insights and adequate understanding of the electrical network under study, the adaptation of well-proven visualization precepts from power systems to the peculiarities of VEDS will be highly relevant. In this respect, color contouring [43, 44] (see Fig. 2.5a) would enhance visual VEDS diagnosis as color serves as an effective highlighting feature allowing a rapid localization of problematic zones or elements in large and complex networks [60]. Under this approach, nodes voltages and branch currents are usually employed to build the corresponding background color grid. A similar tactic to this strategy is color coding [61] where transmission lines or buses themselves are represented with discrete colors according to their voltage or current levels (see Fig. 2.5b). On the other hand, the incorporation of time plots will permit to observe the evolution of varying data (voltage, current, power) over time once temporal simulation is included in the software (see Fig. 2.5c). Additionally, as in vehicular-DC networks there is a vast amount of paths, wires and components; the automatic generation of one-line diagrams [54–56, 59] will be beneficial. If needed, the inclusion of navigation panes (see Fig. 2.5d) and animations representing the power flow direction can be beneficial. Nevertheless, all these aforesaid visualization techniques should be handled with care and given on-demand. Otherwise, the user could be overwhelmed with the amount of information visually given [60].



a)

b)

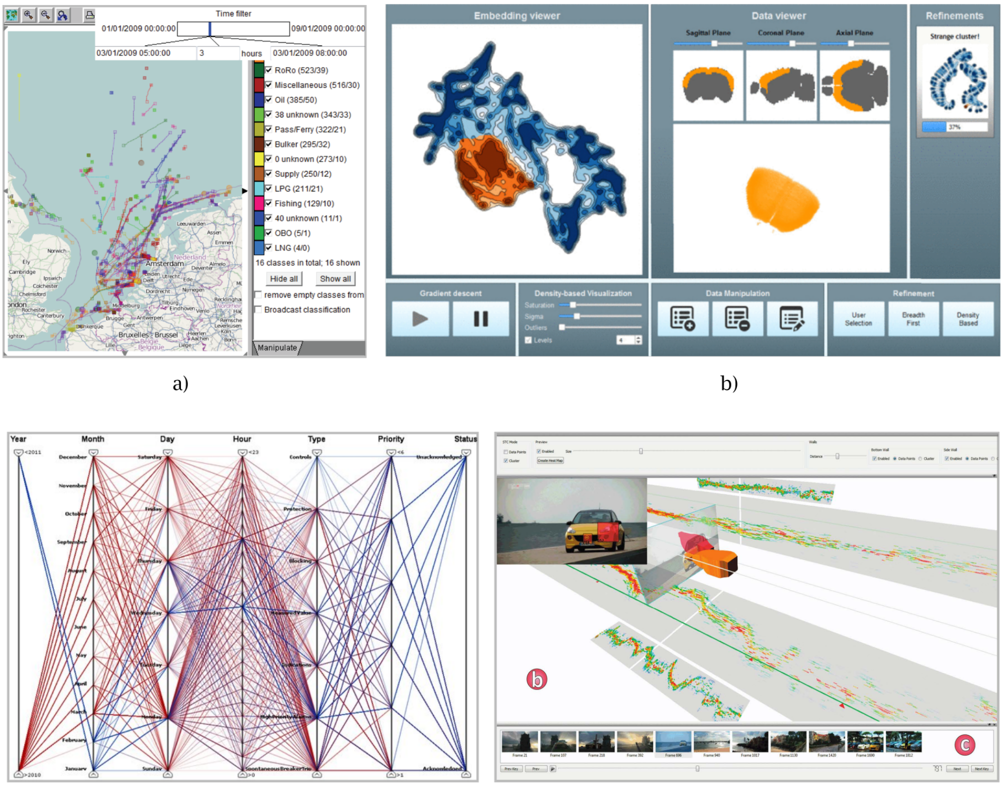
c)

d)

e)

f)

Figure 2.3: Examples of Visual Analytics applications. a) Interactive visual analysis of a cooling jacket simulation [17], b) CVG interactive graph visualization system to support the simulation of climate models [22], c) VA application for Twitter big data exploratory analysis [23], d) Interface for analyzing urban network centralities by means of Taxi Trajectory Data [24], e) Visualization of anomalous user interaction behaviors [25], f) VA approach to study electronic-transactions time-series [26]



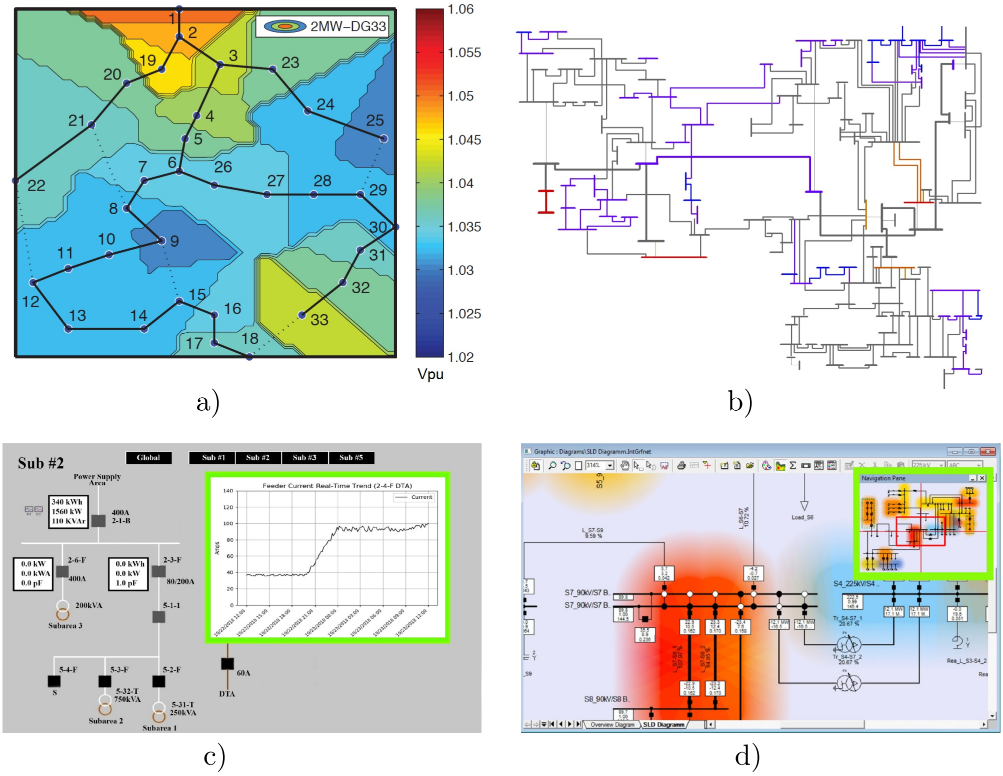
a)

b)

c)

d)

Figure 2.4: Visualization-based VA classification examples. a) Interactive map with trajectories of ships [27], b) A high-dimensional data viewer using tSNE [28]. c) PCP for interactive alarm filtering [29], d) Space-time visual examination of eye-tracking data for automobile animated analysis [30]



a) b) c) d)

Figure 2.5: a) Color contouring, taken from [62]. b) Discrete buses coloring (Blue≤0.96 pu and Red≥1.04pu), taken from [61]. c) Time plot, adapted from [63]. d) Navigation pane, adapted from [63]

2.3 Data Analytics (DA)

As exposed in Section 2.2.1, once data has been pre-processed, data visualization and optionally data analysis take place. While visualization mainly deal with transforming data into suitable interactive visual representations as previously remarked in this section, data analysis refers to the process of analyzing and modifying the data to observe its parts and extract valuable information by means of statistical and logical techniques [64]. Under this perspective, data analysis mainly tries to answer the question: ¿what happened in the light of recorded data?.

However, in the last years it has become increasingly important to use data to also answer the question: ¿what will happen later?. This implies not only to perform a deep review of current facts, but also to cluster, segment, score and predict what scenarios are most likely to occur based on data by means of a systematic computational analysis. This further data treatment has been referred in the last years as data analytics [65]. Moreover, data analytics is usually employed as a wider concept that involves not only analysis but also extraction, knowledge inference, prediction, visualization and management of data and all the required techniques during the process [66]. In addition, latest authors highlight that DA should be seen as a technology oriented term related to the use of techniques and methods aimed to acquire knowledge, find connections, identify trends and extract novel useful patterns from data [67,68]. For all this potential relying on data, businesses and organizations nowadays consider data as the new currency in the modern world [69].

The degree of applicability of data analysis and further data analytics depend on the size and complexity of the data under study. As it will be explained below, the use of data analytics in VEDS is currently not feasible given mainly to the reduced observability of voltages and currents of modern on-board electrical networks. Nonetheless, the review of ongoing data analytics deployment for other vehicle applications and also for the case of electrical power systems will be highly relevant for future research so that the ongoing methodologies from those ambits can be synthesized and later scaled down to the context of VEDS. Moreover, potential coming challenges could also anticipated and mitigated favoring a prompt incorporation of data analytics in VEDS when sufficient monitoring conditions unfold as it is expected to occur in the near future.

2.3.1 DA in vehicle applications

In recent years, the amount of data generated by vehicles has grown substantially. The new generated data mainly corresponds to applications related to autonomous driving, on-board communication systems, traffic monitoring, fleet energy management, comfort driving, road accidents prevention and secure vehicular data transmission [70]. To manage these large amounts of data (around 30 gigabytes/hour per autonomous vehicle [71, 72]) generated mainly by radars, laser scanners, ultrasonic sensors and cameras; some initiatives have proposed the Internet of Vehicles (IoV) framework [73]. This approach procures some benefits such as accidents avoidance, better user experience, fast emergency response and improved traffic control. However, some challenges have also been detected and should be taken into account for the design of future VEDS and the electronics that supports these systems. For instance, higher data processing and connectivity standards will be demanded to ensure acceptable levels of latency, data reliability, network connectivity and bandwidth [74]. Additionally, cyber-security has been remarked as a major concern, from the vehicle level and up to router and central server instances [75]. Finally, human behavior has also been denoted as a challenge as in different scenarios users usually bypass cooperative or driving assistance technologies [76].

On the other hand, to pave the way towards intelligent transportation systems and also favor a prompt integration of electric vehicles in urban distribution networks, the Big Data Analytics (BDA) scheme has also been adopted [77, 78]. It has already assisted different research fields that are witnessing the data explosion phenomenon. BDA merges data science fields such as Big Data, Data Analytics and Artificial Intelligence (AI) (See Fig. 2.6) in order to attain real benefits from massive, distributed, unstructured yet information-rich datasets. By means of BDA, some benefits have been anticipated in urban transportation such as assets maintenance, traffic forecasting and control, and public assets planning [77]. In the realm of electric vehicles incorporation, BDA has been useful in applications related to optimized charging, battery energy management, status tracking and carbon footprint reduction [78, 79].

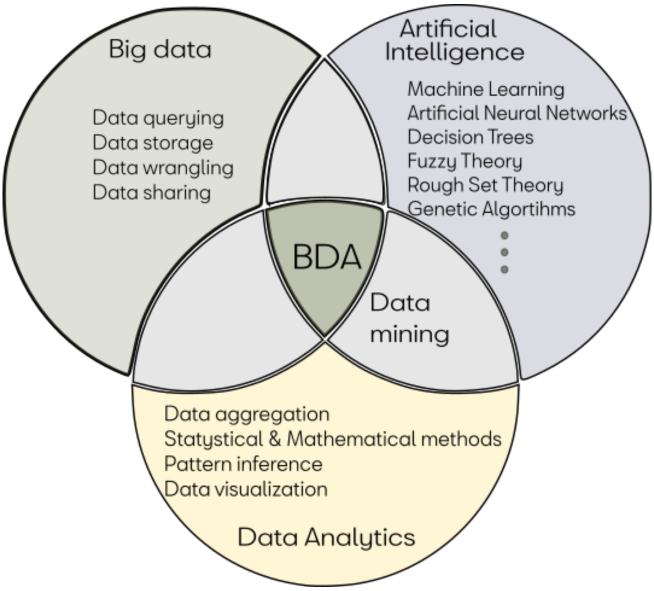


Figure 2.6: Big Data Analytics Framework

Despite of all the previous advancements towards a smart transportation sector, a granular observability of electrical data in VEDS is still a pending task in the automotive industry. Despite the fact that sophisticated Electronic Control Units (ECUs) and sensing devices are already being installed in modern cars to withstand the above-mentioned applications, these are not intended to provide sensing and logging of electrical variables in representative nodes and consumers of VEDS. As a consequence, most of the data analysis contributions at a vehicle-level are related with energy consumption and driver behavior analysis considering primarily speed, distance and voltage/current in the battery (such as in [80]); but lack on having a fine-grained decomposition of the power delivery along the entire on-board electrical network for such testing conditions. Nevertheless, as claimed for some automotive equipment manufacturers, this circumstance is expected to be overcome in future years with new VEDS architectures and the greater insertion of electric traction which requires higher system diagnosis and power management [81, 82].

2.3.2 DA in electrical networks

Since the 1980's, electrical power systems are witnessing an exceptional up-growth in the complexity and volume of its monitored data [83]. Such an increase has been caused by the continuous advancements of the information and communication technologies [84] and further deepened by several factors such as market deregulation, incorporation of renewable energy sources and the extended insertion of SCADAs and WAMSs [84, 85]. To manage the information overload within this context, Data Mining (DM) has been exhibited as a convenient and versatile approach to perform effective data processing, find patterns, meet correlations and make knowledge inference. By virtue of these capabilities, several applications in different areas of the power systems field have arisen within the DM framework. Moreover, in the last years the pursue for Smart Grids [86], advanced metering infrastructure (AMI) [87], application of novel sensor and ICT technology [83], smart cities [88], the Electric Power Internet of Things (EPIoT) [89], electrified transportation [90], energy blockchain [91] among others, have significantly challenged the paradigms of the power industry regarding the knowledge extraction from continuously growing databases.

To cope with the current power systems requirements (e.g. optimal integration of sustainable energy sources, maintaining high levels of the system security, reliability and flexibility, efficient and economical power delivery, robust approaches for the system monitoring, protection and control, integration of different energy vectors) the latest research has migrated from the former perspective of manual-data handling towards an automated data management approach using the BDA paradigm [88].

Given the relevance of extracting representative information from data in power systems, hundreds of activities and incentives, using DM techniques, have been presented since the arrival of the digital era to propose advancements in the whole electricity chain process. Besides, over the last few years, the amount of scientific projects regarding the integration of BDA in power systems can be overwhelming for a reader who is interested in promptly having a solid understanding of the evolutionary context and relevance of knowledge extraction from data in this field. Some review papers have been published related to BDA in power systems. Most of them focus in particular areas, for instance smart grids [92–94], distribution networks [95], smart meters data [96], household energy consumption [97] and electrical utilities [98]. Those works mainly focus their time-span interest only in the last years where BDA has become mainstream. However, none of them provide readers an encompassing understanding of the development of knowledge mining from data in the broad power systems spectrum from a historical perspective, since the early beginnings of the data digitization phenomena in the 1980's up to the ongoing big data explosion scenario. Doing so may facilitate the understanding of the context on which the modern BDA stands in this field.

With this background, this subsection aims to favor the comprehension of the up-growth, applications, lessons learned, current challenges and prospects of knowledge extraction from data in power systems.

2.3.2.1 Beginnings of Data Mining in Electrical Power Systems

As a consequence of the significant computational improvements experienced during the 1980's, electrical facilities and power systems

SCADA experienced a significantly growing digitization [84], deriving into the generation of medium and large-scale data banks. Simultaneously, the new computation capabilities permitted acceptable yet time-consuming offline [99] and real-time [100] simulations. The abundance of monitored and simulated data moved forward the exploration of data-driven Artificial Intelligence (AI) techniques to power systems applications, where the use of classical numerical methods were not able to fully meet the requirements. For instance, in the course of that decade, none of the classical time-domain and direct strategies were capable to properly assess the online transient stability analysis of power systems [101] as a consequence of the intrinsic nonlinear modelling complexity.

In this context in the 1980's, one of the first extended techniques of AI in the power electrical field were the rule-based expert systems [102]. Their algorithms relied on decision trees (DT) [103] based on the "if-then" type rules that were derived from a knowledge inference mechanism fed from the expertise, practices and criteria from specialists, operators and field engineers [104]. Indeed, the use of this tactic in power systems was natural as most operating procedures had a specific logical criteria and were developed following a flowchart scheme having unique responses for a set of given conditions [105]. As a consequence, numerous application proposals and high academic interest were exhibited following this approach [106]. However, expert systems also presented some issues such as difficulty to handle unconsidered scenarios, costly maintenance and laboriousness to construct a reliable knowledge base [107]. Given these limitations and the improved computing possibilities of the early 1990's, the research focused in more AI strategies such as Artificial Neural Networks (ANN) [108], fuzzy set systems [109], rough set theory [110], genetic algorithms [111] and Machine Learning (ML) [112]. From this last field, genetic algorithms were the most popular provided their ease of use and effective adaptive search process [113]. In contrast to DTs that alone were unable to learn from experience and adapt to new scenarios, the inclusion of ANN and ML overcame this limitation. Thus, the extent of AI techniques in power systems was such, that by 1997, more than four hundred related papers were traced [105].

In the second half of the 1990s, deregulation [84] and the integration of renewable energy generation, took place [85,86]. Hence, the size and complexity of electrical infrastructures and databases increased even more, making crucial the refinement of AI approaches to systematize knowledge acquisition. To do so, power systems researchers embraced the emerging multidisciplinary field known as Data Mining (DM) or also referred as Knowledge Discovery from Data. Foundations and techniques from statistics, database management, pattern recognition and AI were gathered by DM [114] in order to "identify valid, novel, potentially useful and ultimately understandable patterns in data" as one of the first most cited definitions stated [115]. In particular, DM was highly useful in power systems to handle their great scale nature (huge datasets and vast amount of state variables), complex statistical analysis (combining deterministic and stochastic events), mixture of discrete and analog information, variable temporal character (from milliseconds to years), effective visualisation requirements, need of rapid decision-making and highly-uncertain data handling [116]. A timeline of the DM unfolding can be seen in Fig. 2.7.

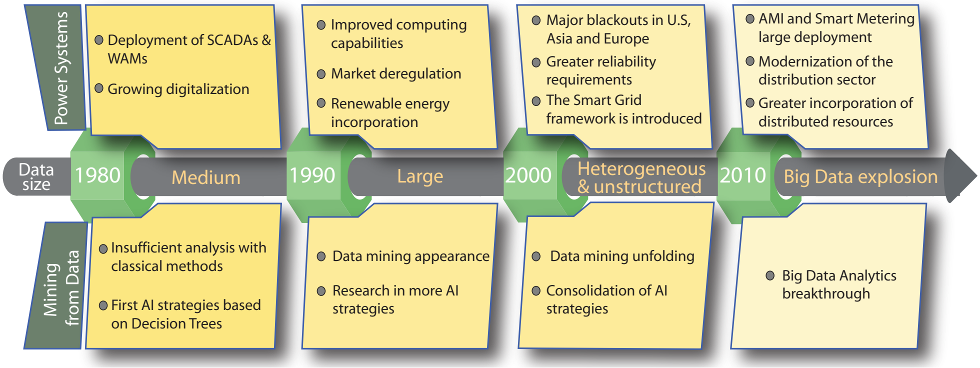


Figure 2.7: A timeline of Data Mining in power systems

2.3.2.2 Data Mining Goals and Applications in Electrical Power Systems

First of all, it is important to highlight that mining in data is not a lineal process but an iterative one. Besides, there is no matching of specific techniques for a given application as the literature reveals. Indeed, even when a method has been chosen, it is common to recurrently adjust the selected strategy or even use other complementary DM tools to infer different prospects of the data and improve the results. With this perspective, DM was conceived as to achieve two major goals: prediction and description [117]. For prediction, the mining tools carry out an induction process on data to develop models suitable for classification or estimation of future values of variables under study. For instance, in the first decade of this century, advanced prediction approaches were highly demanded as a consequence of major blackouts [118] and the smart grid framework introduction [119] which demanded enhanced ancillary services and higher reliability standards. On the other hand, for description motives, techniques characterize the general properties of the datasets to attain an understanding of the system by revealing patterns and relationships [120]. Both perspectives have been employed by the power system community in a large variety of ambits going from dynamic security assessment, passing through expansion planning and arriving to monitoring and visualization issues (See Table 2.1).

It is also worth to recall the multidisciplinary nature and wide scope of DM. For this reason, there is no clear boundary on the literature to decide either if DM was applied or not in a particular scientific article. For this reason, this section mainly refers to representative research in power systems where the authors have explicitly mentioned the intended use of DM by using techniques from AI, statistics and other allied disciplines. In this regard, in the last two decades, the DM process [120] and its different methods have been largely employed in the power systems scope. Nevertheless, ANN with ML purposes has been the preferred approach [121,122] as a consequence of its salient capabilities to learn from training, classify patterns and perform feature extraction [123, 124]. After this strategy, DTs, fuzzy systems, statistical analysis (SA) and rough set theory have also been consistently employed in that order [122, 125]. To provide the reader an insightful on the relevancy and applications of DM in power systems, Table 2.1 presents a summary of the most relevant application areas along with some highly cited contributions for each case.

2.3.2.3 The Big Data Analytics Unfolding

In the last years, big data topics have become a part of the mainstream research in power systems as a vast amount of scientific papers in this field demonstrate. This is a result of the ongoing data-intensive era. For instance, in distribution networks, installed smart meters are expected to surpass 1.1 billion by 2022 while a three thousand fold increase in the amount of data is already being faced by utilities which now record energy consumption in a range from 15 minutes to one hour, contrary to once a month as they did a few years ago [95]. Regarding transmission system operators (TSOs), the situation is highly challenging as well as PMUs can take 30 to 60 samples per second. Thus, a single data concentrator gathering data from 100 PMUs (each one collecting 20 measurements at a 30-Hz sample rate) can generate up to 50 GB of data per day [154]. Nevertheless, big data goes far beyond the mere collection of structured and unstructured large quantities of data [92] and rather "describes a new generation of technologies and architectures, designed to economically extract value from very large volumes of a wide variety of data, by enabling high-velocity capture, discovery, and/or analysis" [155]. This popular definition evidences the main big data characteristics summarized in the 5 V's criteria. The first 4 V's were highlighted by the early works on BDA, being these volume, velocity, variety and value; while later research began to include also veracity as a key trait [156]. In the power energy sector other features referred as the 3 E's have also been exhibited as highly relevant, being these energy (that can be saved), exchange (data interchange between energy players to add value to big data) and empathy (increase user satisfaction) [95].

Table 2.1: DM Contributions by Application Area

Application area	**Reference**	**DM Technique**	**Citations in Scopus (May/2021)**
Dynamic security assessment	[126]	DT	108
	[127]	DT	104
	[128]	DT	38
	[129]	ML, SA	16
Faults detection and classification	[130]	DT	140
	[131]	DT, ML	114
	[132]	ML, SA	91
	[133]	Fuzzy	85
Protection design	[134]	ML	166
	[135]	DT	59
	[136]	DT	51
Load profiling and forecasting	[137]	SA	306
	[138]	DT, SA	96
	[139]	SA, Fuzzy	88
	[140]	SA	38
	[141]	SA, ML	34
Planning	[142]	DT, ML, SA	268
	[143]	Fuzzy	28
	[144]	SA	13
Electricity pricing	[145]	ML, SA	125
	[146]	SA, Fuzzy	1107
	[147]	ML	110
State estimation	[148]	SA, Fuzzy	28
Power quality	[149]	SA	12
	[150]	SA	11
Monitoring and visualisation	[151]	SA, ANN, Fuzzy	130
	[126]	DT	108
	[152]	SA, DT	31
	[153]	SA	19

The aforementioned distinctive BDA features are represented in Fig. 2.8.

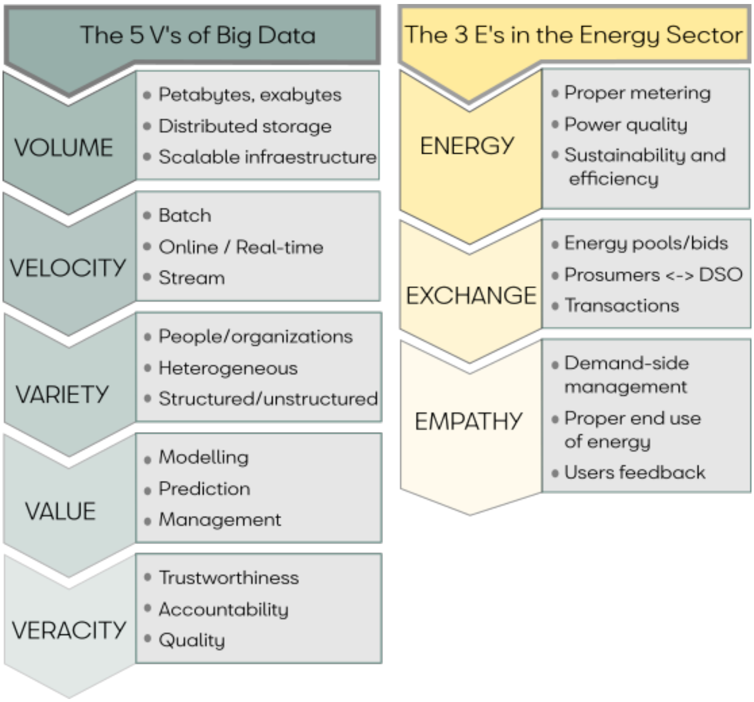


Figure 2.8: Big Data characteristics

To face the inherent challenges, a complete BDA data management process (see Fig. 2.9) must encompass: (i) data collection, (ii) data storage (iii) pre-processing, (iv) analytics, (v) visualization and (vi) decision making [88, 157, 158]. Just as DM permitted to extract knowledge from traditional datasets, emerging big data analytics (BDA) frameworks [88, 89, 93, 158] are more than ever expected to attain real benefits from overwhelming but information-abundant datasets coming from different origins. In this aspect, the numerous big data sources in modern power grids can be categorized as Fig. 2.10 exhibits, this is considering its data structure [92] (structured, un-structured and semi-structured) and also its origin [159] (measurement data, business data and external data).

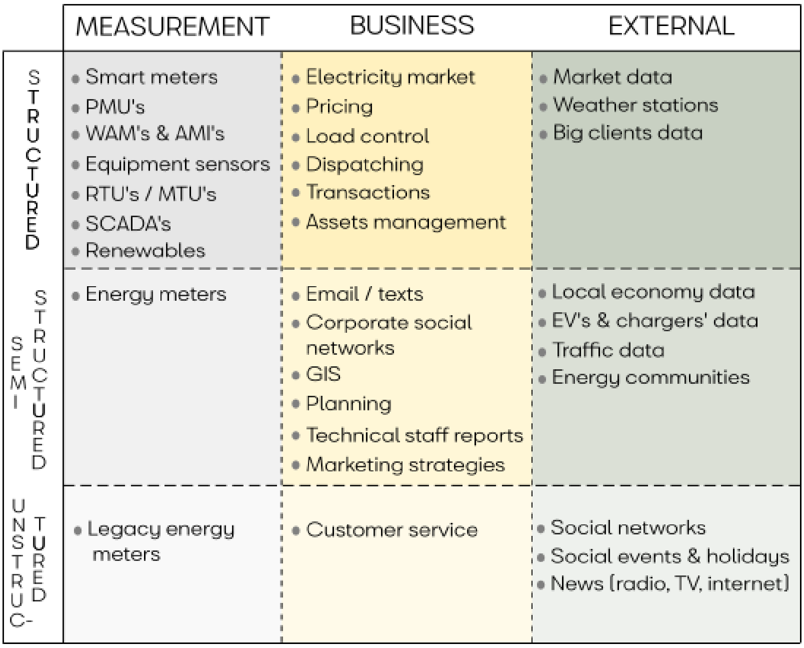
Undeniably, the potential advantages and applications of BDA are present

Figure 2.9: BDA process

in the whole electricity chain process [89, 92] ranging from renewable energy planning at the generation level to real-time interaction and energy saving at the demand-side management level. It is also noteworthy to remark its prominent role in smartgrid communication systems [87] and in distribution networks as next section elaborates on this latter. Having rooted foundations in DM, BDA takes advantage of a wide variety of AI tools and intelligent processing methods in different power system extents as reference [160] exemplifies.

2.3.2.4 The Relevancy of BDA in Power Distribution Networks

Smart energy metering has been experiencing a continuous growth in the last years. For instance, only in the U.S. it was expected to have more than 100 million smart meters in operation by the end of 2020 [161] while at the UK this number was projected to be around 10 million [162]. The smart electric meter market worldwide represented USD 9 billion in 2019 and is expected to expand at over 5% Compound Annual Growth Rate (CAGR) up to 2026 [163]. It is worth to recall that to handle the smart meters generated data, robust communication infrastructures and frameworks are required. To exemplify, reference [87] studies the IEEE 123-bus distribution model and states that to



	MEASUREMENT	BUSINESS	EXTERNAL
STRUCTURED	• Smart meters • PMU's • WAM's & AMI's • Equipment sensors • RTU's / MTU's • SCADA's • Renewables	• Electricity market • Pricing • Load control • Dispatching • Transactions • Assets management	• Market data • Weather stations • Big clients data
SEMI STRUCTURED	• Energy meters	• Email / texts • Corporate social networks • GIS • Planning • Technical staff reports • Marketing strategies	• Local economy data • EV's & chargers' data • Traffic data • Energy communities
UNSTRUC-TURED	• Legacy energy meters	• Customer service	• Social networks • Social events & holidays • News (radio, TV, internet)

Figure 2.10: Power systems data sources

properly manage the common 15-minute non-periodic data from 4000 smart meters, five typical base stations are needed to wirelessly cover a geographical area of 2 km^2. On this issue, reference [164] proposes a system architecture for smart metering BDA to perform data storing, querying, analysis and visualisation; while [165] elaborates an evaluation of different BDA frameworks.

On the other hand, we have been witnessing an increasing incorporation of Distributed Energy Resources (DER) in distribution networks mainly as a consequence of governmental incentives and the significant cost reductions of PV modules as prices have fallen roughly 80% since 2009 [166]. Subsequently, DERs will be able to supply by 2050 up to 45% of electricity needs in countries like Australia [167]. This decentralized energy generation incorporates additional advanced metering demands to achieve successful estimation and control over these systems. Handling the data created by the different metering devices at the distribution level nowadays represents a great challenge that will substantially deepen in the future.

In this overall context, it has been recently reported [168] the unreadiness of Distribution System Operators (DSO) to face these demands as they were mostly conceived as oversized, rigid-structured, conservative, non-automated passive agents [89, 98, 158] which are now unable to promptly integrate electric vehicle charging and a more active participation of end consumers now becoming energy producers (prosumers). Moreover, to this day modern distribution systems may present insufficient topology information (e.g. phase/transformer-to-client connection) [169], inaccurate state estimation [170] and power flow analysis [171] as well as a highly challenging reactive power control [172].

To cope with these circumstances, BDA arrives as a powerful tool to support DSOs to extract valuable knowledge from datasets and enable optimal utilization of existing equipment and grids. This will lead to reduce expenditures in conventional bulky infrastructures such as centralized generators or substations and favour more digitized, observable and resilient power distribution networks. The applicability of BDA in distribution networks is ample but it can be categorized according to their impact on either short-term or long-term planning as detailed in Fig. 2.11. In this sector, to face most of the case studies, the use of ML has been widespread considering mainly five types of algorithms: (i) unsupervised [173], (ii) supervised [174], (iii) reinforcement learning [175], (iv) imitation learning [176] and (v) generative models [177]. Ultimately, the use of these techniques in different applications derive to lower and more efficient investments, more efficient energy production, transport and dispatch, better use of assets and greater mitigation of outages and contingencies. Further discussion of these applications and their benefits can be found in [95] and [178]. Lastly, it should be emphasized the relevancy of BDA to procure awareness, efficiency and sustainability at the end-user level; considering not only energy features but also social and behavioral aspects as those found in [97].

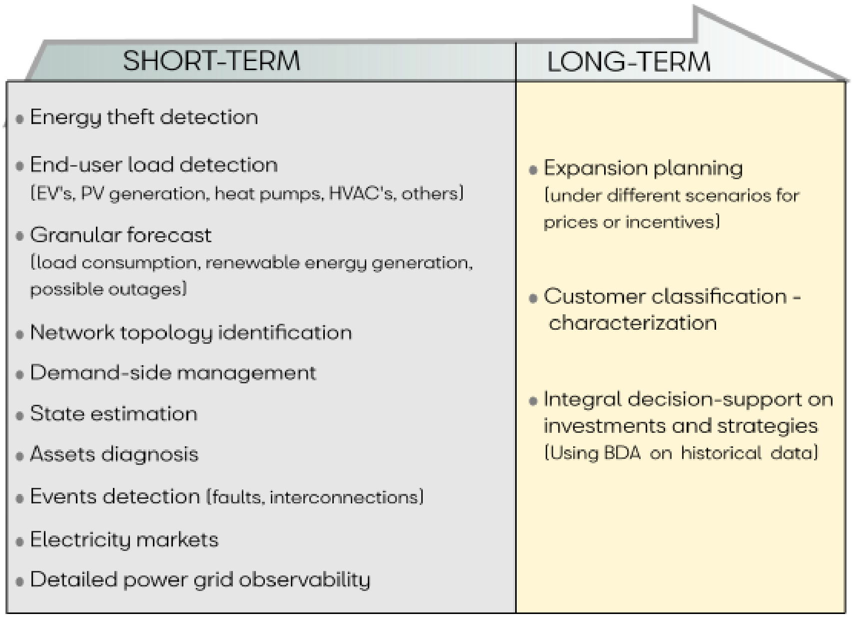


Figure 2.11: BDA applications in power distribution systems

2.3.2.5 Lessons Learned, Challenges and Future Prospects

Being a relatively novel framework, one of the biggest challenges of BDA consists on increasing long-term field experiences regarding its implementation and management in real applications. However, in the last years some sustained initiatives have come up with some results and lessons learned. For instance, BDA has promoted the development of several commercial data-driven smart energy management startups [157]. In this regard, BDA can be embraced as a key enabler to leverage businesses impact and profitability while improving social and sustainable development at the same time. From the prior initiatives, it is important to highlight the use of core technologies such as cloud computing, distributed databases, IoT and novel intelligent sensing devices.

As expected, not only startups have taken advantage of BDA capabilities. Large companies involved in the power industry such as IBM, T-Systems, Siemens and Cisco are offering big data solutions for analysis and management. Furthermore, some collaboration projects between some of these companies and utilities or governmental agencies have taken place [89]. Also some BDA benefits have been exposed by operators related to predictive assets maintenance and transformers protection from geomagnetic disturbances using PMUs data [88]. These experiences may encourage other energy players to gradually adopt BDA to support their decision making. On the other hand, due to the nature of their business, utilities have evidenced the relevance of counting with dynamic interactive visualizations to emphasize the nature of data instead of presenting the information in pre-designed manners [89, 158]. Moreover, 3D visualisations have been introduced to overcome the significant limitations of conventional 2D GISs when analysing geospatial and power data [160]. Therefore, visual analytics will be given more relevance in the future when deploying big data-driven interfaces. Finally, it is also worth mentioning real-world implementation experiences [88] from academic research groups where for instance, successful peak-saving was achieved by means of a utility BDA-based platform [179] and a demonstrative electrical distribution system was developed to incorporate self-healing, flexible power transfer and demand-side management actions [180]. These projects evidence a couple of the many successful partnerships between the academia and the private sector. Hence, these initiatives should be promoted and sustained on a long-term basis.

Recent demonstration of wide area monitoring and control systems for transmission and distribution networks, in which PMUs are used to support power system monitoring and operation, are a proof that adequate management of large quantity of data can lead to optimal utilization of the system assets, as well as flexible integration of renewable energy sources. In [181–183], both representative monitoring applications and data inquisition-management architectures are presented. Furthermore, in [184–186] a fast-response PMU-based wide area frequency control is presented for transmission networks. Such a control can be adapted and leveraged by BDA frameworks to be also used in controlling micro-grids, or islanded distribution networks.

In respect to the challenges and future prospects, most of the references already agree that privacy and information security are two of the biggest concerns. Thus, there is a need for superior cyber-security, regulations and laws required to protect all the energy players and keep safe sensitive information. Nonetheless, basic agreements about smart meter ownership have not been addressed yet such as who owns the data and how much of these data can be mined [96]. For instance, reference [157] states that consumers must have the right to own their measured and personal data which should only be used with explicit agreement. However, this still represents an open debate. Other demanding issues deal with data science and mathematical challenges to collect vast unstructured incomplete data to then be filtered, compressed [187] and processed with robust and rapid algorithms [95]. The difficulty to achieve real-time big data intelligence for instantaneous detection of anomalous occurrences has also been evidenced [94]. To tackle these requirements, new machine learning technologies such as deep learning and online learning have been remarked as opportune alternatives [96].

Complementary, the lack of universal data format standards has also been pointed out [92] along with the need for increased network bandwidth capacities [88]. Therefore, greater research on high-performance computation processing and the practical deployment of AI techniques is still needed. Otherwise, the final purpose of BDA to extract valuable information for successful decision-making may not be achieved given the trend of ever increasing amounts of data. Finally, to ensure a thriving deployment of BDA infrastructures, new retail business models [96], prolonged investments and well trained professionals with multidisciplinary backgrounds from energy and computer sciences will be required [88, 157]. Last but not least, the creation of integrated frameworks for adequate incorporation of BDA, particularly focused on service-oriented architectures [188], can lead to their successful application in future power networks.

2.4 Conclusions

- For humans to make better sense of processes and systems, the employment of tools and methods that include suitable data analysis and interactive visual representations significantly leverage the awareness and understanding of those systems. Indeed, this is the aim of Visual Analytics (VA) which is a multidisciplinary field that merges the strengths from machines and humans, this is automated data processing and visual cognition capabilities, respectively.

- The sense making-process of VA, considers the approach of human in-the-loop in a six-step data treatment: (i) pre-processing, (ii) analysis (optional), (iii) visualization, (iv) perception, (v) interaction and (vi) update.

- No former research exists in the literature regarding the specific use VA in Vehicle Electrical Distribution Systems (VEDS). In this sense, a review on the employment of VA in vehicular technology and also for the case of electrical networks was conducted. Under this deductive approach, the benefits and challenges derived from the use of VA in these ambits have been inferred. This will permit to latter adapt those good practices to the particular needs of visualization and simulation of VEDS as future sections will discuss.

- Regarding to automotive vehicle applications, VA has not been considered for the case of VEDS but in turn it has been employed for other vehicle requirements such as computed-aided-design, artificial vision, engine multi-body dynamics, virtual reality, sensor data examining and on-board communication networks.

- Despite the fact that a few software tools are commonly employed in the automotive industry to design VEDS, these do not include VA precepts in their interfaces. They neither allow high-level interaction such as simulation. In turn, to favor the interactive validation of VEDS by means of mathematical modelling and tailored numerical methods, these thesis addresses these aspects as future sections elaborate.
- Within the scope of power electrical networks, in the literature VA has been included in the design of interactive aesthetic network representations that include functionalities such as colour contouring, animations, colour coding, time-plots and easy model navigation and exploration. Additionally, to procure an easy visual hierarchy observation of the network, the incorporation of algorithms that automatically generate single-line diagrams is of great significance. However, it is worth mentioning that the previous tactics should be handled with care and given on-demand, so that the user does not get overwhelmed with the amount of information visually given. All the before mentioned precepts have been taken into account in the current project as Section V specifies.
- Data analysis is an optional step of the overall VA process. The degree of applicability of Data Analytics (DA) relates to the size and intricacy of the data under study. In this regard, DA in VEDS is nowadays not viable as a consequence of the actual reduced observability of voltages and currents of modern on-board electrical networks. However, automotive equipment manufacturers claim that the situation will be overcome in the near future with new VEDS architectures. Therefore, the review of ongoing DA unfolding in other vehicle applications and in electrical networks has benefited the anticipation of key challenges that may face forthcoming VEDS.
- For vehicle applications, some benefits have been reported when DA is compromised. Among these we have accidents avoidance, reliable autonomous driving, better user experience, fast emergency response and improved traffic control. Nonetheless, some challenges have also been

identified and should be taken into account for the design of future VEDS and the electronics supporting these systems. For instance we have demands related to higher data processing and connectivity standards, and cyber-security.

- One of the key aspects of DA relates to a systematic knowledge extracting from data which is usually referred as Data Mining (DM). It permits to identify connections, trends and patterns that allow to segment, cluster and predict the most likely to occur scenarios which represents a crucial advantage for today's business and organizations.

- The need to face the ubiquitous data explosion phenomenon we are witnessing, added to higher system performance requirements in every field, has influenced the creation of the multi-disciplinary Big Data Analytics (BDA) framework. It merges data science fields such as Big Data, Data Analytics and Artificial Intelligence to leverage the value relying on massive, distributed yet information-rich datasets.

- In recent times, some review papers related to Big Data Analytics (BDA) in power systems have been presented. Most of them focus in particular areas, for instance smart grids, distribution networks, smart meter data and electrical utilities. Those works mainly focus their time-span interest only in the last years where the BDA explosion has become evident. However, none of them favor readers an encompassing understanding of the development of knowledge mining from data in the broad power system spectrum from a historical perspective, since the early beginnings of the data digitization phenomena in the 1980's up to the ongoing big data explosion scenario. Doing so, as this section has elaborated, can facilitate readers a comprehensive understanding of the context on which modern BDA stands in this field and the transition towards more data analytics-driven decisions in the power industry. Moreover, as the amount of research related to BDA in this sector can nowadays be overwhelming, the review here presented can be of great value for researchers who are interested in having a prompt solid understanding of the evolutionary context and relevance of knowledge extraction from data in this sector.

- From the early beginnings of the electric power industry digitization in the 1980's, knowledge mining has played a prominent role to take benefits from complex and ever increasing datasets. Since the 1990's, the extended deployment of SCADAs along with market deregulation and distributed generation substantially increased the need for robust data analysis techniques. In this context, data mining (DM) emerged as a convenient approach that permitted the deployment of a broad range of applications suitable for transmission and distribution networks. Nonetheless, the ongoing power system challenges that have taken place in the last years, provoked the evolvement of the DM framework into a big data analytics (BDA) scope to face the inherent demands of the data-intensive era we are experiencing.
- Similarly to the challenges experienced in DA deployment in vehicle applications, concerns related to demanding data processing, privacy, security and universal data formats have been highlighted in the case of electric power networks. Therefore, these aspects should be highly taken into account for the design of future VEDS architectures.

> ”Electricity is doing for the
> distribution of energy what the
> railroads have done for the
> distribution of materials.”
>
> Charles Proteus Steinmetz -
> German-American
> mathematician, 1911

Chapter 3

Vehicle Electrical Distribution Systems (VEDS)

3.1 Introduction

To provide the reader enough context, this chapter begins exposing the characteristics inherent to VEDS from the automotive product development perspective and justifying the need of electrical simulation. An explanation of the intricate VEDS topology and wiring design process is exhibited. Prior to the execution of visualization and simulation duties, the need for custom-made factory data pre-processing is elaborated. Then, the power flow methodologies developed to face the complexity of these on-board DC networks are discussed. Finally, additional research opportunities in VEDS are mentioned.

3.2 VEDS in the context of the automotive industry

In the automotive industry organization, all the wires and the different components (electrical and mechanical) that allow energising every single consumer within the vehicle are considered as part of VEDS. Additionally, from a product development point of view inside an Original Equipment

Manufacturer (OEM), VEDS do not include electrified traction, the battery and alternator as these elements are regarded as subjects of the energy systems division. Sizing of the energy systems is performed on a previous stage of the car development process based on the technical concept design of the vehicle. VEDS, similarly to any other kind of electrical network, are dimensioned as a function of the allocated loads. Thus, an starting point for planning VEDS is the study of the current consumption of every load, which is then documented and stored in a database saving primarily the average and peak current values under nominal voltage conditions.

Then, VEDS design takes into consideration several aspects such as optimization of cable lengths, integrity of the wiring harnesses, electromagnetic compatibility and risk prevention. These aspects condition the peculiarities of the electrical network, for instance, the quantity and location of fuse boxes inside the vehicle, the type of protections that should be used on the harnesses depending on temperature, humidity and friction, among others. To establish a trust-worthy operation of VEDS components, standards with clear specifications are also considered. That is the case of the ISO 8820 [189] which details the general test requirements for fuse-links in the DC electrical network of road vehicles. Being fuses the key protective elements, their proper selection is of main importance for a fail safe operation of the system. Their main function is to protect the wiring. Automotive fuses evolved from glass tube fuses to the current common blade fuses and slow blow fuses among others. In particular, blade fuses usage is widespread in the industry due to their compact size, lightweight and durability.

VEDS themselves have to respond to the activation and deactivation of the power consumers depending on the many functions that are available within the vehicle and are triggered either automatically or manually by the driver. Nowadays, a vehicle can register around 300 functions. This introduces the need for intermediate control devices that coordinate and extend the right signals shapes to the different components. Such intermediate control devices are the Electronic Control Units (ECU). Moreover, the power delivery in ECUs must be guaranteed to also provide a physical-media fail safe communication in all data buses. EDS as of today connect many decentralized ECUs that manage the operation of specific systems. Almost for every particular system that we can identify in a vehicle, there is a primary ECU managing the corresponding functions. For instance, for the window motor, the battery charging, the lighting, braking system, transmission motor, acclimatization, and so on.

In urban networks, the concept of electrical distribution systems usually include substations, transformers, protections, feeders and consumers. Although VEDS are appreciably smaller than metropolitan urban grids, they are representative of what one typically finds. There is: (i) a main energy supply, in this case a battery, (ii) electro-mechanical protection devices (fuses and relays) safeguarding the integrity of the system, (iii) elaborated wiring paths to efficiently transport energy to loads within a range of acceptable voltage levels for variable current consumption and (iv) there might be DC energy conversion stages between high and low voltages as in the case of electric and hybrid vehicles. Validation of the components' quality and the correct network design is cyclically addressed all along the VEDS development process and includes a set of experimental procedures on real prototypes. Contrary, experimentation within the development of metropolitan electrical networks to guarantee their correct operation is inherently difficult. Typically, once the infrastructure in these grids is deployed, they are expected to be immediately "plugged" and launched to favor immediate energy supply for a given community. Therefore, simulation is a mandatory step for urban electrical networks. In this regard, power flow numerical methods are widely used tools to calculate the electrical variables all along the network, anticipate proper energy balance and quality assurance of the voltage feed and identify the conditions deriving to instabilities in the system.

In turn, simulation in VEDS is still not a common practice as manufacturers so far have usually relied on empirical procedures with step-by-step regulation guides to size cables, select protections and estimate voltage drops assuming mainly steady-state conditions. The inclusion of simulation in VEDS would be of high significance to test different architectures and configurations, anticipate unwanted voltage drops and detect design failures in an early stage of the design process. Hence, the prototyping phase would just be focused to validate the optimized EDS design earlier attained via simulation. This design includes the correct selection and dimension of all the wires, protections and auxiliary coupling elements. Beyond the electrical aspects, the thermal response of the wires and electrical components become of paramount importance. As an example, a wire should never reach temperatures leading to melting of the isolation.

Hence, to properly assist VEDS designers, it is particularly relevant the development of a computer tool able to infer temperatures from the estimated electrical parameters and thus assist the appropriate match between a fuse with its wire-load combination. To analyze this match it is not enough to rely on standards, but to take into account the maximum peak energy that the fuse has to withstand during its operation. To evaluate this, it is necessary to have the amplitude and duration of peak currents for loads presenting this behaviour. As an example, every time a motor axis is blocked, its current experience peaks. For instance, an scenario could be the case of a driver in a highway under heavy rain or snow and thus using the wipers. Due to the freeze on the windshield the current consumption of the wiper motor will be higher than under regular conditions. The deployment of a tailored simulation tool will allow the verification of the previous scenario and many others, beyond to what is feasible through on-the-road characterization.

3.3 VEDS characteristics

The automotive industry is experiencing unprecedented requirements to fulfill higher expectations from customers and include new functionalities in vehicles, such as driving assistance, gadget connectivity, sharing capabilities, and electrified traction. The electrical network is currently one of the most challenging on-board systems to be designed and prototyped due to these demands added to its intrinsic complexity. 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 of more than 50 kg [3, 4]. As a consequence, there is huge number of possible wiring architectures, which requires a great logistics effort to efficiently integrate all the cabling in an automobile.

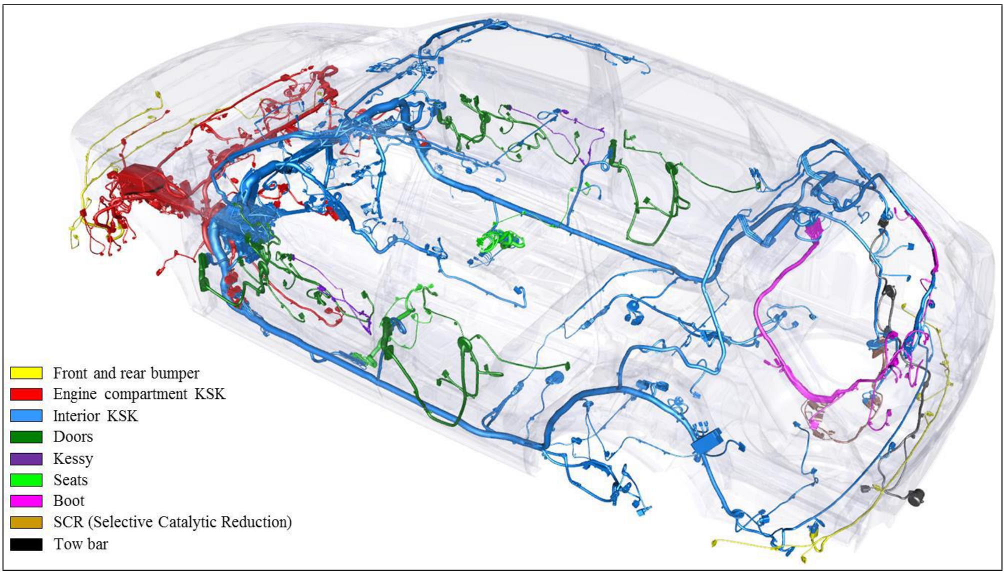


Figure 3.1: On-board electrical network harnesses inside a vehicle

Owing to assembling requirements, VEDS might be formed by a main harness (blue in Fig. 3.1) which delivers, through couplings, power supply as well as communication and control signals to different secondary harnesses (non-blue harnesses in Fig. 3.1) such as those related with the bumpers, doors, seats or engine. Every harness is basically an assembly of bundled cables protected by tapes, fittings and plastic coatings capable to maintain safe electrical operation of the network for the demanding conditions that may exist in the surroundings. For instance, Fig. 3.2 exhibits a picture of the main harness of the SEAT Ibiza car model.

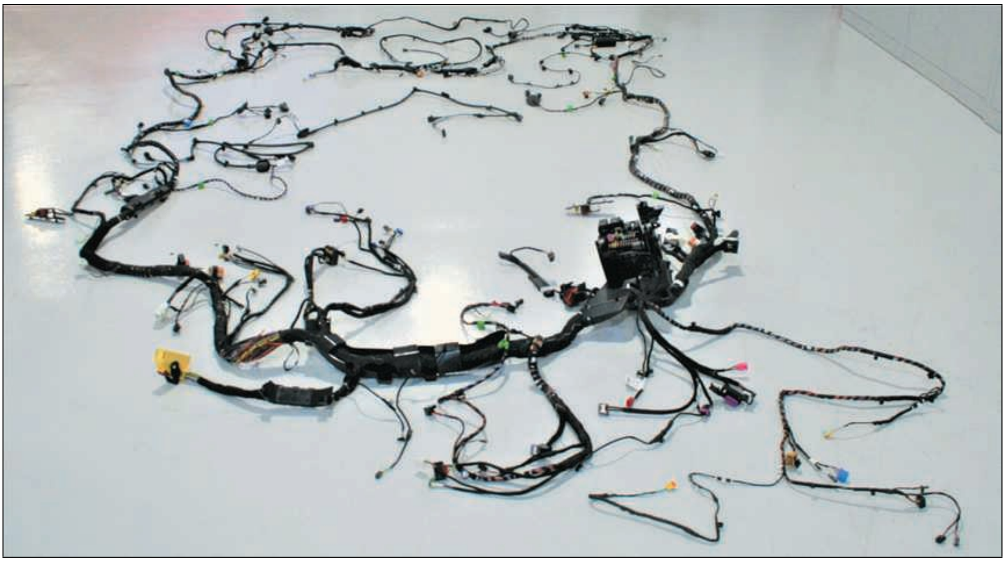


Figure 3.2: Picture of the main harness of the SEAT Ibiza car model

A wire harness has a tree configuration topology conformed by nodes and segments that allow cables to be conducted from their source spots to their destination ends as Fig. 3.3 exemplifies. Therefore, a cable *A* going from node *N0* and arriving to node *N9*, passes through different segments (*S1, S2, S8, S9*). This cabling configuration translates (with few exceptions) in a mostly radial power topology distribution.

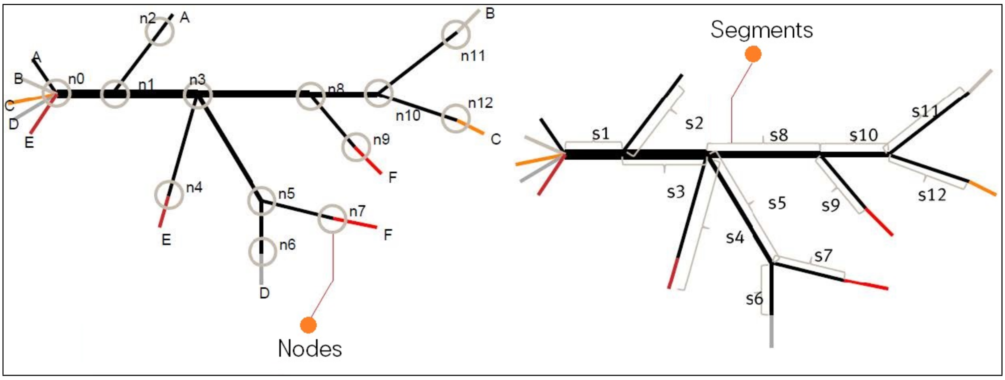


Figure 3.3: Segments and nodes in a wire harness. Adapted from [9]

3.4 The wiring design process in vehicles

Currently, most manufacturers offer selectable functionalities to customers for a particular car model, even if this greatly increases the logistics complexity of the development process. A modularity strategy is used to allow this customization while ensuring proper electrical operation in all of the configurations. This approach is based on the use of families and modules. A family consists of a group of elements able to perform a specific function, such as the sound system, which is made up of different components, including the radio, front speakers, back speakers, touchscreen, and so on. The components, in turn, are organized inside modules. With this technique, a family can be formed by different modules, each composed by predefined components, that might represent a different level of complexity of the required functionality (see Fig. 3.4). In the example of the sound system family, possible configurations could include modules A and B. Module A could represent a better-equipped sound system compared to module B.

The elements in a specific family are not only electrical (fuses, wires, relays, connectors, and loads as the speakers 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

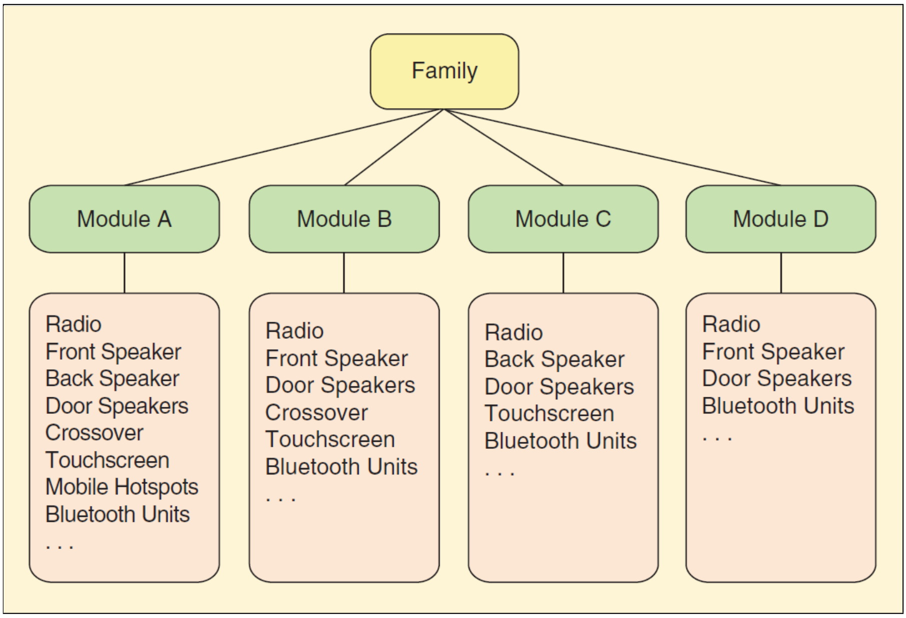


Figure 3.4: There may be some module options to fulfill a specific vehicle functionality (family).

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 selections, the complete EDS of a vehicle is finally composed by a prime harness, that transports energy and signals to a great number of consumers but also to secondary smaller harnesses as it has been mentioned in the previous section (see Fig. 3.1). The types of loads included in the harness have a significant impact on the selection of its wiring cross section and electrical protections. The final product of this stage is the complete description of the wiring harnesses as they would be installed inside the vehicle, maintaining the modularity information.

Next, the process continues with the design of the Wiring Schematics (WS), which includes diagrams of the logical connections among all of the components inside the full on-board network. The WS shows 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, in what is referred as Wiring Plans (WP), the numbering of the cables, wiring cross sections, couplings, and other physical characteristics are added to the WS.

The elaboration of the routing files for the wires takes place simultaneously with the development of the WS and WP files. Here, all of the wire paths between components are designed, with the mechanical constraints considered, and then traced into 3D CAD files. Similar to the case of the WS and WP, there is a database containing the graphical information of every component. After this, the WP files are combined with the routing diagrams to generate a full graphical description of the wiring harness, which also contains the cable-length information. From this merge, a KBL file from the German "Kabel Baum Liste" ("Cable Tree List" in English) with a XML (eXtensible Markup Language) tree-structured extension is created. The KBL file embeds all of the required manufacturing information of a wiring harness and also contains 3D information that can be later represented in elaborated 2D WS layouts known as full-wiring drawings. There is a KBL file for each harness in a vehicle. The overall process is shown in Fig. 3.5.

To complete the database creation process for manufacturing needs, two Excel files are automatically generated from the KBL file: the Wire List (WL) and Bill Of Materials (BOM). The WL includes a numbered list of all of the wires present in the harness, along with information, such as the identification tag, origin and destination node with pin information, total length, cross section, color, and insulation type, among others, together with the family and module to which each cable belongs. This list is critical because it contains all of the connections performed with wires. On the other hand, the BOM file lists electrical components that are not wires, but includes fuses, relays and also elements from the wire harness that have only mechanical purposes (such

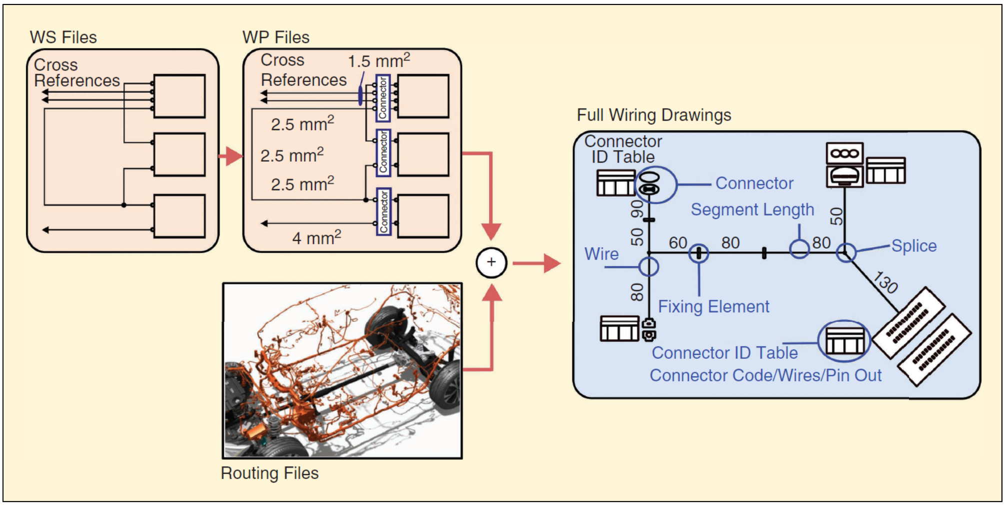


Figure 3.5: The full-wiring drawings' design process.

as fixings, wire guides, and so on), specifying the module and family for each one.

3.5 VEDS data pre-processing

It is worth to recall that the original factory data related to VEDS was primarily structured for exchanging manufacturing information, it was not conceived for data visualization and electrical simulation. Hence, the necessary factory data must be firstly integrated and conveniently pre-processed.

As previously explained, the data containers having the greater amount of electrical information from the harnesses are the XML files. These were originally designed to embed all the possible modules that exist in a given family within a car model. In practice of course, a specific vehicle is described by the selection of only one module per family; thus, the pre-processing includes a filtering of the XML file. To achieve this, the user also introduces the particular vehicle equipment configuration under study as a list of modules (one per family) in the form of a Comma-Separated Values (CSV) table file. Considering this table, the pre-processing algorithm removes the unnecessary information.

However, the previous files by themselves do not contain all of the necessary data to perform power flow analysis, such as data related to time-current characteristics of fuses, the temperature class of each cable, or pin-out information of the consumers, among others. Therefore, additional files are also needed to perform the entire pre-processing for a single harness. Considering this, all the necessary input data files (see Fig. 3.6) are the following: (i) the factory wire harness .XML data container which is different for every harness in the vehicle according to its corresponding car model, (ii) the vehicle equipment configuration, (iii) input variables values such as the nominal voltage of the battery, the ambient temperature, the need to perform static or time-profiles simulation, the type of car harness under study (main or secondary) among others, (iv) time-current profiles of the loads if applies, (v) the fuse boxes internal connectivity and (vi) the parameters of the different wires in the harness such as their cross-section area, thermal conductivity and maximum/minimum temperature.

With all the aforementioned files, by means of Python scripts allocated in a web-based software scheme (specified in Chapter 4), the pre-processing extracts, arranges and correlates all the required electrical information from the nodes, lines and loads in the network. In this respect, Algorithm 1 exhibits the pre-processing procedure. The ability to handle the VEDS data formats that are specifically used in the automotive industry, makes the pre-processing stage a semi-automated process in the simulation workflow. Hence, intricate vehicle harness configurations can be directly inserted by the user without requiring him the manual insertion of electrical elements to create the network topology as most simulation tools demand.

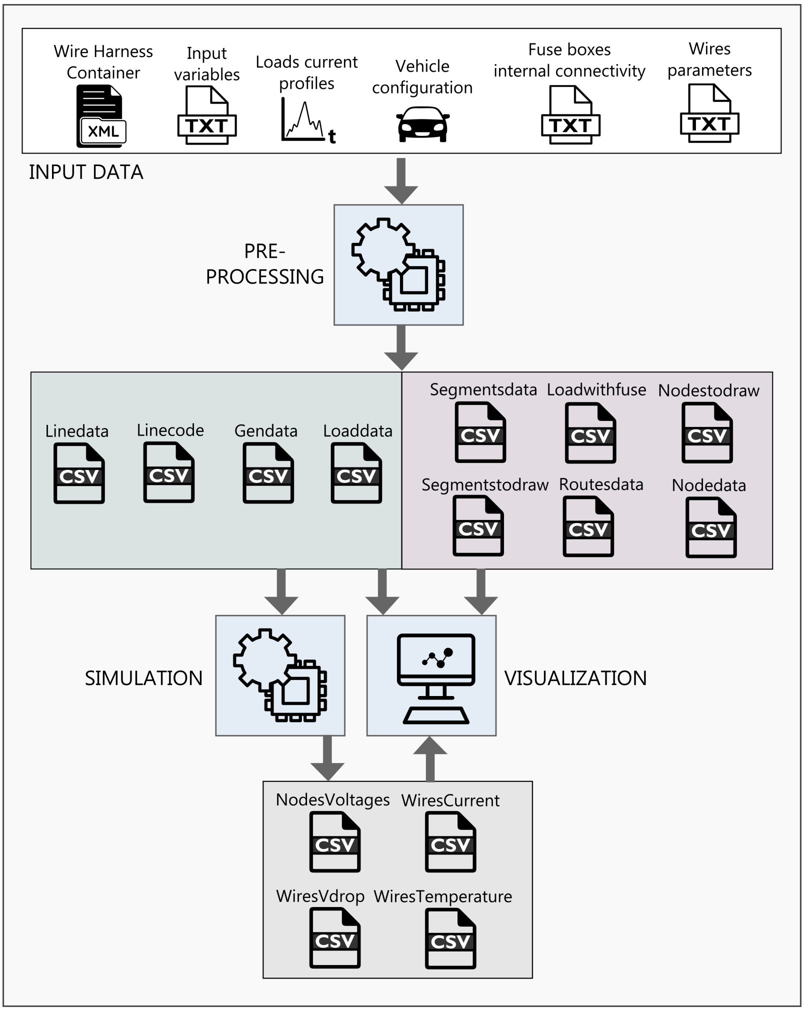
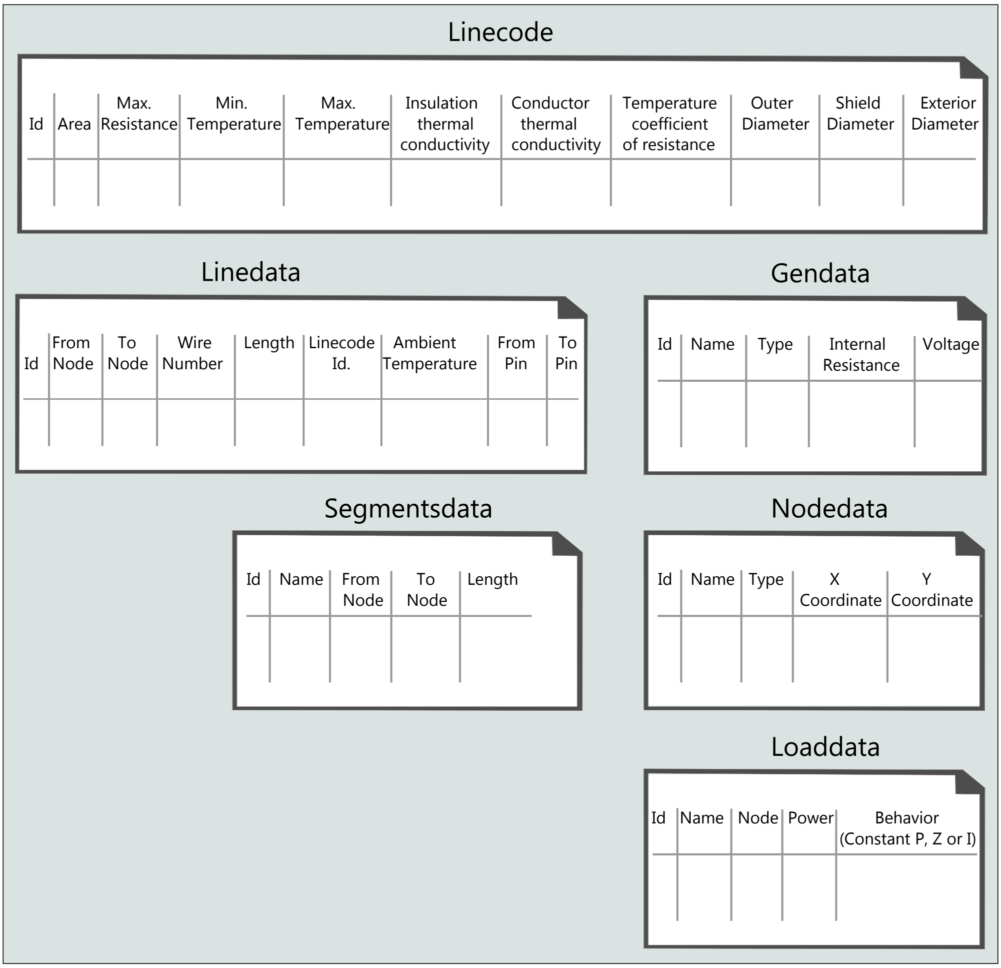


Figure 3.6: Data generation workflow

Once the pre-processing has taken place, further data treatment related to visualization tasks (elaborated in Chapter 4) and simulation (explained in the next Section) can take place as the information is suitably organized in a set of CSV files (e.g. *Gendata*, *Linecode*, *Linedata*, *Nodedata*, *Segmentsdata*, *Loaddata*) having a data structure similar than the one employed in [190] which is common within the power systems domain to perform power flow studies. The data format of these files are presented in Fig. 3.7. Further details on the aforementioned process are described in reference [191].

```
Require: Set of input data files as shown in Figure 3.6
Ensure: Set of output files for power flow, variants analysis and visualization
    purposes
 1. Extract and save into variables the lists of fuses, wires, connectors
 2. Filter out elements depending on the vehicle configuration and write new
    reduced XML
 3. Generate files with the total amount of modules in the XML and the
    simulated modules
 4. Filter out wires that carry digital signals or ground signals
 5. Categorize the nodes depending on the original nodes name. The possible
    categories are: fuse node, junction node, battery node, coupling node and
    consumer node
 6. Sub-categorize the fuses nodes depending on the fuse box to which they
    belong
 7. Expand list of fuses with their technical information (temporary files)
 8. Match each fuse with the wire it is protecting (temporary files)
 9. Extract load description data (visualization)
10. Extract load profiles and technical data for power flow
11. Extract list of nodes with their Cartesian coordinates (visualization)
12. Extract routes and wires segments data (visualization)
13. Define a network architecture limited to the first hierarchy pending from
    the fuses (Elements hanging from ECUs are not considered)
14. Generate the main files for the power flow simulation: Gendata, Linedata,
    Loaddata and Linecode
15. Generate the files required for visualization: Segmentsdata, Loadwithfuse,
    Nodestodraw, Segmentstodraw, Routesdata and Nodedata
```

Algorithm 1: Pre-processing process, adapted from [191]



Linecode

Id	Area	Max. Resistance	Min. Temperature	Max. Temperature	Insulation thermal conductivity	Conductor thermal conductivity	Temperature coefficient of resistance	Outer Diameter	Shield Diameter	Exterior Diameter

Linedata

Id	From Node	To Node	Wire Number	Length	Linecode Id.	Ambient Temperature	From Pin	To Pin

Gendata

Id	Name	Type	Internal Resistance	Voltage

Segmentsdata

Id	Name	From Node	To Node	Length

Nodedata

Id	Name	Type	X Coordinate	Y Coordinate

Loaddata

Id	Name	Node	Power	Behavior (Constant P, Z or I)

Figure 3.7: Organization of electrical data in different CSV files

3.6 Power flow analysis of VEDS

The power flow problem consists in computing the voltage magnitude $|V_i|$ and angle δ_i in each bus of a power system where the power generation and consumption are provided. Given that VEDS are deployed using DC current, the analysis can be simplified at a certain level. The battery is assumed as an ideal voltage source having between 14V and 14.5V. Wires are considered as resistive elements whose resistance depends on the assigned ambient temperature that depends on their location inside the vehicle. Loads are modelled using the ZIP approach [192], this is considering factors for having constant impedance, constant current or constant power; where the individual factors must be between 0 and 1 and the overall sum of the factors must add up to 1. In this regard, most of the analysis have been satisfied considering the loads as merely having a unitary constant current factor. In addition, for single-time simulations, the nominal Power field from the *Loaddata* file in Fig. 3.7 is considered. If current-time profiles are demanded in the simulation for the loads, their instant power demand is represented by a vector where its elements are attained by multiplying the nominal battery voltage with the current for each time step.

To allow a rapid and reliable power flow simulation for the particular characteristics of VEDS (complex weakly meshed low-voltage DC networks), the Backward/Forward Sweep (BFS) [193] and the Current Injection (CI) [194] methods were considered as they have been exposed to perform better than traditional approaches such as Newton–Raphson and Gauss–Seidel in terms of computational intensity in radial or slightly meshed systems [195]. Additionally, the mathematical formulation for these kinds of DC networks is more straightforward when these methods are employed. The BFS and CI techniques count on an initial guess of the voltage profile to infer the demanded or injected currents in the nodes. After this, the voltage profiles are updated considering the voltage and current Kirchhoff laws as detailed in [195] .

3.6.1 The Backward/Forward Sweep (BFS) Method

In [196], we remarked that the BFS tactic is around 8 times faster than the Newton–Raphson method in terms of convergence in radial networks when testing a fully radial DC system with 200 nodes, being half of them generators and half of them loads. The previous reference elaborates on the mathematical modelling, details and considerations to deploy the BFS method for the particularities of VEDS. There, some case studies are analyzed for given sample vehicle networks. Note that under this tactic, all elements in the VEDS network are included in the simulation, comprising also consumers being fed by ECUs. To do so, these electronic elements are considered as static power distribution boxes. It is worth to recall that the implemented approach incorporates minor variations to manage possible existent network loops as VEDS are not entirely radial, this approach is called Meshed Network BFS (MN-BFS).

To apply the MN-BFS tactic to VEDS, the network is seen as a two-fold grid having a “positive” and a “negative” grid. The “positive” grid, comprises the nodes and segments between the positive terminal of the battery and the pins where currents enters into the consumers. The ”negative” grid relates to the nodes and segments that connect to the negative terminal of the battery. The branches creating loops in both grids are identified and suppressed so that the network becomes radial. As a consequence, the traditional BFS technique can be applied but then the Meshed Network (MN) compensation algorithm must be applied in the cut branches as exhibited in [195]. This compensation relies on the use of the Thevenin equivalent resistance. Algorithm 2 overviews the implementation of this strategy.

Satisfactory results were achieved with this methodology and were presented in [197]. There, the sample vehicle network in Fig. 3.8 was studied. This network topology is a result of having chosen a specific car modularity. It considers a 14V battery as the supply element. Node A1 represents a connection

```
Require: Pre-processing output data
Ensure: Branch currents and node voltages
Network components categorization in correspondence to the type and identifier related to their pins
Partitioning of the network into a “positive” and “negative” grid to face complex paths to ground and improve the model accuracy
Incidence matrices ($\mathbf{\Gamma}_p$, $\mathbf{\Gamma}_n$ ) and creation representing connections data. Rows represent branches of the network while columns outline to nodes
Determination of the “cut” ($l_c$) an “non-cut” branches ($l_{nc}$)
Calculation of the branch resistances matrices ($\boldsymbol{R}_{bp}$, $\boldsymbol{R}_{bg}$ ) considering possible temperature variations
Computation of the Thevenin resistances in the “cut” branches ($R_{th}$) by means of a unitary current sequential injection tactic [195]
In view of the incidence matrix, withdrawal of unneeded branches having loops in the “positive” and “negative” grid
for i = 1 : Max. number of iterations do
    Calculation of the “non-cut” branches currents $\boldsymbol{I_B}(l_{nc})$ as the nodal currents $\boldsymbol{I_n}$ are already defined
    Determination of the node voltages $\boldsymbol{V}$(2:N) utilizing the “non-cut” branches resistances and the branch currents
    Obtention of the voltage drops in the “cut” branches considering the node voltages $\boldsymbol{V}$
    Obtention of the voltage drops in the “cut” branches considering the branch currents $\boldsymbol{I_B}(l_c)$ and the “cut” branches resistances $\boldsymbol{R}_b(l_c)$
    if The computed voltage drops from the previous two approaches are consistent then
        Break
    else
        Compute the new “cut” branches currents $\boldsymbol{I_B}(l_c)$ employing the Thevenin equivalent resistance compensation algorithm [195]
    end if
end for
```

Algorithm 2: Pseudo-code of the implemented BFS approach

to a metal plate, which distributes energy to the network through different fuses (elements having the prefix “F”). The nodes identified with the prefix “Sp” are splices nodes; splices represent ultrasonic soldered connections of multiple wires. Consumers have been named with the prefix “C,” while couplings and ECUs have the prefixes “K” and “E”, respectively. The numeration is not exactly consecutive to represent the fact that, given the modules selected, certain components were filtered out in the data preprocessing stage. Component E1 is an ECU, classified as “source.” It has four pins: pins 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 interconnected through the vehicle body itself. The battery ground or negative terminal is identified with the code gr00.1. The different node voltages and branch currents are shown in Fig. 3.8. Voltage drops are encountered in the lines as a result of the calculated line resistances, given their physical characteristics. Nominal node voltages decrease following the power flow, as expected. In addition, the voltage drop in fuses depends on their type, and the calculated branch currents are consistent all along the circuit.

3.6.2 The Current Injection (CI) Method

In contrast to the MN-BFS technique, the CI tactic does not require to perform any topological modification of the network for a proper mathematical modelling and therefore can be solved in its original disposition. This translates into time savings as no branches removal and compensation algorithm are needed. Indeed, in [198] we reported slightly lower accuracy but three-fold reduction in simulation time when using the CI instead MN-BFS in a mid-sized DC network under different load conditions. Additionally, the CI method is suitable for bidirectional power flow studies such as those that can be encountered in DC railways networks [199] or in hybrid and electrical vehicles; in regenerative breaking conditions for instance. Hence, the CI approach will present faster adaptation in future on-board vehicle networks when more interaction between the high-voltage traction system and the low-voltage network (VEDS) is incorporated. Therefore, the preferred approach to

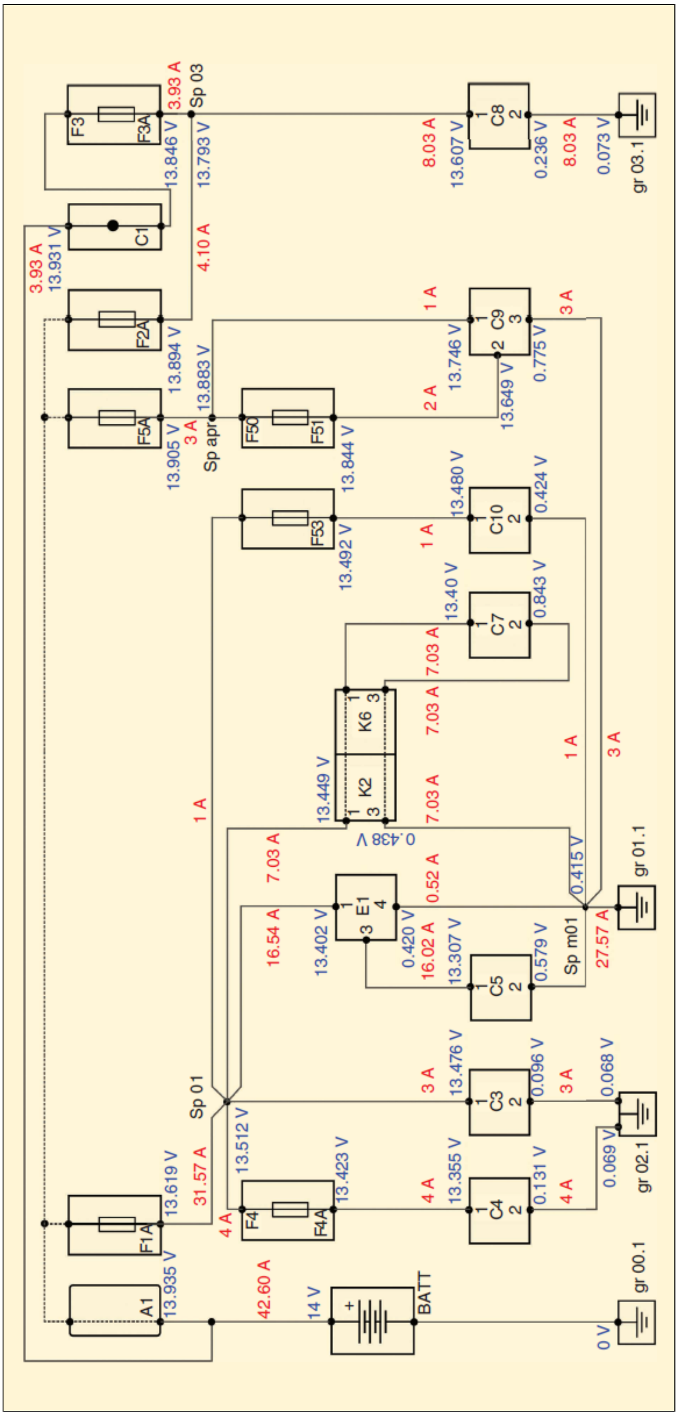


Figure 3.8: Sample network showing node voltages and branch currents

perform power flow studies in VEDS is the CI method.

Before the deployment of CI technique is elaborated, it is worth deepening on the way that the VEDS topology was managed to implement this approach. As explained in Section 3.3, the entire on-board vehicle network is made-up of the connection of wire harnesses. In a particular car model, a main harness placed directly downstream the fuses-box can feed secondary harnesses such as those related to the bumpers, seats or tailgate. This interconnection is achieved by means of couplings. Nonetheless, a secondary harness may also be fed by an ECU that in turn can be fed by the main harness. Due to this casuistic, to ease the electrical analysis of the network, two types of VEDS devices can be considered for a main harness: the first-level and the second-level hierarchy devices (see Fig. 3.9). The former are "upstream" elements directly connected after the fuses and thus are closer to the slack node, in this case the battery. Devices having high-current demand (such as the motor fan or heaters) are commonly part of this category. The above mentioned couplings and the elements that control current flow to specific user-controllable loads (such as the joysticks and buttons) also belong to this collection. These switching elements are assumed to inherit the current consumption from their associated consumers, current that should be already known by means of a previous simulation. Bearing this in mind and the fact that the pre-processing withstands individual harnesses, the simulation is also intended to be run in single wire harnesses under this approach. This means that for a main harness simulation for instance, currents consumption related to couplings, buttons or ECUs must be attained in a prior simulation step where the corresponding secondary harness was firstly considered, assuming there that interconnection couplings act as slack nodes themselves. In turn, the second-level hierarchy is conformed by the different sensors and actuators being feed from the ECUs. Among these we have "downstream" consumers with diverse current demand.

In advance to the power flow analysis, output files from the pre-processing stage (explained in Section 3.5) are considered to construct the matrices

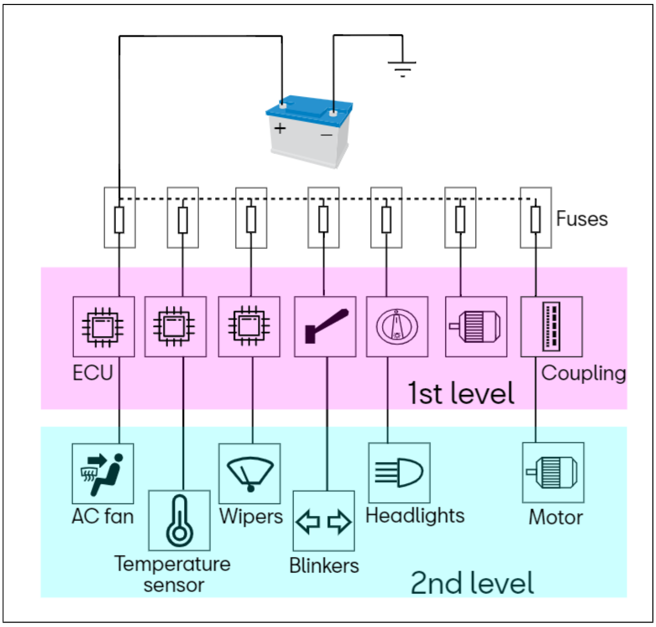


Figure 3.9: Devices hierarchy in VEDS for the CI method [198]

encompassing the data topology of the network. This process is exhibited in Algorithm 3. The newly created matrices are then employed in the core of the power flow calculation as in Algorithm 4. There, the matrices having the expression “device” refer to the first-level consumers previously mentioned. A complete discussion of this custom-made CI tactic for VEDS can be found in a paper we presented in [198]. In that work, simulation results were also presented and compared against experimental data in a door wire harness test bench and a prototype vehicle, exposing satisfactory results.

```
Require: Gendata, Linedata, Loaddata, Linecode
Ensure: $\mathbf{\Gamma}$, $Device_{con}$, $\boldsymbol{Y_N}$, $\boldsymbol{Y_s}$, $\boldsymbol{I_s}$, $V_s$, $K_p$, $K_i$, $K_z$, $\boldsymbol{P_{j,k}}$
Get nominal battery voltage $V_s$ and nominal battery resistance $R_s$ from Gendata
Get wires resistance vector Line_R from Linedata and Linecode
Get loads ZIP model current factor vector $K_i$, impedance factor vector $K_z$ and power factor vector $K_p$ from Loaddata
if Simulation is static (single time) then
    Assign load nominal power vector $P_k$ from Loaddata
else if Simulation considers time-profiles then
    for k=1:1:number of devices Dev_count do
        Import current profiles $I_k(t)$
        Calculate power vector $P_k(t)$ by multiplying $\boldsymbol{I_k(t)}$ with $V_s$
        Create power matrix $\boldsymbol{P_{j,k}}$ for each time step $j$ by column stacking $P_k(t)$
    end for
    Create Incidence matrix $\mathbf{\Gamma}$ from Linedata
    Calculate adjacency matrix $\boldsymbol{A_m}$ using $\mathbf{\Gamma}$
    Check connectivity of all nodes to battery using $\boldsymbol{A_m}$
    Calculate lines admittance vector Line_Y as 1/Line_R
    Create devices connectivity matrix $\boldsymbol{Device_{con}}$
    Obtain admittance matrix $\boldsymbol{Y_N}$ excluding source
    Obtain admittance matrix $\boldsymbol{Y_s}$ of the battery
    Calculate battery current vector $I_s$
end if
for j=1:1:number of time steps do
    Calculate power flow with Algorithm 4
end for
```

Algorithm 3: Creation of the necessary matrices for power flow calculation

```
Require: $\boldsymbol{\Gamma}$, $j$, $Iter_{max}$, $Device_{con}$, $\boldsymbol{Y_N}$, $\boldsymbol{I_s}$, $V_s$, $K_p$, $K_i$, $K_z$, $\boldsymbol{P}$, $\epsilon$, $D$
Ensure: $V_{out}, I_{out}, V_{devices}, I_{devices}$
Initialize node voltages vector $V$ to source voltage $V_s$
for it=1:1:max iteration number $Iter_{max}$ do
    Get the connected-devices voltage vector:
    $Device\_V{=}Device_{con}{*}V$
    Get the connected-devices power vector:
    $Device\_P = P_{j,k} * (K_p + K_i * Device\_V/V_s + K_z * (Device\_V)^2/V_s^2)$
    Get the connected-devices current vector:
    $Device\_I = Device\_P/Device\_V$
    Get the branch currents vector
    $I_n = -I_s - (Device_{con})^T * Device\_I$
    Get the new nodes voltage vector:
    $V_{new} = {Y_N}^{-1} \cdot I_n$
    Find the current tolerance:
    $tol = norm(V - V_{new})$
    if tol< $\epsilon$ then
        break
    end if
    Get the voltage vector:
    $V = D * V_{new} + (1 - D) * V$
    Update according to the actual voltage vector:
    $V_o = V$
    Get the line voltage drop matrix:
    $\boldsymbol{V_{drop} = \Gamma * V_o}$
    Get the line currents matrix:
    $\boldsymbol{I_{line} = Y_N * V_{drop}}$
end for
if j>0 then
    Column stack $V_{drop(j)}$ to get the all-nodes voltage output vectors $V_{out}$
    Column stack $I_{line(j)}$ to get the all-nodes current output vectors $I_{out}$
    Column stack $Device\_V$ to get the connected-devices voltages $V_{devices}$
    Column stack $Device\_I$ to get the connected-devices currents $I_{devices}$
else
    $V_{out} = V_{drop(j)}$
    $I_{out} = I_{line(j)}$
    $V_{devices} = Device\_V$
    $I_{devices} = Device\_I$
end if
```

Algorithm 4: Core of the power flow algorithm.

3.7 Additional research opportunities in VEDS

Beyond the research opportunities previously mentioned in this thesis regarding the incorporation of Visual and Data Analytics (Chapter 2), and suitable power flow simulation methodologies to study VEDS (Section 3.6); hereafter are exposed other key research opportunities related to VEDS analysis and simulation that should be taken into account in the near future. These themes will play a significant role in forthcoming on-board electrical networks and the way in which simulations platforms are developed for these systems. Topics such as thermal analysis, new electric/electronic architectures, Electronic-fuses, mild hybrid power trains, hardware in the loop and high voltage networks are discussed.

3.7.1 Advanced Thermal Analysis

The electrical simulation of VEDS is closely tied to the conduction thermal characteristics of the wires but also to the thermal radiation and convection from the elements and environments surrounding the cables. However, an adequate determination of the wires temperature in VEDS is a challenging goal. To face this demand, in this thesis a model that infers the maximum temperature of single wires surrounded by air in steady-state conditions has been considered. We discussed this approach in [196] and reference [191] deepens on the thermal estimations modelling discussion. The latter reference intends to provide an estimation of the wire surface temperature considering the radial temperature transfer from the wire conductor to the insulation. However, to achieve more accurate power flow simulations, there is room for future research regarding an improved estimation of the wires temperature, considering for instance: (i) the axial temperature transfer, (ii) impact of wires covers and (iii) transient temperature behaviors. Moreover, as wires in bundles transmit heat between each other, all the wires in their particular harness segment should be also taken into account. Indeed, the wires temperature inference is not trivial given [200]: (i) the great number of wiring harness paths and combinations, (ii) the random distribution of wires in bundles as they are manually assembled, (iii) the presence of wires carrying only control or communication signals, (iv) the non-uniform heat dissipation along the wire's section and length and (v) the difficulty to infer neighboring temperatures due to the thermal particularities of the different vehicle car compartments such as those which house the motor, doors, the bumper, the roof or the base platform.

As an starting point, to simulate the thermal response in wire bundles in nominal conditions and during short-circuits, the use of finite element analysis has been presented as a reliable technique [1]. In Fig. 3.10, the radial thermal behavior in a harness for two different wire bundles configuration is exhibited. This figure provides a brief insight on the complexity to perform accurate electro-thermal simulation when different elements and thermal environments are involved. However, the extension of this tactic to VEDS zones or complete harnesses would provide the user with valuable information and intuitive representations of troublesome thermal areas, paths or elements in the electrical network given certain conditions or scenarios.

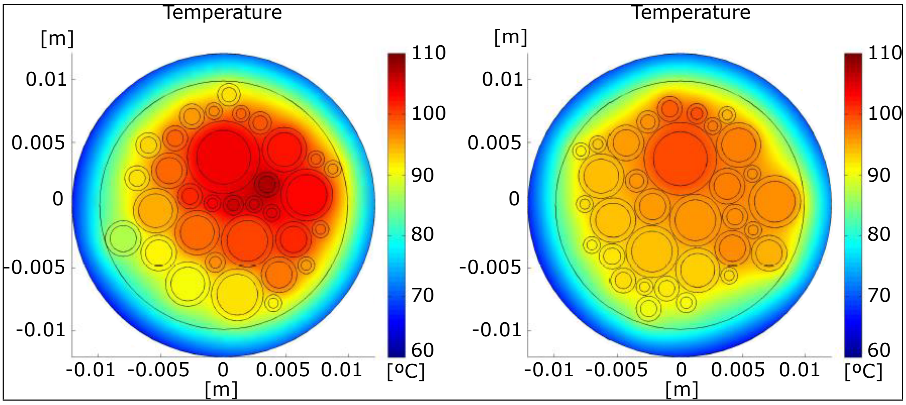


Figure 3.10: Thermal response for two different wire bundles configuration, adapted from [1]

3.7.2 New Electric-Electronic (E/E) architectures. Electronic-fuses (E-fuses)

Contrary to isolated hardware-oriented architectures, future E/E systems will be designed to integrally merge the vehicle hardware (ECUs, sensors, actuators, loads, protections, wires, communication and connecting devices) by means of a central computing platform and a unified software. In this respect, VEDS are moving towards standardization and scalability. To do so, the incorporation of robust power devices and a new conception of vehicular E-fuses is required [201]. Indeed, E-fuses will dramatically outperform typical electromechanical protection devices (fuses and relays) given their controlled short-circuit current, rapid precise reaction-time and fault-tolerance capability. For instance, specialized VEDS software could permit engineers an intelligent parameterization of time-current curves for the different E-fuses in the network, allowing a robust protection coordination. Moreover, some work has been proposed toward enhanced reliability functions by means of safety mechanisms at device and system levels [201] and decentralised modular architectures [202]. Under this last approach, smart distributed power devices can be achieved with different DC/DC converters where conditions such as over-temperature and overcurrent are constantly informed to a master control. Despite some efforts on the initial development of E-fuses some years ago [203–205], it must be mentioned the lack of academic research regarding the integration of smart E-fuses into on-board EDS. Relevant information on this topic can be mainly found in manufacturers or vehicles societies websites as in [202,206,207].

In this context towards a paradigm shift favoring universal E/E architectures, significant efforts must be devoted to the development of modular software packages having combined design environments. This will permit to analyze the interaction and avoid conflicts between different vehicular subsystems which are currently designed independently such as VEDS, the high-voltage power conversion system, electric charging, communications network, battery energy management and electro-mechanical traction. This convergence will be reflected on an improved system reliability, programmability and coordination.

3.7.3 Mild Hybrid Electric Vehicles (MHEVs)

In 2019, the amount of fully Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) sold worldwide (around 2.2 million) represented a 2.5% market share over all vehicle sales [208]. However, by 2030 it is expected to raise up to a 30% share [209]. Hence, until HEVs and EVs get consolidated in the market, sustained efforts are taking place to improve the conventional internal combustion engine (ICE) technology and fulfill European regulations such as the limit of 95 g/km of carbon-dioxide emissions in new passengers cars [210]. In this respect, the incorporation of mild hybrid powertrains have been exposed as a convenient approach to improve fuel efficiency up to 20% with reduced costs [211]. It consists on adding to the conventional 12V-battery system, an additional 48V supply. This higher voltage availability in Mild Hybrid Electric Vehicles (MHEVs) permits the extraction of sufficient power to use a small electric motor/generator intended only to assist and act as a power booster for the ICE. By doing so, no insulation upgrades are required and the fuel consumption is reduced by decreasing the engine idling time when the vehicle is stopping, braking or cruising. Moreover, the electric motor can guide the ICE to efficient operating points and even accomplish partial regenerative braking [212]. Given these benefits, automakers are showing high interest in the mild hybrid technology. This is evidenced with some international industrially oriented conferences and expositions which have been taking place in the last years with the aim of consolidating the 48V power supply systems [213].

From the software design point of view, simulation capabilities can be leveraged by considering recent related academic contributions. Between these we have an optimal hybrid energy management [212], low-cost 48V switched reluctance drive [213], DC/DC converter architectures [214, 215], hybridization degree levels [216], motor-inverter power module for electric compressor [217], modelling and validation of lithium-ion battery packs [218] and integrated converters for mild hybrid starter-generators [219, 220].

3.7.4 Vehicular high voltage networks and power converters

In the last years, as the literature reveals, most of the academic effort related to electrical systems in vehicles has been devoted to the development of new power conversion and charging systems towards electrified traction. On this subject, towards electric mobility, two main scenarios are being witnessed: (i) the short-term migration from internal combustion engine vehicles (ICEVs) to MHEVs, already contextualized in the previous subsection and (ii) the progressive strengthening of PHEVs and EVs in the market. For this second scenario to promptly unfold, the design of future on-board E/E architectures and powertrains must be reformulated to suitably integrate high voltage machines (beyond 200V) requiring high torque and power densities such as those based on permanent magnet materials [221]. The DC-link voltage is nowadays normally designed around 400V but it is expected to raise up to 800V where wide-bandgap or silicon-carbide devices are used on the power inverters [222]. Furthermore, automotive manufacturers have started integrating in common enclosures the inverter with the other vehicular power electronics systems in order to minimize connections, reduce size and weight and reuse common functionalities [222]. Additionally, the use of multi-phase and multi-level drivers have been exhibited as an attractive solution to improve torque-density and handle DC-link voltages higher than 800 V respectively [223]. On the other hand, regarding the energy storage in batteries and their charging systems, consistent work has been exposed towards fast and wireless charging [224, 225] and flexible vehicle/grid interaction [221].

As the actual litium-ion based technologies are arriving their theoretical specific energy limits, some research on the use of solid-electrolyte based litium batteries and hybrid energy storage systems (including supercapacitors or fuel cells) has been proposed to favor longer operating cycles, improve power density and increase lifetime [226]. It is also noteworthy the relevance of Battery Management Systems (BMS) to monitor and control proper States Of Charge (SOC) and State Of Health (SOH) in the battery packs [226]. In future VEDS, the BMS will be required to be a functional aspect of a universal software able to monitor and control all the relevant low and high voltage electrical components and systems part of the entire E/E architecture. Finally, to enhance VEDS resiliency, some efforts have been proposed to achieve energy assistance from the high-voltage to the low-voltage side during normal operation modes [227, 228]. Nevertheless, these approaches should be extended to critic or extreme conditions.

3.7.5 Hardware in the Loop (HiL)

VEDS design and simulation platforms can also take significant advantage from HiL systems in order to attain accurate dynamic models for the different electrical elements, emulate if needed some system components (sensors, ECUs, actuators, mechanical parts) and thus refine and validate the numerical methods. To do so, some HiL experiences in vehicles should be considered and adapted. For instance, HiL has been employed to emulate vehicular ECUs, improve plant models, facilitate rapid-prototyping and perform standardized tests [229, 230]. Research on the use of HiL for assisted and autonomous driving has also been presented [231–233]. An analysis on mechanical-electrical traction shift in HEVs is exhibited in [234]. Additionally, an Internet-based HiL testbed for HEVs, able to integrate distributed vehicular subsystems can be found in [235].

3.8 Conclusions

- As a consequence of new regulations, novel electrification trends and higher user demands, the complexity in VEDS has significantly increased in the last years. Hence, VEDS design represents a highly demanding step in the product development process of a present-day vehicle. Some aspects should be taken into account for a proper design such as optimization of cable lengths and paths, integrity of the wiring harnesses, electromagnetic compatibility, robust and secure power distribution among others.

- Despite the fact that VEDS are considerably smaller than conventional power distribution systems, they present the typical components of modern urban networks such as the power supply (battery), protection devices (fuses), intricate conductors paths, DC energy conversion elements (Electronic Control Units - ECU) and different power consumers. Contrary to urban distribution networks, simulation in VEDS is still not a common practice as manufacturers so far have mainly counted on empirical approaches and predefined guides to size conductors and protections that are expected to fulfill specific requirements related to voltage drops, fuses matching, wire temperatures and maximum currents for instance. Hence, the incorporation of electrical simulation in VEDS would permit to study in advance different network topologies and scenarios in a versatile manner, so that undesired electrical conditions can be anticipated in an early stage of the design process. Under this approach, the timing of the prototyping stage could be reduced as this phase would be mostly employed to validate prior VEDS designs achieved via simulation. Simulated scenarios can include the analysis of vehicle conditions that are complex to be reproduced in prototypes or on-the-road tests. For these circumstances, the development of a computer tool that allows an adequate VEDS visualization and simulation would be of high significance for the automotive industry.

- VEDS are intricate systems conformed by distinct elements such as fuse-boxes, splices, couplings, ECUs and consumers. These elements are interconnected considering assembling constraints by means of electrical harnesses containing bundled conductors. Every harness has a tree topology conformed by nodes and segments. This configuration translates into a mostly radial power distribution network. The wiring design of a vehicle is an elaborated process that takes into account a modularity strategy. It has been seen that some steps are necessary to create data files containing the harnesses manufacturing needs. In this regard, the data containers holding the greater amount of electrical information from the harnesses are the XML files. Nonetheless, the previous files do not contain all the required information to infer a complete electrical understanding of the network topology. Hence, additional files were also needed to perform the entire data pre-processing. Once the data pre-processing has conveniently organized all the electrical information in a set of CSV files, further visualization and simulation tasks can be held.

- Considering that VEDS are deployed using DC current, the power flow analysis can be simplified at some extent as the beginning of Section 3.6 elaborates. In respect to the employed power flow methods, the Meshed-Network Backward/Forward Sweep (MN-BFS) and the Current Injection (CI) techniques were considered as they have been exposed to perform better than traditional approaches (such as Newton–Raphson and Gauss–Seidel) in terms of computational intensity in radial or slightly meshed DC networks. Indeed, we have reported that the BFS technique achieves convergence eight times faster than the Newton-Raphson method in a test DC network. Nonetheless, contrary to the MN-BFS approach, the CI method does not require any network topological modification for the mathematical modelling with further compensation algorithms. This resulted in the CI tactic presenting a three-fold reduction in computing time when compared to the MN-BFS method in a mid-sized test DC network under different load conditions. Moreover, as the CI method is suitable for bidirectional power flow studies, this method is the preferred approach to also procure a rapid adaptation of the present methodology in the analysis of future on-board vehicle networks, where it is expected to exist higher interaction between the high-voltage traction system and the low-voltage network (VEDS).

- The custom-made data pre-processing stage along with the CI power flow method have been validated beyond simulation in a door wire harness test bench and a prototype vehicle, exhibiting satisfactory results. This encourages further research and integration of the here presented methodologies in order to achieve enough reliability and robustness that will permit the incorporation of power flow simulation as a required step in the VEDS design process.

- To provide sufficient insights to researchers related to vehicle on-board electrical networks, novel trends within this domain have been presented and discussed. These deal with advanced thermal analysis, new electric/electronic architectures, electronic-fuses, mild hybrid power trains, hardware in the loop and high voltage networks. With no doubt, these aspects should be given enough attention as they will play a significant role in the development of forthcoming automobiles.

> ”Simulations create some kind of
> parallel world in which
> experiments can be conducted
> under more favourable conditions
> than in the “real world.” ”
>
> Roman Frigg - Swiss philosopher, 2009

Chapter 4

Computer platform for visualization and simulation of VEDS

4.1 Introduction

This chapter firstly provides some background about the role of computer simulation in the automotive industry and specifies for the case of Vehicle Electrical Distribution Systems (VEDS). Later, the software development cornerstones employed in the present project are presented and individually discussed. Next, the need to include Visual Analytics (VA) strategies is commented to then elaborate on the development of suitable electrical schematics for VEDS. The incorporation of tailored VA-based functionalities is also addressed.

4.2 Computer simulation in the automotive industry

As part of product design in the industry, computer simulation nowadays plays a major role given its benefits such as high analysis capacity, prototyping reduction, improved product quality and attractive cost-efficiency [236]. This is the case of automotive manufacturing where specialized simulation platforms are being employed to meet current performance standards, newest environmental policies, superior product reliability and higher user demands. Conventionally, the majority of simulation tools in this sector have mostly focused in aerodynamics, vehicle collision, autonomous driving, communication systems, electric drive-train and energy management [237]. Moreover, the latest simulation trends in automotive systems deal with advanced functionalities such as scalable models for autonomous-driving cars [238], energy-efficient networking for electric vehicles networks [239] and Internet of Vehicles for automation and orchestration [240]. However, regarding Vehicle Electrical Distribution Systems (VEDS) which are responsible for delivering power supply to the different consumers within a vehicle (except by those related to electrified traction); few research has been evidenced. In this regard, to close the gap in this ambit, we have recently presented tailored visualization and simulation approaches for VEDS [196, 237, 241] that have been reported in this thesis.

Regarding the commercial computer tools related to VEDS, software such as Power Net Simulation and Simulink permit to examine overall energy optimization strategies considering general models for the battery and the loads but lack on analyzing in detail the on-board EDS in full network models containing all wires, fuses, ECUs, loads and other components. Other tools like EBCable, Vesys, Eplan Harness proD and LDorado are commonly employed in the automotive industry and permit the design and the visualization of VEDS. Nevertheless, the previous tools are mainly designed for Computer-Aided Design (CAD) and manufacturing data exchange between Original Equipment Manufacturers (OEMs). Some of these platforms allow the automatic routing of wiring schematics for assembling and documentation duties. For these needs, the inclusion of Visual Analytics (VA) strategies or power flow analysis has not been traditionally considered in the automotive sector. The kind of visualizations that one could find in these tools are as Fig. 4.1 and 4.2 expose.

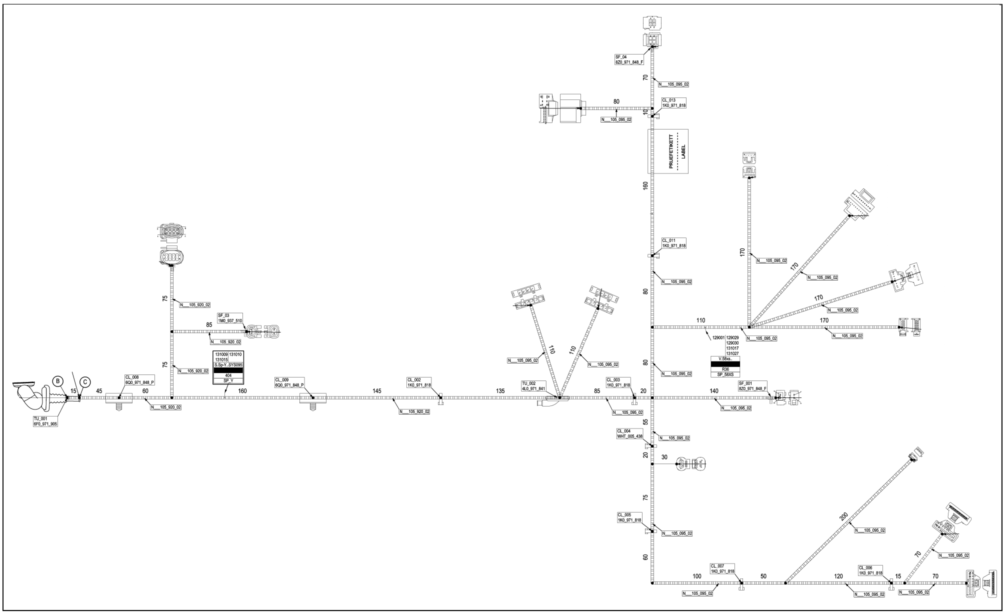


Figure 4.1: Harness-level view of software commonly employed in the automotive industry

Beyond the design tasks, other software like Harness Studio, Siemens Solid Edge and Saber RD have recently included additional modules to perform VEDS simulation. However, these computational packages do not provide detailed information regarding those add-ons, they neither specify the modelling parameterization of the different components and the included numerical methods to perform power flow analysis.

Moreover, considering the inherent complexity of VEDS (explained in Chapter 3) and the need to permit vehicle design engineers an early detection of unsuitable configurations, such as those leading to undesired voltage drops, excessive temperatures or mistaken components sizing, the development of versatile visualization and simulation platforms in this ambit is compelling. To do so, it is worth to highlight that a large-scale industry like the automotive presents particular characteristics given its organizational intricacy, higher specialization and distributed administration [242]. In the previous reference

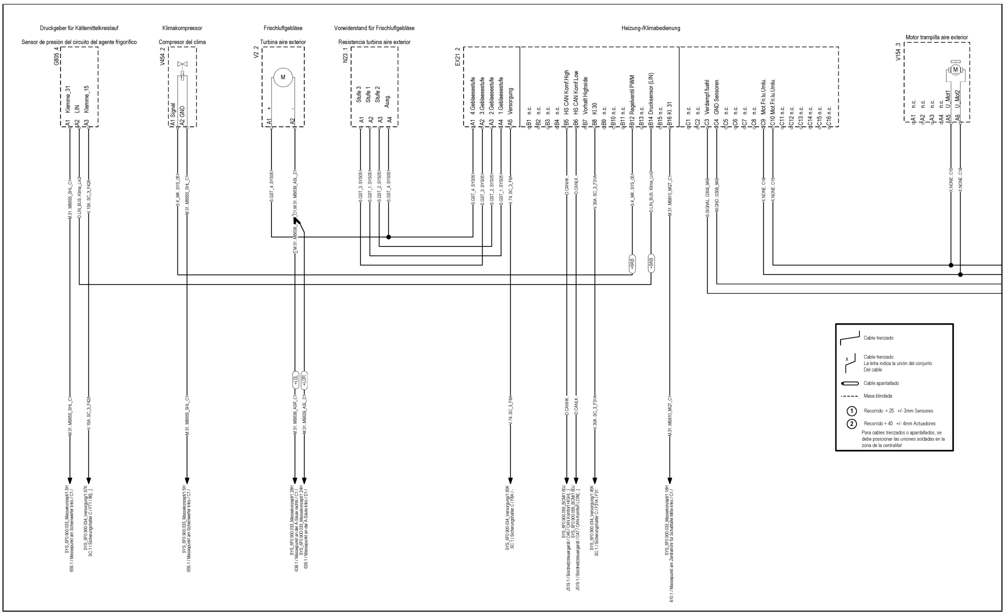


Figure 4.2: Wiring-level view of software commonly employed in the automotive industry

the author also denoted that "large companies provide a lot of interesting challenges and complex real-world datasets for information visualization research". This exhortation and the lack of specialized tools in this ambit motivate the development of a custom-made VA-based computational platform oriented to the simulation and validation of VEDS, which is part of the scope of this thesis. To do so, the recommendations exhibited in [242] for software development in this ambit have been considered. These can be synthesized in some key-points such as:

- Learn from the domain-experts practices.
- Efficiently coordinate activities between developers and experts.
- Conjugate software usability and aesthetics.
- Favor smooth software installation and support.

- Be aware about confidentiality policies, required permissions and publishing conditions.
- Develop a custom-made solution based on close cooperation.
- Procure productive time-constrained meeting.
- Try to integrate all the required data and processes in a single platform
- Favor incremental prototyping considering usability requirements.

Taking into account the aforesaid suggestions and the particularities of the present project, six relevant software development cornerstones to deploy VEDS visualization and simulation were defined (see Fig. 4.3). Among these we have: (i) custom-made data pre-processing and (ii) effective power flow simulation (both elaborated in Chapter 3), (iii) agile software development, (iv) use of open-source tools, (v) web-based architecture deployment and (vi) the inclusion of Visual Analytics based techniques. The latter four cornerstones are discussed in the next sections.

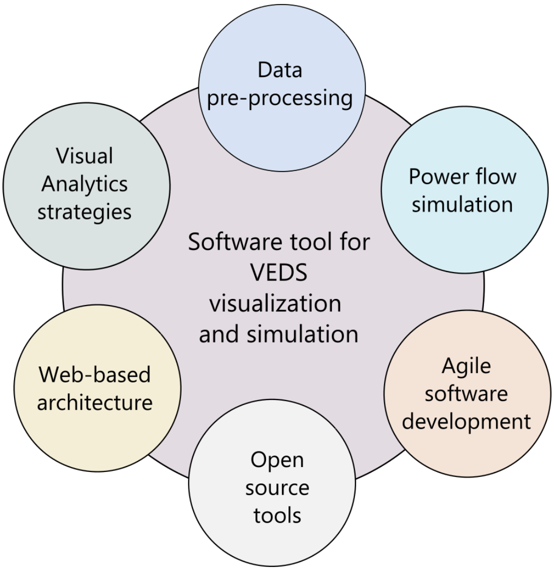


Figure 4.3: Computer tool foundations

4.3 Agile methodologies

Plan-driven traditional software development, where sequential and rigid temporal stages exist for the different phases of the process, has been reported to present some drawbacks such as focusing on goals rather than teamwork, delayed working versions and reduced adaptability to rapid-changing requirements [243, 244]. Based on these evidences and the aim to develop a rapid-testing yet robust computational tool to be used in a daily basis by engineers related to VEDS, agile methodologies [245] were considered as a cornerstone to leverage team productivity and collaboration. Moreover, these approaches have proved to shorten the process in automotive software development [246]. For these reasons, in the present work the targeted Scrum agile tactic framework [247] was chosen and adapted according to the time-constraints and profile of the personnel assigned to this project. Nevertheless, the Scrum methodology premises were tried to be satisfied as much as possible to take advantage of its benefits. In this regard, the Scrum Team consisted on a small, multi-disciplinary group of researchers and software developers organized in different roles:

- The Product Owner who decided what was required to be done and prioritized the Product Backlog which is an ever-evolving list containing all the software requirements.
- The Scrum Master who removed impediments, facilitated meetings and guaranteed that Scrum practices were satisfied.
- A Development Team that generated product increments.

Scrum splits a project into cyclical increments named as Sprints. For medium-high complexity projects, a two week Sprint is suggested to procure rapid iteration and incorporation of new functionalities. Depending on the Scrum Team members availability, the so-called Daily Scrum meetings were conducted onsite or remotely to review the advancements (activities done or in progress), comment any obstacles, find solutions and share future planned work.

In every first Daily Scrum, the Sprint Planning took place to socialize the Sprint Backlog, being this the set of Product Backlog items (User Stories) chosen for the Sprint. For every item, the corresponding daily activities were listed in a spreadsheet that served as the Scrum Board. In the last Daily Scrum of the Sprint, the results of the work were evaluated and accepted if they fulfilled the expectations; this as part of the Sprint Review. Finally, a Sprint Retrospective took place when needed to propose improvements in the Scrum process. All the previously described Scrum methodology is exposed in Fig. 4.4.

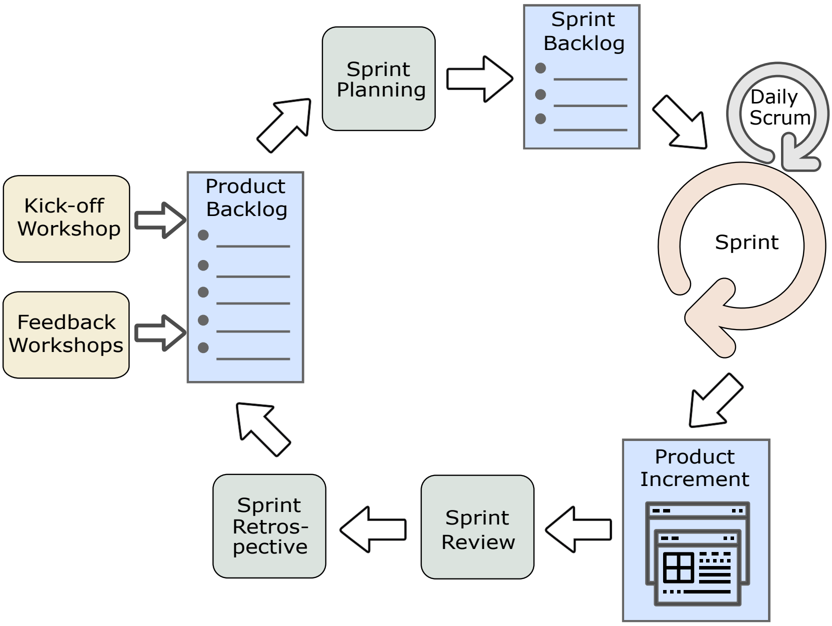


Figure 4.4: SCRUM process

In addition to agile software deployment and in order to enhance intrinsic knowledge from VEDS experts, user-centered design (UCD) [248] perspectives were incorporated into the SCRUM methodology as suggested in [249]. Therefore, to develop a functional tailored software by means of a proper understanding of the nature of the problem, workshops were carried out to gather all the user needs, suggestions and perspectives concerning the computational tool. The kick-off workshop took place prior to the beginning of the Scrum process and gathered potential users and engineers related to VEDS design and testing. In this meeting, some context on the project was initially exposed by the Scrum Team to the assistants regarding the time planning, development software tools, the need for users involvement, expected outcomes in virtue of preceding related work, among others. Then, a simple software process-flow [250] was conducted to propose a basic procedure to upload, visualize and simulate an electrical harness. This was achieved by means of low-fidelity prototypes (wireframes) [251] which are graphical representations (layouts) of the computer tool containing the most relevant interface elements and content. After this, comments from the participants were received regarding their impressions and suggestions on the process-flow, the wireframes and the corresponding interface elements. This was highly useful as it permitted to understand users' needs and therefore make a proper initial definition and item prioritization of the Product Backlog (See Fig. 4.4).

Also, regular feedback workshops were organized to receive opinions and validation of the interface process-flow and the proposed (general and detailed) VEDS graphical representations. On this, for the general illustration (harness level visualization), it was agreed to exhibit schemes familiar to other software tools commonly employed by VEDS engineers. On the other hand, for the detailed representation (wire-by-wire visualization), the regularly used electrical layouts were not considered as an starting point as they did not permit and straightforward understanding of the electrical routes and connections.

4.4 Web-based architecture

When talking about key pillars that can significantly enhance the capabilities of simulation tools, web and cloud-based architectures are currently an accelerating trend given their capacity to boost collaboration, increase flexibility and tackle complex product-oriented designs [252]. Moreover, these web-based deployments present advantages not only for end-users but also for applications developers given the convenience of remote access, usage of any operative system and simplified software installation and upgrading. Hence, web and cloud-based computing have been recognized as the third revolution in the Information Technology (IT) industry [253]. Due to these benefits, in the last years different simulation tools from the electrical engineering field have been developed or updated to include web-based functionalities. This tendency has been applied with varying architecture complexity depending on the magnitude of the projects, going from electric-electronic circuits schematics [254–257] and arriving to power system analysis, cost optimization and state estimation as reference [258] elaborates. This gives us an insight of the relevance of web-based technologies to develop a flexible, scalable, collaborative and easy-to-maintain simulation tools to face the challenging design demands of VEDS.

In the conventional paradigm of traditional simulation tools, each user has an individual software copy installed in his own computer. Under this approach, the software and the computing resources are confined and scalability is not possible. On the other hand, in cloud and web schemes, an IT service provider supplies computing resources to clients on-demand. This allows the stringent modelling and simulation tasks to run on robust vendor servers (Back-End) while the clients' workstation (Front-End) mainly focuses on the user input and the interface display duties. This alleviates hardware upgrading in final users who are only required modest computational capabilities and a rapid reliable Internet or proprietary network connection which is becoming easier and more affordable day by day. Therefore, users and programmers can remotely access the application for its use or debug respectively, and thus simplifying software licensing, maintenance and updating [259].

Taking advantage of the former benefits, web-based simulation software and research have been carried out to conduct electrical network studies. Most of these initiatives have primarily focused within the power systems analysis scope. In this field, some open source and commercial tools have reported to include web-based architectures. For instance, we have InterPSS [260], MatPower [261], Neplan [262] and Simulink from Matlab [263]. With respect to web/cloud-based research in this ambit, a few works have been reported. The initial contributions dealed with power flow and contingency examinations [264], dynamic transient assessment [265], distributed generation allocation and dispatch [266], cost optimization by the use of cloud-computing [267] and PMU-based estate estimation [268]. On the other hand, the latest studies are associated with a PHP-language application library [269], planning analysis for the ISO New England system operator [270, 271] and a hybrid AC/CD network cloud-based simulation [272].

The most common architecture in the aforesaid web-based simulation platforms is a 3-tier scheme (web browser, web server and simulation engine). Given its maturity [269], this was also the architecture implemented in the present project as Fig. 4.5 exhibits. It is worth mentioning that only open-source web development tools have been employed to do so. At the client side, the user access the application with a web browser. Here the Front-End interface was deployed using the Angular framework [273]. The latter permits a rapid and well-documented design of aesthetic, dynamic, single-page applications by means of hierarchically integrated components, templates and services [274]. Additionally, Javascript-based D3 library [275] has been used to generate customized Scalable Vector Graphics (SVGs) for the interface. When the client inserts the corresponding URL, the browser requests the page (via HTTP) from the web server that hosts the page. Then, using the Node.js environment [276], the server returns the page to the requesting IP address so that the browser renders and displays the interface. Later, when computing intense data preprocessing or simulation is needed by the user at the Front-End, a new particular request is made again to the web server which now passes this specific petition to the simulation engine. In this work, this latter is settled on the same Back-End server but it can be hosted in another remote server if needed. It was deployed using Python language given its convenient libraries for data preprocessing and development of tailored power flow analysis. In this stage, the simulation engine executes the necessary scripts and returns the corresponding data to the Front-End via the web server. As previously mentioned, the simulation engine performs two main tasks: data preprocessing and power flow analysis. For further insights on the entire process, a complete simulation workflow is exemplified with a case study in Chapter 5.

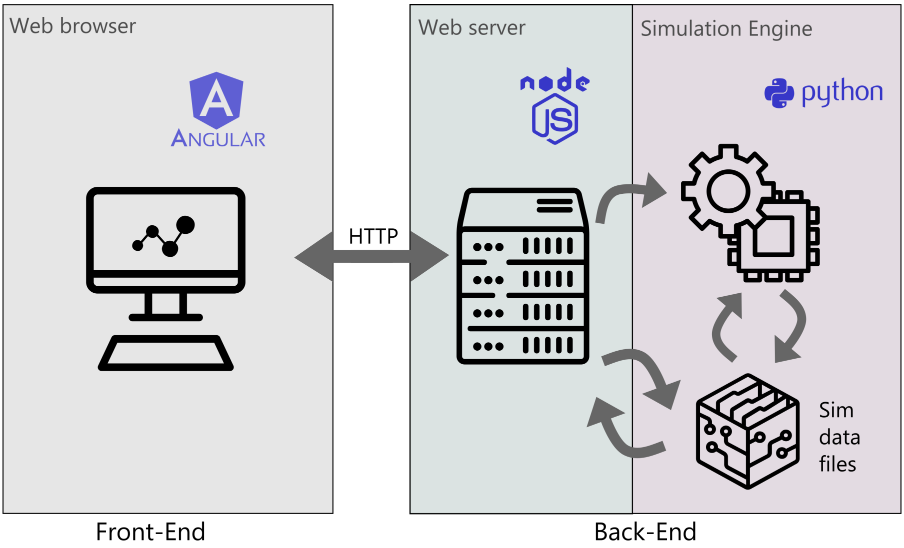


Figure 4.5: Web-based environment architecture

4.5 Open source tools

Well supported programming languages (Javascript, Python), well-known data-base managers (SQlite [277]) and specialized open-source libraries and frameworks (e.g. D3 Data-Driven Documents [275], Node.js [276], Angular) have been used in this project. For instance, Javascript-based library D3 is nowadays being employed in a broad variety of information visualization projects as it permits with ease to add interaction and animation to complex datasets by using Scalable Vector Graphics (SVGs). Moreover, D3 has been recently used to increase the awareness on power distribution infrastructure by means of aesthetic interactive representations [278]. Representative open-source frameworks and libraries that have been employed are specified in Table 4.1

Table 4.1: Employed Open-Source Tools (Frameworks and Libraries)

Tool	**Used to**	**Front-End**	**Back-End**
Angular	Build the front-end interface with a single-page client application approach by means of HTML and Typescript code.	✓	
bootstrap	Create responsive layout in developed web pages as it includes HTML and CSS based design templates.	✓	
D3	Create dynamic, interactive data visualizations using Vector Graphics (SVG). Useful to create the harness-level and wire-by-wire level schematics.	✓	
file-saver	Save files on the client-side when needed. Mostly when the users add input data.	✓	
jszip	Create, read and edit .zip files added by the user or interchanged between client and server.	✓	
papaparse	Parse CSV files	✓	
rxjs	Compose asynchronous or event-based functions such as elements search boxes.	✓	
xlsx	Create Microsoft Excel .xlsx files when exporting simulation data.	✓	
cors	Allow or block requested resources on the server based on the origin of the HTTP request.		✓
express	Handle http requests between Front-end clients and server.		✓
extract-zip	Unzip .zip files coming from the Front-End.		✓
fs	Store, access, and manage data and folders in the operating system.		✓
Node.js	Develop the platform to support the entire Back-End application as a run-time environment.		✓
Python	Handle all the data pre-processing and power flow simulations.		✓
SQlite	Manage data bases regarding users, permissions and simulation scenarios.		✓

4.6 Tailored Visual Analytics

4.6.1 Automatic generation of electrical diagrams

For a better representation of VEDS, two types of visual schematics have been implemented: the General View and the Detailed View. The first presents a broad harness-level outlook of the nodes and the harness segments that interconnect them. These segments are drawn according to their from-to nodes that were tabulated in the *Segmentsdata* file that was generated in the pre-processing stage as previous chapter described. It is worth mentioning that not all the nodes are related to electrical needs. That is the case of mechanical fixations, which stand for a high number of nodes that are relevant for the harness construction but negligible for the power flow simulation. It also must be noticed that every segment represents a bundle section containing different cables whose characteristics are defined in the *Linecode* file. Therefore, a single wire may have a number of segments from one edge to the other. To correlate the specific path of every cable in the *Linedata*, the *Routesdata* file contains for every wire the different segments it goes through. For the General View, the positioning of the elements is obtained scaling down the XY coordinates of the *Nodedata* according to the available screen size in pixels. To facilitate a cleaner visualization, only the electrical nodes and segments present in the studied vehicle configuration are shown and also the nodes related to mechanical events are left aside. This filtering is achieved by means of the *Nodestodraw* and *Segmentstodraw* files. Among the type of electrical nodes, we have: (i) battery, (ii) main fuse box (HSBfuse), (iii) interior fuse box (EMBOXfuse), (iv) engine fuse box (LVIfuse), (v) coupling, (vi) splice and (vii) consumer. The power characteristics and the description/protection of the consumers are inferred from the *Loaddata* and *Loadwithfuse* correspondingly. The pseudo-code in Algorithm 5 elaborates on the overall process to create the broad General View and the wire-by-wire Detailed View. As it can be seen, both views share the initial stages and the last coding phase which are related to make meaning of the .CSV files and setup the interface functionalities respectively.

```
Require: .CSV files resulting from the preprocessing stage (e.g.: Gendata,
    Nodedata, Nodestodraw, Segmentsdata, Loaddata, Linedata ...)
Ensure: General and Detailed Views
Create the web-interface elements and components
    using the Angular framework
Parse input .CSV files
Convert input files into data objects (e.g.:
    NodedataObj, LinedataObj, SegmentsdataObj... )
Correlate nodes with consumers and their protection fuses matching
    LoaddataObj, LoadtitlewithfuseObj and NodedataObj
Correlate harness segments with the wires and their routing using
    SegmentsdataObj, RoutesdataObj and LinedataObj
Infer nodes and segments to draw considering NodestodrawObj and
    SegmentstodrawObj
Create the SVG containers and configure their functionalities such as
    zoom and panning
if The General View is required then
    Scale down the XY positioning of nodes from NodedataObj considering
        the available screen size
    Use D3 library to draw nodes, segments, patterns, texts and others
end if
if The Detailed View is required then
    Infer child-parent correlation in LinedafirstneighObj for main harnesses
        and LinedaObj for secondary harnesses
    Use D3.tree to give tree-hierarchy structure to the data
    Use base D3 library to draw nodes, links, texts and others
    Detect and individually draw redundant links
end if
Assign colors and styles to the different elements
Create and setup additional elements and interface functionalities (e.g.:
    interactive legend, tooltips, mouse-over highlighting, elements search-box,
    contextual menus, draggable nodes, correlation between views,
    simulation results export)
```

Algorithm 5: General and Detailed Views Generation

For the second view type, the Detailed View, a hierarchical wire-by-wire representation of the network is set up. This is a challenging task given the large amount of electrical elements and wires that can be present in a harness. Discarding elements related to communication and instrumentation purposes, the main harness of a modern car may have hundreds of electrical nodes for supply needs and a similar number of wires for feeding the different power consumers. As a consequence, complexity is added to automatically position all the nodes and then create aesthetic wire routing paths favoring a clean, intuitive scheme of the electrical network. In the literature, a few works report research on the automatic generation of electrical diagrams [237]. These are encompassed in the power systems domain. Some references address one-line diagrams creation considering XY coordinate constraints related to the nodes geographic information [57, 279], while in other references restrictions in the nodes positioning are not a requirement [54, 55]. In the case of vehicular EDS, the factory XY coordinates of the nodes are not determinant for a proper wire-by-wire hierarchical understanding of the network. Hence, a tailored approach based on a tree-like scheme was implemented for satisfactory forming aesthetically functional drawings. This was achieved using as a base the Javascript-powered *D3.tree* library which generates node-link diagrams that layout the connectivity between nodes in a parent-child correlation considering the tree representation algorithm exhibited in [280]. Under this approach, every child element is expected to have only one parent element. However, on-board EDS are not purely radial but slightly meshed and some cross-feedings may exist in some cases to procure supply redundancy. Therefore, redundant links existing when a child node has two or more parent nodes are detected and individually generated. The stages for the creation of the Detailed View are included in Algorithm 5.

Extracts of the type of layouts that are generated for the General and Detailed Views are exhibited in Figures 4.6 and 4.7 correspondingly. Next chapter will discuss in detail about these schematics considering case studies with real harnesses from commercial vehicles. Moreover, there it will be exposed full software workflows to provide step-by-step details about the overall simulation process.

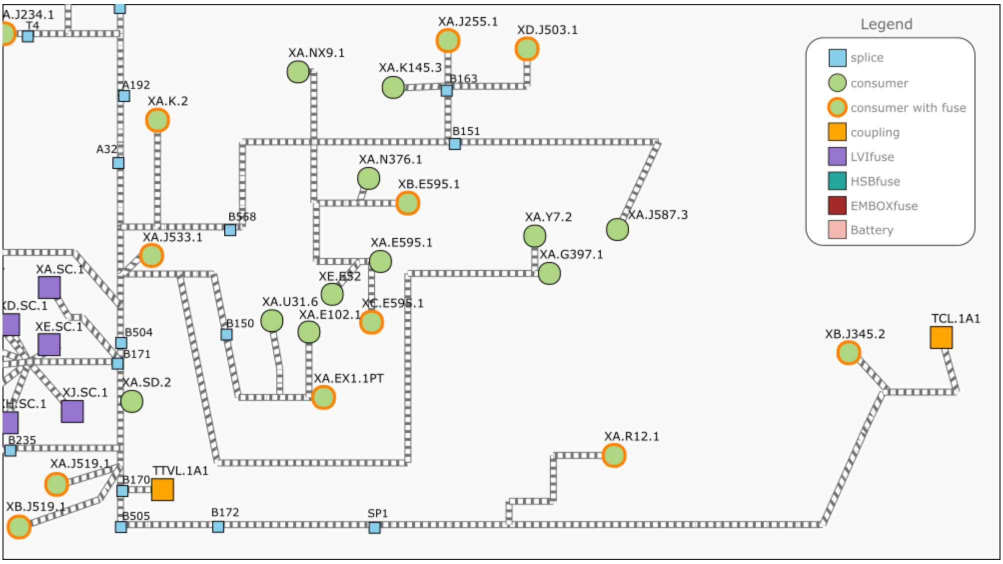


Figure 4.6: General View extract example

4.6.2 Tailored VA-basde features

To improve user experience, ease human-information interaction and permit an intuitive understanding of on-board electrical networks, Visual Analytics (VA) strategies have been enclosed into the implemented web-based simulation environment to handle the inherent intricacy of VEDS (discussed in Chapter 3). Similarly to other engineering fields, VA has been also denoted as a relevant tool for software deployment in the transportation and automotive sectors for applications related to urban mobility patterns inference [281], urban congestion-control [282] and in-car communication networks [41,283]. To adjust on-board EDS designs, engineers are nowadays demanded to consider isolated pieces of information related to construction guides, standards, electrical layouts and elements datasheets. Thus, some software platforms are typically used in parallel and thus further increasing the design complexity of VEDS. Under this

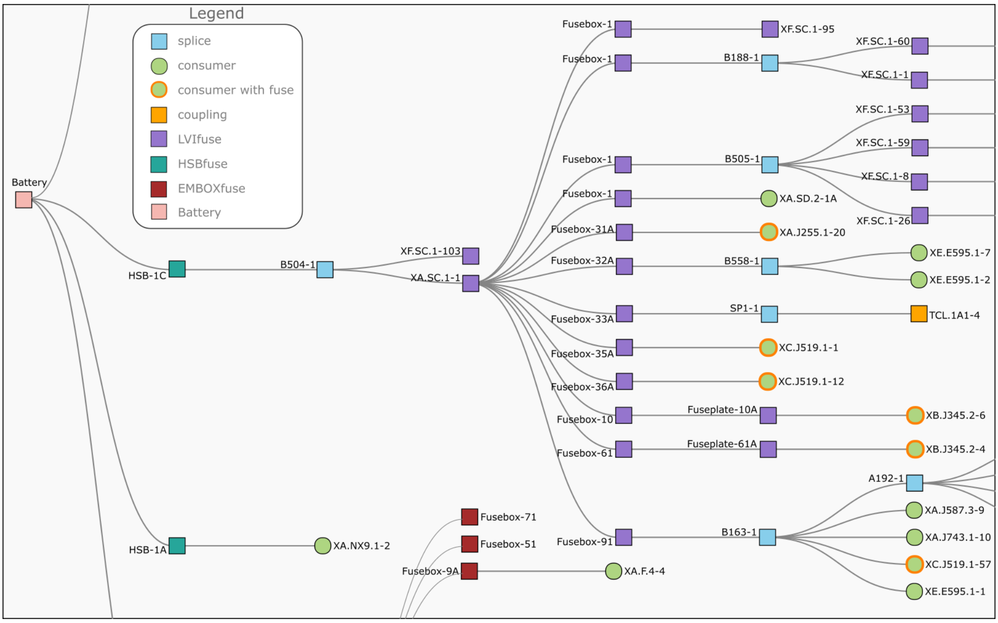


Figure 4.7: Detailed View extract example

approach, understand the network topology and infer the consequences in the modification of components and their sizing exhibits a significant challenge. To overcome this situation, the here proposed computer platform, whose approach represents a novelty application in this industrial ambit, has been developed considering three main VA-based cornerstones:

1. Automate the integration of all the necessary information. Once the user inserts the necessary factory input data files, the platform pre-process, derives and organizes all the information required for visualization and electrical simulation of the harness as the previous section elaborated.

2. Provide the user with a functional user-friendly interface. This was fulfilled by means of the following features:

   ⓶ⓐ Intuitive electrical diagrams via the already mentioned broad (General View) and wire-by-wire (Detailed View) schematics.

(2b) Elements highlighting and tooltips on mouse-over actions to ease the visualization and understanding of the selected items.

(2c) Interactive nodes legend to highlight in the schematic all the elements of the selected node type.

(2d) Preprocessing and simulation pop-up messages to keep the user informed along the process.

(2e) Pan and zoom options for a proper navigation into the electrical diagrams.

(2f) Shape and color coding of nodes, wires and harness segments to favor a prompt distinction of elements and risky simulation outcomes such as excessive temperatures.

(2g) Elements search box to rapidly locate specific wires and nodes in the network. When the desired element is found, it is highlighted and the screen is zoomed close to it.

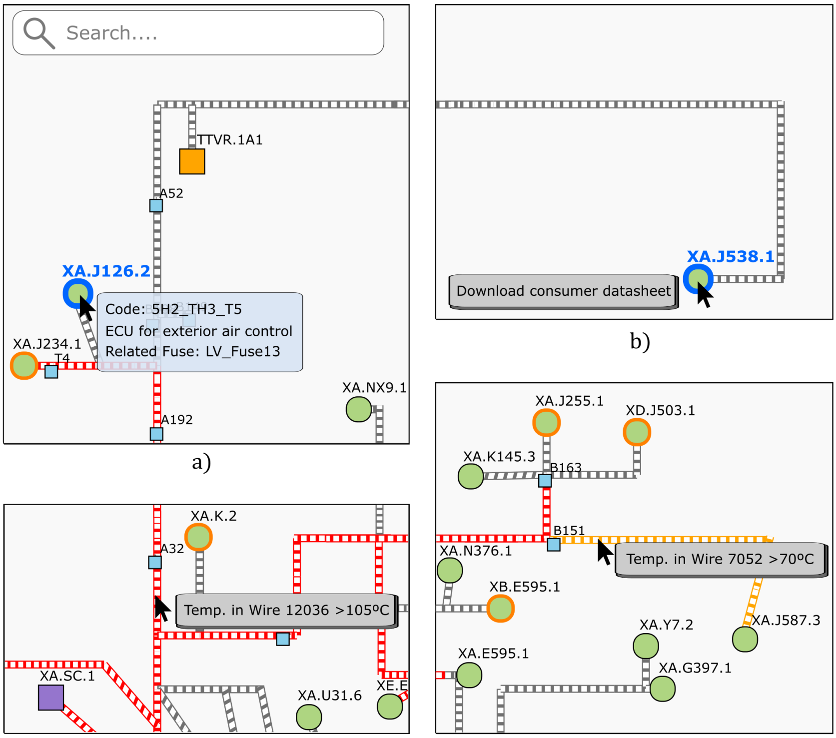
(2h) Contextual menus via right-click over elements to download datasheets (consumers) or see troublesome temperature conditions after simulation (harness segments). On the latter, once the user clicks the contextual menu related to the problematic wire in the General View, the tool automatically shifts to the Detailed View to represent the risky condition in a wire-by-wire basis.

(2i) Draggable consumer nodes in the General View to permit the user a cleaner visualization of the network.

(2j) Option to export simulation results in a spreadsheet.

Some of the above functionalities have been exemplified in Fig. 4.8 as well as in Figures 4.6 and 4.7.

3. Facilitate the understanding of the electrical behavior of the network via simulation, including:



a) b) c) d)

Figure 4.8: Examples of VA-based features. a) Elements search box and tooltip on mouse-over. Contextual menus on right-click: b) Download consumer datasheet, c) Harness with wire having temperature>105ºC , d) Harness with wire having temperature>70ºC.

(3a) Static or time-dependant power flow simulations where the user can add personalized current profiles for the loads.

(3b) Simulation logs exposing undesired conditions (wires over temperatures and fuses mismatches) as well as different tables detailing all the simulation results regarding voltages, currents and temperatures in wires.

(3c) Simulations with parameters variations where the user can modify the length, section and ambient temperature of wires.

(3d) Time plots to visualize electrical variables when consumers current profiles are inserted.

4.7 Conclusions

- Computer simulation has been permeating the industry as it contributes to higher system analysis, greater robustness, prototyping reduction and economic savings. This has been the case of some vehicular systems such as aerodynamics, autonomous driving, energy management and electrified traction. However, this is not the condition of VEDS where physical prototyping is still a common practice in early stages of the product development process. To bridge this gap, we have recently exposed custom-made visualization and simulation approaches to deal with the design validation of these on-board networks.

- Despite the fact that some commercial software tools are oriented to VEDS at the industry, these are mostly intended to design and exchange VEDS information from a manufacturing point of view. In addition, the few computer tools that lately have claimed to perform power flow simulations, do not provide specific information about their modelling and numerical methods. Hence, the development and reporting of tailored computational platforms for this aim, as the one presented in this document, represents a significant contribution in this research ambit.

- To cope with the inherent complexity of VEDS and meet the objectives of the present project, six cornerstones were defined for a successful software development process. These encompass the use of convenient data pre-processing, power flow simulation, agile software development, open-source tools, web-based methodologies and Visual Analytics (VA).

- Rapid software prototyping and team productivity were favored by adopting the SCRUM agile methodology. Moreover, initial and feedback workshops were conducted to validate the achieved and proposed functionalities with prospect users. This was highly helpful to align the software development with user-centered design recommendations.

- The mature 3-tier web-based architecture (client, server and simulation engine) has been selected in alignment with the ongoing software development revolution to afford flexibility for both, developers and users. By doing so they take benefit from simplified maintenance and update practices.
- The computer platform was entirely built using open-source frameworks and libraries. This proved to be robust enough to achieve the required software reliability and scalability.
- Considering VA-based precepts to boost user productivity, features such as data preprocessing, visualization and simulation have been incorporated in a single computer tool for this aim. In addition, different functionalities have been incorporated to deliver a user-friendly interface that delivers relevant information to the user in a suitable visual manner.
- The automatic generation of electrical layouts for VEDS has been addressed to favor an intuitive understanding of the network from a harness level (General View) and from a wire-by-wire basis (Detailed View).

”Design is not just what it looks like and feels like. Design is how it works.”

Steve Jobs - North-American
entrepreneur, 2001

Chapter 5

Case Studies

5.1 Introduction

To provide readers with detailed insights about the implementation of the deployed Vehicle Electrical Distribution Systems (VEDS) visualization and simulation platform, this chapter exposes typical simulation workflows in a step-by-step manner considering as case studies main wire harnesses from two Internal Combustion Engine (ICE) vehicles from the SEAT automotive manufacturer, the Ibiza and the Leon sedan models (See Figures 5.1a and 5.1b, correspondingly). Representative electrical characteristics of those harnesses are exposed in Table 5.1. It is worth to recall, as stated in Chapter 1, that the approach proposed in this thesis to analyze on-board electrical networks can be applied to all kind of car (e.g. ICE, electric, hybrid) independently of its traction technology. Indeed, VEDS can be seen as the electrical veins of any vehicle as they deliver energy to the different in-car power consumers, only excluding those related with electrified traction (e.g. inverter) that are in turn fed by a dedicated higher-voltage network having its own battery pack.

Figure 5.1: Seat vehicles: a) Ibiza model, b) Leon model. Taken from [284]

Table 5.1: STUDIED HARNESSES CHARACTERISTICS

Feature	Ibiza main-harness	Leon main-harness
Mechanical nodes	557	486
Electrical nodes	175	25
Harness segments	369	192
Lines	180	53
Consumers	46	18

[*] These numbers are only indicative as they refer to the specific car equipment configuration selected for these case studies.

5.2 Simulation workflow

Once the user access the computer tool with the corresponding URL in the web-browser and then provides his login credentials, the workflow process occurs as described in this section:

5.2.1 Data pre-processing and General View generation

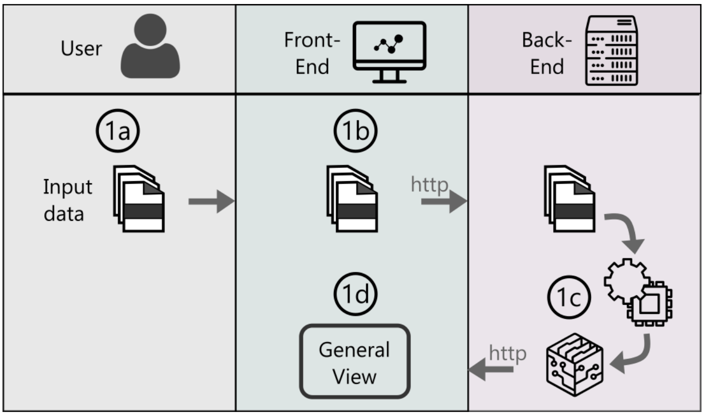


Figure 5.2: Workflow for data pre-processing and General View generation.

(1a) The user inserts the corresponding input information (see Fig. 5.2) as described in Section 3.5. Every harness has its particular network configuration and therefore has its specific input datasets. In this stage, as required by the user, he provides information related to the network configuration (battery nominal voltage, type of harness, vehicle's model, ambient temperature, among others). In addition, the user selects to either perform static (single-instant) or time-dependant power flow simulations. If the former is selected, the user provides a steady-sate current consumption value for the different consumers. On the other hand, if time-dependant simulations are chosen, time-varying current profiles for the consumers are provided by the user.

(1b) Once all the needed input data is added, the web-browser packs the information and sends it to the Back-End attached to an HTTP request.

(1c) Now, as detailed in Section 3.5, the pre-processing takes place over the input data executing different Python scripts that extract and arrange the electrical information in CSV files. The latter are now sent to the Front-End via an HTTP response.

(1d) The General View is generated as in Algorithm 5 and the user can interact with this view. For instance, he is able to drag consumer nodes to procure a cleaner visualization, make zoom or pan, see specific elements information via informative tooltips, search for elements, access to contextual menus, among other functionalities as already mentioned in Section 4.6.2. These tools aim to provide useful information and ease a rapid understanding of the characteristics of the network and its elements. Figures 5.3 and 5.6 are the generated General Views for the Ibiza and Leon main-harnesses, respectively. In those graphs, the names of representative consumers have been added in red color for didactic purposes. As it can be seen, the Leon main-harness is more simple than in the Ibiza case, given that in the former vehicle the network architecture is more decentralised and there is another main-harness that also supplies energy to other parts of the vehicle as well as to other secondary harnesses.

It can also be observed that the XY factory assembling coordinates of the nodes and segments are evidenced as the generated layouts can be associated to a top-view of the vehicle. For instance, for the Ibiza main-harness in Fig. 5.3 we have in the left side of the graph the front headlights while in the most-right part, we can see a coupling to a secondary harness related to the bumper.

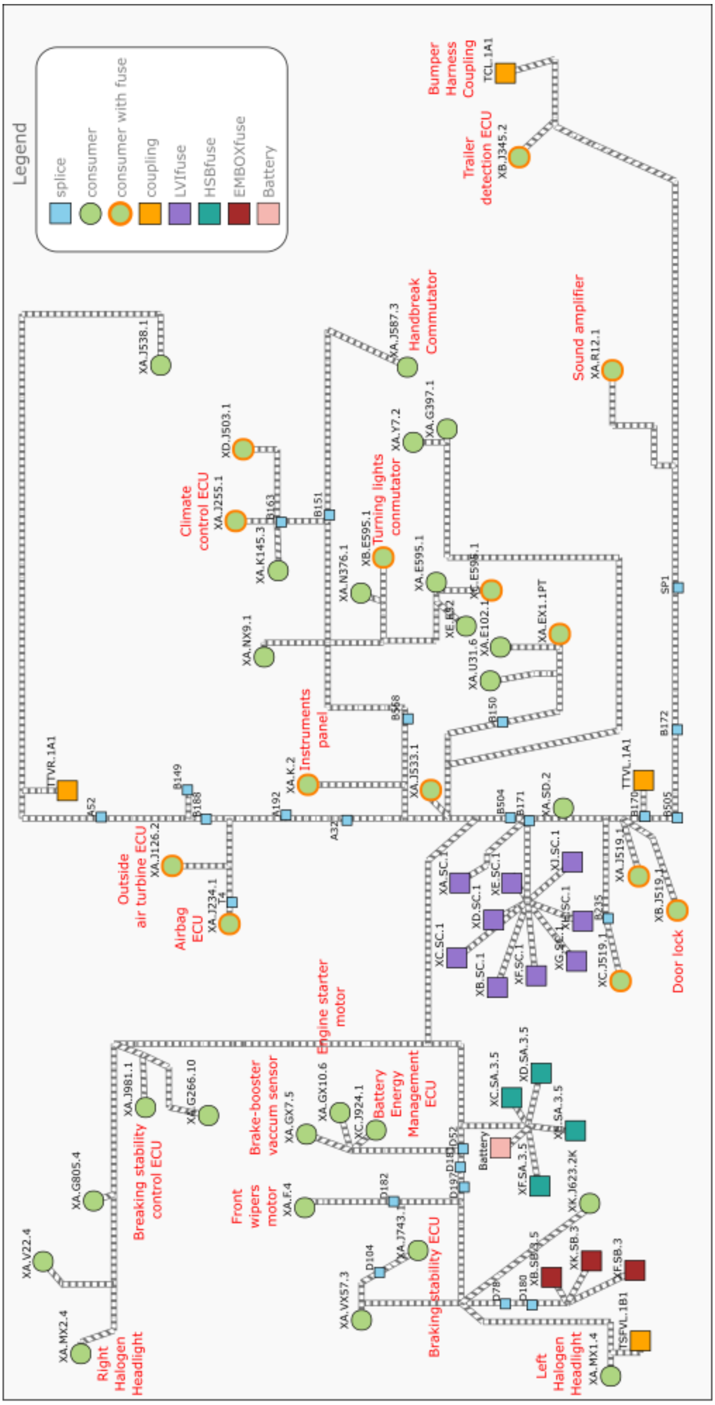


Figure 5.3: General View for the Ibiza main-harness

5.2.2 Power flow simulation and Detailed View generation

Now, to perform the power flow analysis, the necessary steps (See Fig. 5.4) are as follows:

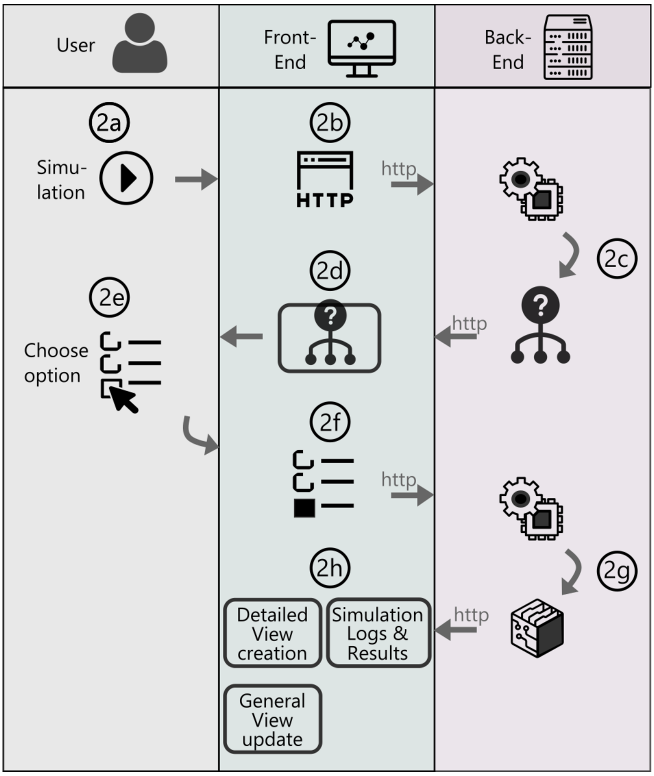


Figure 5.4: Workflow for power flow simulation and Detailed View generation.

- ⓶a The user clicks the corresponding simulation button.
- ⓶b An HTTP request is sent to the Back-End with the simulation demand.
- ⓶c A first stage of the power flow simulation, related to connectivity analysis, takes place. As in some cases the use of the input data itself is not enough to determine all the connection paths lying downstream from the main fusebox, the possible connectivity options for the isolated nodes are sent to the Front-End.

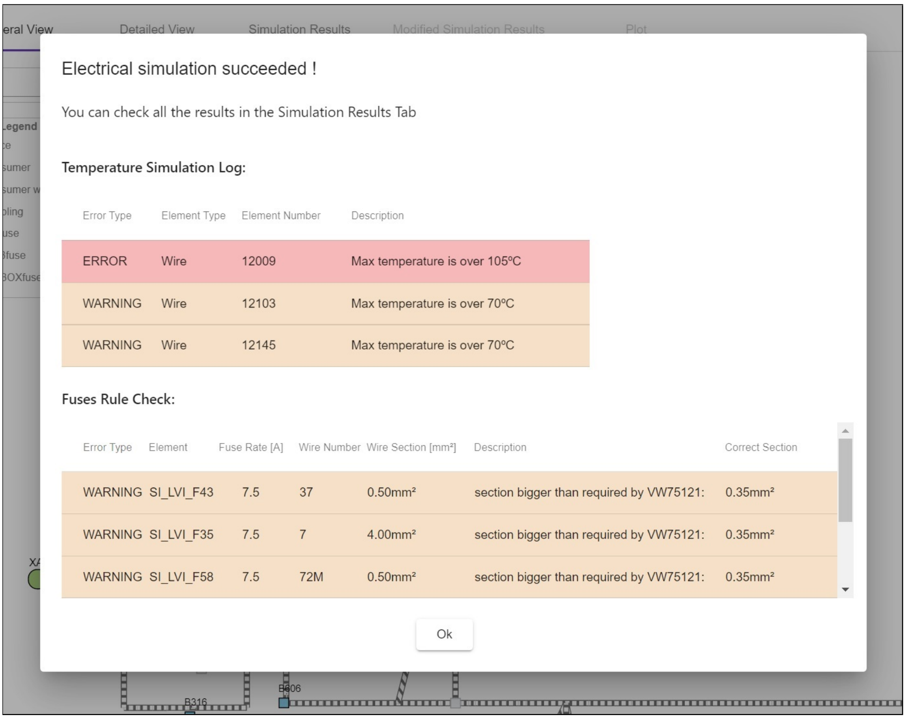
(2d) The interface displays a pop-up dialog that lists the connectivity alternatives.

(2e) The user chooses the corresponding connectivity options for the isolated nodes.

(2f) The interface sends the selected items to the Back-End.

(2g) The second part of the power flow algorithm is executed. The simulation results are organized in different CSV files, some of these are related to voltages and currents in the consumers, while the others are associated to the nodes and lines in the network. The latter (see Figure 3.6) are sent to the Front-End.

(2h) The interface shows a pop-up dialog exposing a simulation log where troublesome conditions, such as over temperatures in wires and fuses mismatches, are highlighted (See Fig. 5.5).



Electrical simulation succeeded !

You can check all the results in the Simulation Results Tab

Temperature Simulation Log:

Error Type	Element Type	Element Number	Description
ERROR	Wire	12009	Max temperature is over 105ºC
WARNING	Wire	12103	Max temperature is over 70ºC
WARNING	Wire	12145	Max temperature is over 70ºC

Fuses Rule Check:

Error Type	Element	Fuse Rate [A]	Wire Number	Wire Section [mm^2]	Description	Correct Section
WARNING	SI_LVI_F43	7.5	37	0.50mm^2	section bigger than required by VW75121:	0.35mm^2
WARNING	SI_LVI_F35	7.5	7	4.00mm^2	section bigger than required by VW75121:	0.35mm^2
WARNING	SI_LVI_F58	7.5	72M	0.50mm^2	section bigger than required by VW75121:	0.35mm^2

Figure 5.5: Simulation log message

These alarms refer to wires with steady-state temperatures higher than 70°C and 105°C that are related to stressed operation (warnings) and insulation damage (errors). Hence, the user can focus his attention on these problematic elements. The temperature modelling in wires is as described in Section 3.7.1. In this simulation stage, the new incoming files are then employed to update the General View. Here the harness segments containing wires with warnings or errors are remarked with red and orange color respectively. With a right click over these alarming segments, a contextual menu with a list of the troublesome wires appears (see harness segment that connects the Airbag ECU in Fig. 5.6). The user can access the Detailed View either choosing one of the problematic wires in the aforesaid contextual menu or by clicking in the corresponding tab. By doing so, the Detailed View is displayed as Fig. 5.7 exhibits for the case of the Leon main-harness for instance. There, the wires with over temperatures can be now individually identified and remarked. In this figure, the inclusion of mouseover informative tooltips has been also exemplified as it can be seen in the bottom-right part of the illustration. This wire-by-wire layout is highly useful to understand the hierarchical connectivity of the different elements and easily detect the paths were corrective measurements are needed.

On the other hand, the Detailed View for the Ibiza main-harness is exposed in Fig. 5.9. There, we can also observe the wires with warnings and errors for a given scenario. For a better correlation with the General View of this harness (in Fig. 5.3), the names of representative consumers have also been added. Additionally in this stage, it is enabled a tab containing all the simulation results (see Fig. 5.8). These are consumers voltages and currents, wires currents and voltage drops, wires maximum temperatures, fuses mismatches and the simulation log.

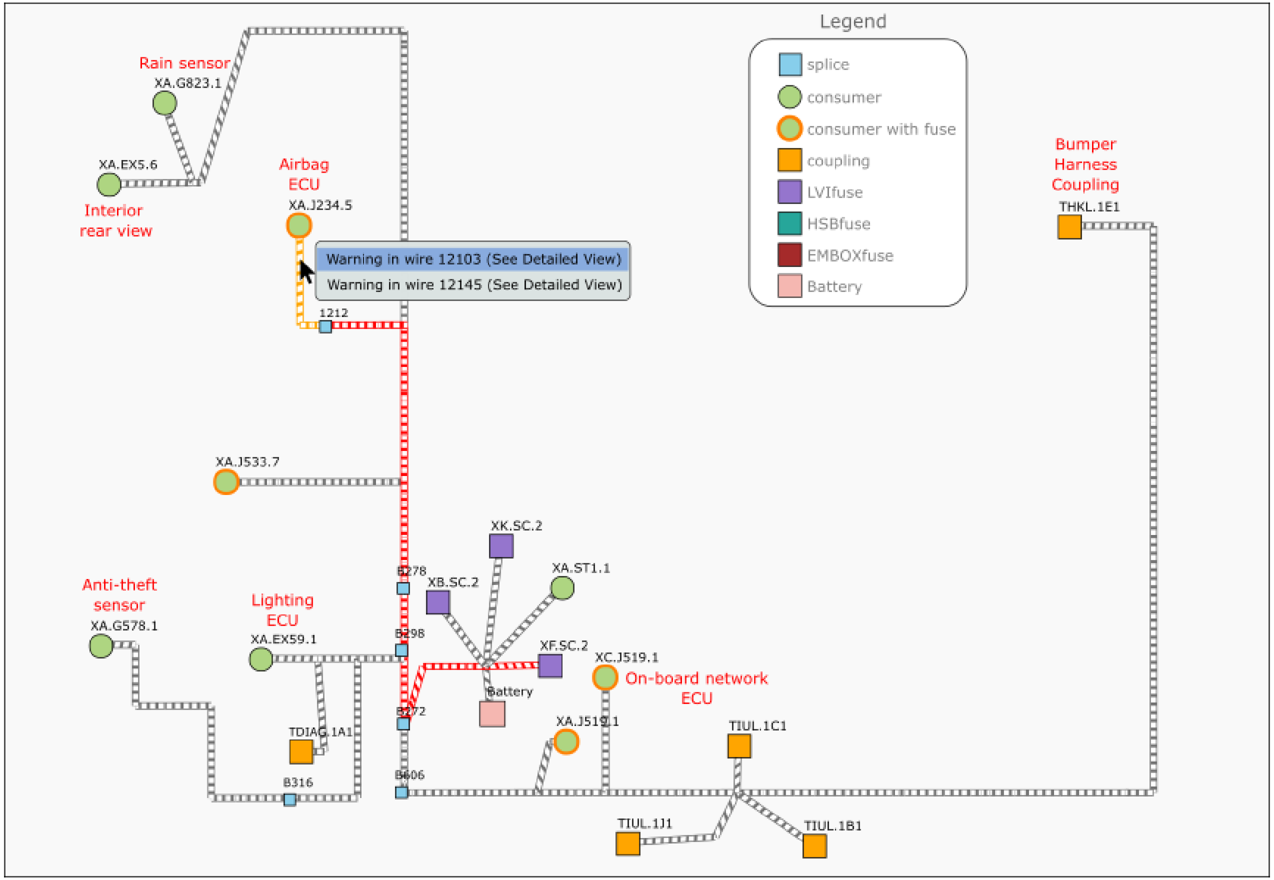


Figure 5.6: Leon main-harness General View remarking segments having wires with over temperatures. A contextual menu is also exemplified.

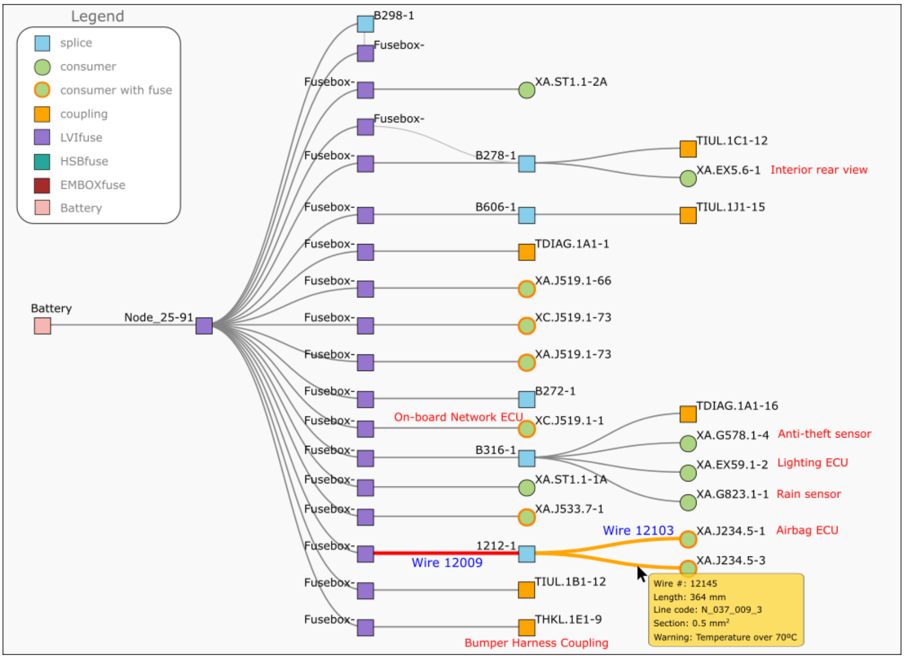
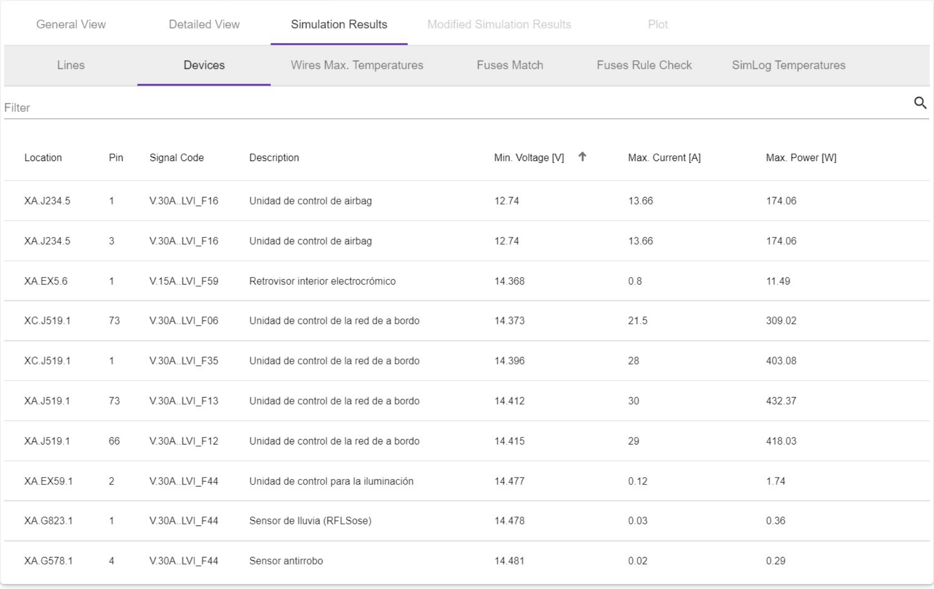


Figure 5.7: Detailed View for the Leon main-harness



Location	Pin	Signal Code	Description	Min. Voltage [V] ↑	Max. Current [A]	Max. Power [W]
XA.J234.5	1	V.30A..LVI_F16	Unidad de control de airbag	12.74	13.66	174.06
XA.J234.5	3	V.30A..LVI_F16	Unidad de control de airbag	12.74	13.66	174.06
XA.EX5.6	1	V.15A..LVI_F59	Retrovisor interior electrocrómico	14.368	0.8	11.49
XC.J519.1	73	V.30A..LVI_F06	Unidad de control de la red de a bordo	14.373	21.5	309.02
XC.J519.1	1	V.30A..LVI_F35	Unidad de control de la red de a bordo	14.396	28	403.08
XA.J519.1	73	V.30A..LVI_F13	Unidad de control de la red de a bordo	14.412	30	432.37
XA.J519.1	66	V.30A..LVI_F12	Unidad de control de la red de a bordo	14.415	29	418.03
XA.EX59.1	2	V.30A..LVI_F44	Unidad de control para la iluminación	14.477	0.12	1.74
XA.G823.1	1	V.30A..LVI_F44	Sensor de lluvia (RFLSose)	14.478	0.03	0.36
XA.G578.1	4	V.30A..LVI_F44	Sensor antirrobo	14.481	0.02	0.29

Figure 5.8: Simulation results tab.

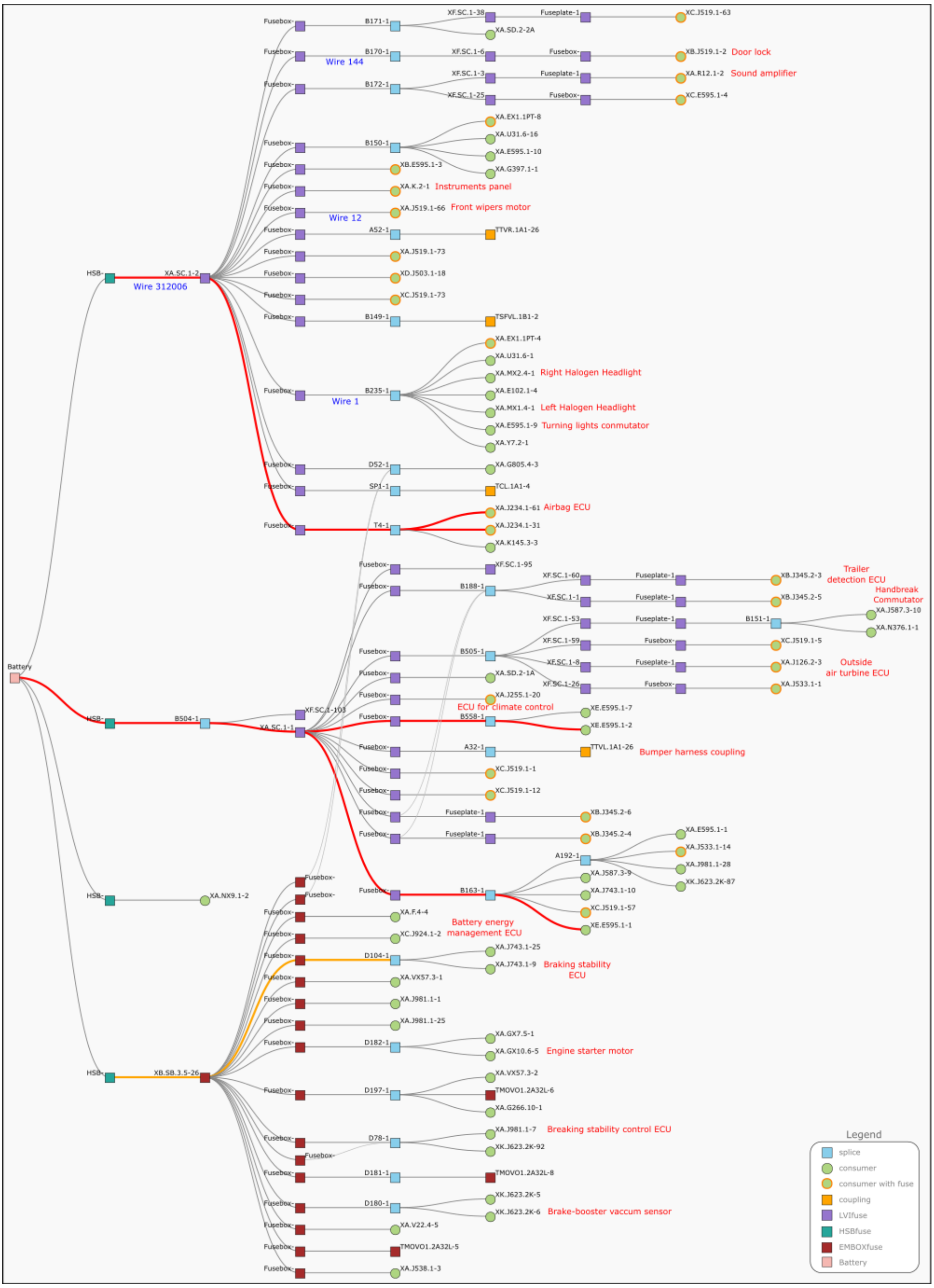


Figure 5.9: Detailed View for the Ibiza main-harness

5.2.3 Simulations with wiring modifications

To assist users to fine-tune VEDS design, the computer tool includes a functionality to perform simulations including modifications of length, section and ambient temperature in wires. This is a relevant feature as it permits designers to have a rapid feedback about the proper selection of standard wires to fulfill the needs of different testing conditions. For instance, wires length could be reduced with optimized harness distributions and probably smaller wire sections (with less weight) are sufficient to safely fulfill the consumers demands for all the contemplated circumstances. Or on the other hand, assume that it has been detected that some wires are oversized. Hence, it is relevant to evaluate if smaller wire sections are appropriate to still fulfill design requirements such as maximum allowable steady-state cable temperatures and voltage drops. In the previous analyses, the role of ambient temperature is highly significant as it permits to recreate the kind of temperature conditions that may exist in the conductors surroundings in different car compartments and under diverse testing and ambient settings. The process to perform this simulation with wires modifications (see Fig. 5.10) is as follows:

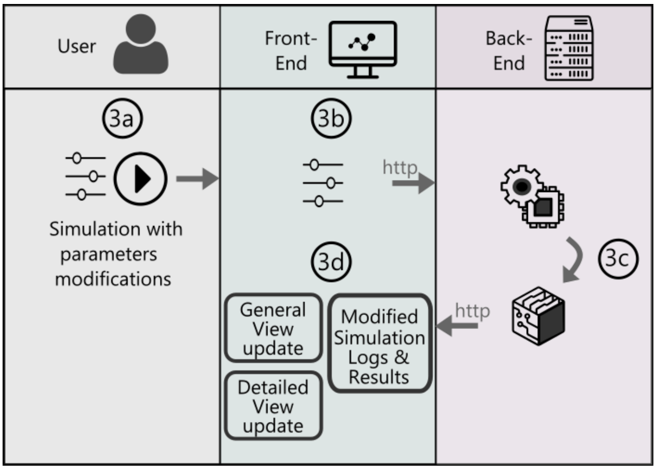
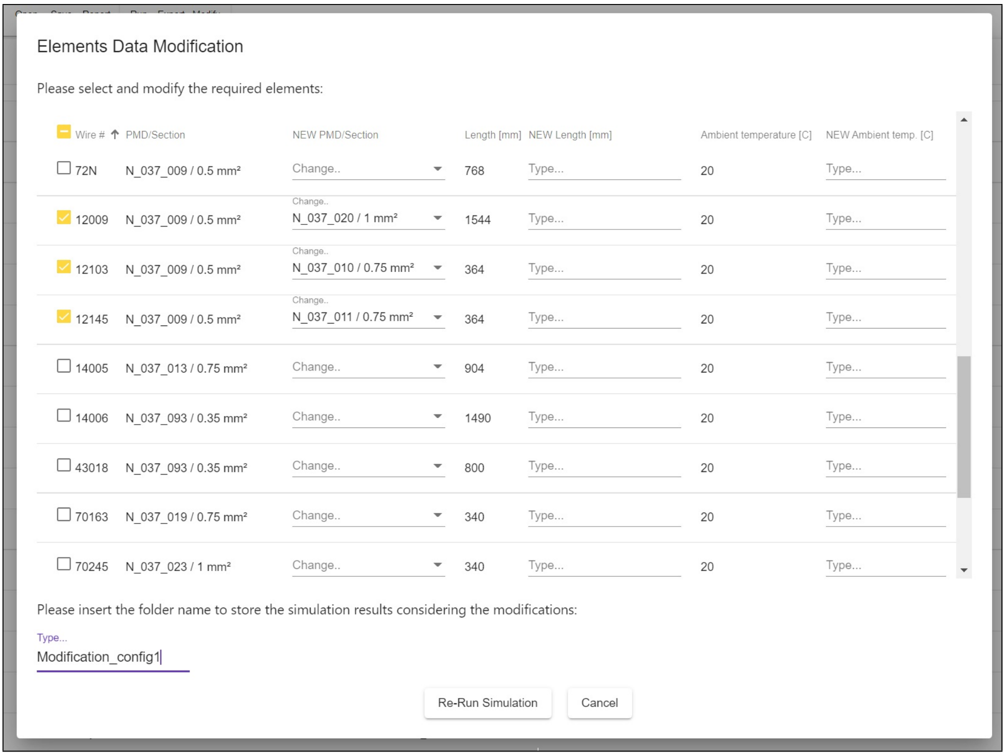


Figure 5.10: Steps to perform simulation with wires modifications

ⓐ The user clicks the corresponding wiring modifications button and then inserts in an emerging panel the desired adjustments. Let's say for instance that for the Leon main-harness in a given scenario, the simulation log (see Fig. 5.5) and the Detailed view have remarked over temperatures in certain cables related with the Airbag ECU (see Fig. 5.7). In this last figure, wires 12103 and 12145 are remarked in orange color as they present temperature warnings (each having 87°C and transporting 13.6 A) while wire 12009, which delivers energy to the previous conductors, is in red color as it exhibits an error (temperature equal to 116°C). The user intends to overcome this incident and define the sufficient wire section increments that will permit a safe operation. Hence, he modifies in the panel (see Fig. 5.11) the initial wire section (0.5 mm^2) of conductors 12009, 12103 and 12145 to 1 mm^2, 0.75 mm^2 and 0.75 mm^2 correspondingly.


Elements Data Modification

Please select and modify the required elements:

⊟ Wire # ↑	PMD/Section	NEW PMD/Section	Length [mm]	NEW Length [mm]	Ambient temperature [C]	NEW Ambient temp. [C]
☐ 72N	N_037_009 / 0.5 mm^2	Change..	768	Type...	20	Type...
☑ 12009	N_037_009 / 0.5 mm^2	Change.. N_037_020 / 1 mm^2	1544	Type...	20	Type...
☑ 12103	N_037_009 / 0.5 mm^2	Change.. N_037_010 / 0.75 mm^2	364	Type...	20	Type...
☑ 12145	N_037_009 / 0.5 mm^2	Change.. N_037_011 / 0.75 mm^2	364	Type...	20	Type...
☐ 14005	N_037_013 / 0.75 mm^2	Change..	904	Type...	20	Type...
☐ 14006	N_037_093 / 0.35 mm^2	Change..	1490	Type...	20	Type...
☐ 43018	N_037_093 / 0.35 mm^2	Change..	800	Type...	20	Type...
☐ 70163	N_037_019 / 0.75 mm^2	Change..	340	Type...	20	Type...
☐ 70245	N_037_023 / 1 mm^2	Change..	340	Type...	20	Type...

Please insert the folder name to store the simulation results considering the modifications:

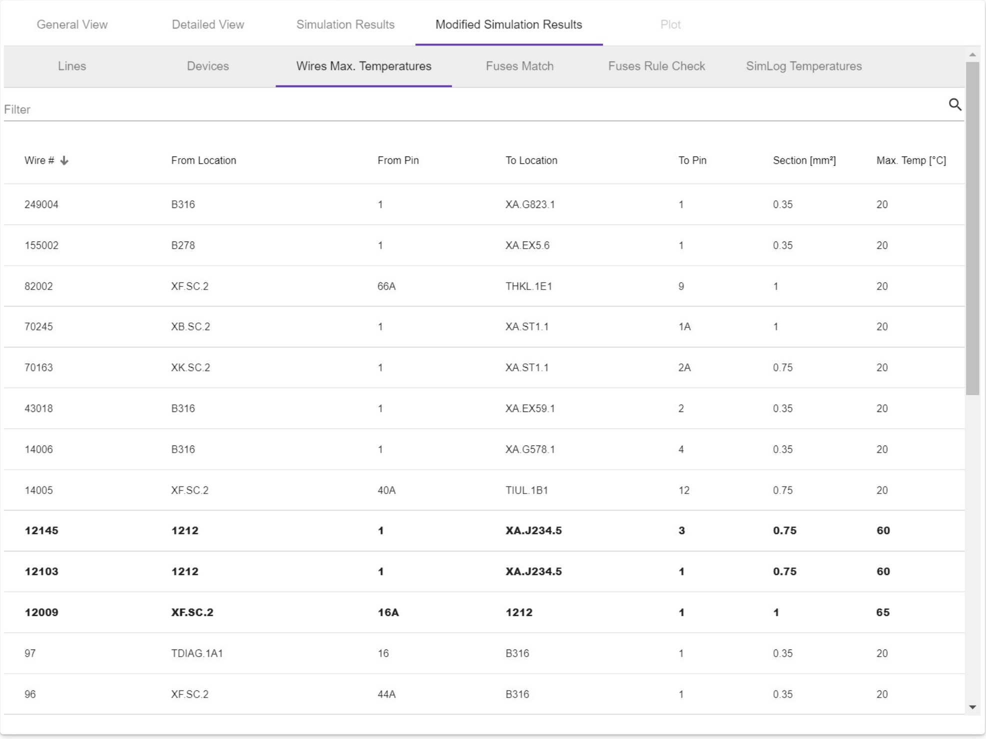
Type...
Modification_config1

Figure 5.11: Panel to define wires variations for a simulation with modifications

Ⓑ A list with the modifications is sent to the Back-End.

Ⓒ The entire power flow simulation takes place as the main fusebox connectivity was already given by the user in the former process. The new simulation files are issued to the Front-End.

Ⓓ A pop-up dialog with the simulation log is also exhibited and all the new simulation results are available to the user in the Modified Simulation Results tab (see Fig. 5.12). There we can see for instance, that the unwanted over temperatures previously encountered in the Leon main-harness have been overcome as the temperature in the three problematic wires is now lower than 70ºC. The thermal modelling that supports this functionality is as described in Section 3.7.1. Finally, the overall warnings and temperature errors in the General and Detailed Views are updated to reflect the new conditions.



Wire # ↓	From Location	From Pin	To Location	To Pin	Section [mm²]	Max. Temp [°C]
249004	B316	1	XA.G823.1	1	0.35	20
155002	B278	1	XA.EX5.6	1	0.35	20
82002	XF.SC.2	66A	THKL.1E1	9	1	20
70245	XB.SC.2	1	XA.ST1.1	1A	1	20
70163	XK.SC.2	1	XA.ST1.1	2A	0.75	20
43018	B316	1	XA.EX59.1	2	0.35	20
14006	B316	1	XA.G578.1	4	0.35	20
14005	XF.SC.2	40A	TIUL.1B1	12	0.75	20
12145	**1212**	**1**	**XA.J234.5**	**3**	**0.75**	**60**
12103	**1212**	**1**	**XA.J234.5**	**1**	**0.75**	**60**
12009	**XF.SC.2**	**16A**	**1212**	**1**	**1**	**65**
97	TDIAG.1A1	16	B316	1	0.35	20
96	XF.SC.2	44A	B316	1	0.35	20

Figure 5.12: Tab containing the results for the modified simulation

5.2.4 Time-plots

If the user chose to perform a time-dependant simulation (in Step ⓵a from Section 5.2.1), time-plots are displayed by means of the following procedure (see Fig. 5.13):

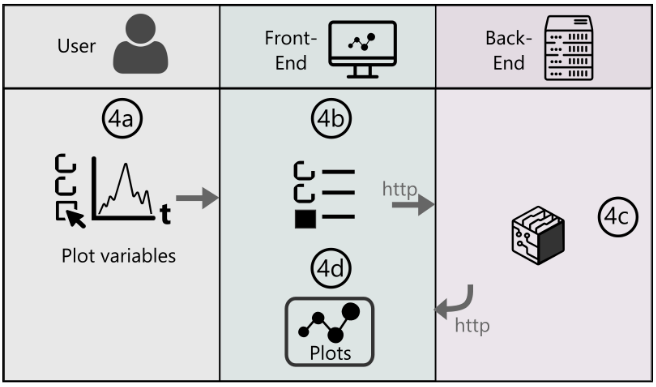


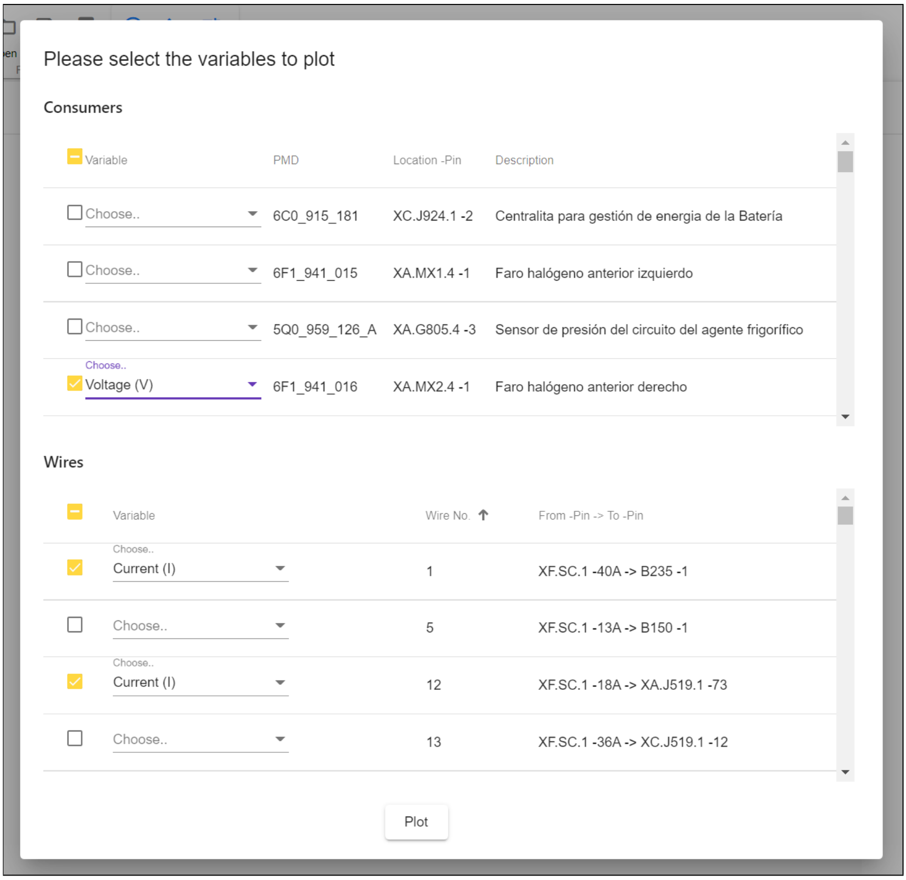
Figure 5.13: Process to display time-plots

(4a) First, in the corresponding tab (see Fig. 5.14), the user selects the variables to plot for the consumers (voltage, current, power) as well as for the wires (voltage drop, current).

(4b) The list of variables to plot are sent to the Back-End.

(4c) The server sends back the simulation files related to the selected variables. This approach was employed to make the process more fluid by delivering on-demand only the desired simulation results. Given the large amount of electrical variables that can exist in a harness simulation, delivering all the results at once would be counterproductive.

(4d) At the web-browser, after parsing the received files, time-plots like in Figure 5.15 are generated using the D3 library. There we can see, for the case of the Ibiza main-harness in a scenario related to the doors opening in the vehicle, how the current in one of the most upstream cables in the network (Wire 312006) follows the currents demanded by the door lock



Please select the variables to plot

Consumers

⊟ Variable	PMD	Location -Pin	Description
☐ Choose..	6C0_915_181	XC.J924.1 -2	Centralita para gestión de energia de la Batería
☐ Choose..	6F1_941_015	XA.MX1.4 -1	Faro halógeno anterior izquierdo
☐ Choose..	5Q0_959_126_A	XA.G805.4 -3	Sensor de presión del circuito del agente frigorífico
☑ Choose.. Voltage (V)	6F1_941_016	XA.MX2.4 -1	Faro halógeno anterior derecho

Wires

⊟	Variable	Wire No. ↑	From -Pin -> To -Pin
☑	Choose.. Current (I)	1	XF.SC.1 -40A -> B235 -1
☐	Choose..	5	XF.SC.1 -13A -> B150 -1
☑	Choose.. Current (I)	12	XF.SC.1 -18A -> XA.J519.1 -73
☐	Choose..	13	XF.SC.1 -36A -> XC.J519.1 -12

Figure 5.14: Panel to select the variables to plot

(Wire 144), front wiper motor (Wire 12) and lightning halogens (Wire 1). The hierarchical configuration of the previous cables can be observed in the Detailed View of Fig. 5.9. In the previous figure, these wires can be found in the top-left part of the diagram where their names have been added in blue color. Additionally, for this scenario we could plot the Right Halogen Headlight voltage as Fig. 5.16 exhibits. This can be useful to observe if the device voltage drop does not surpass predefined limits for instance. The overall interface appearance of the deployed software tool can be seen in Fig. 5.17.

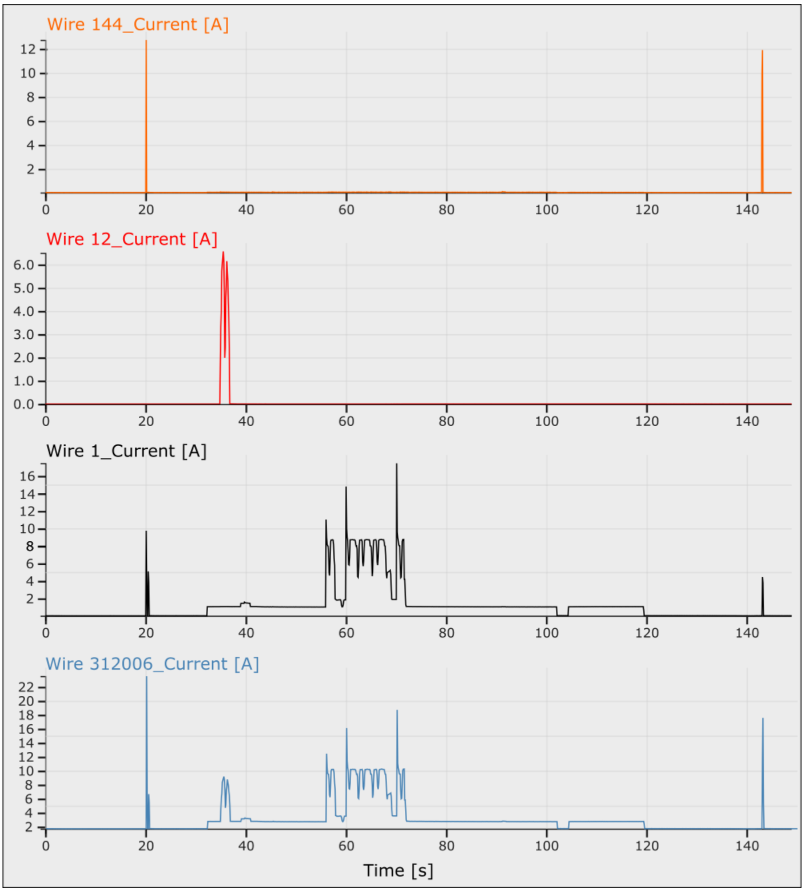


Figure 5.15: Simulation time-plots examples.

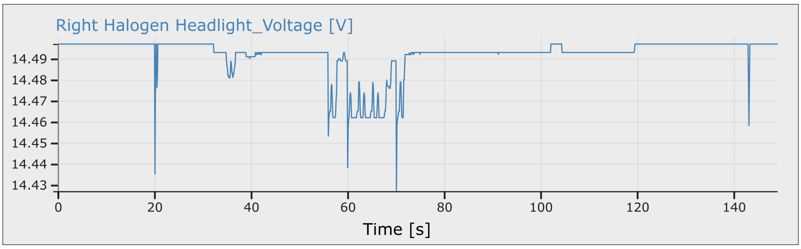


Figure 5.16: Right Halogen Headlight voltage

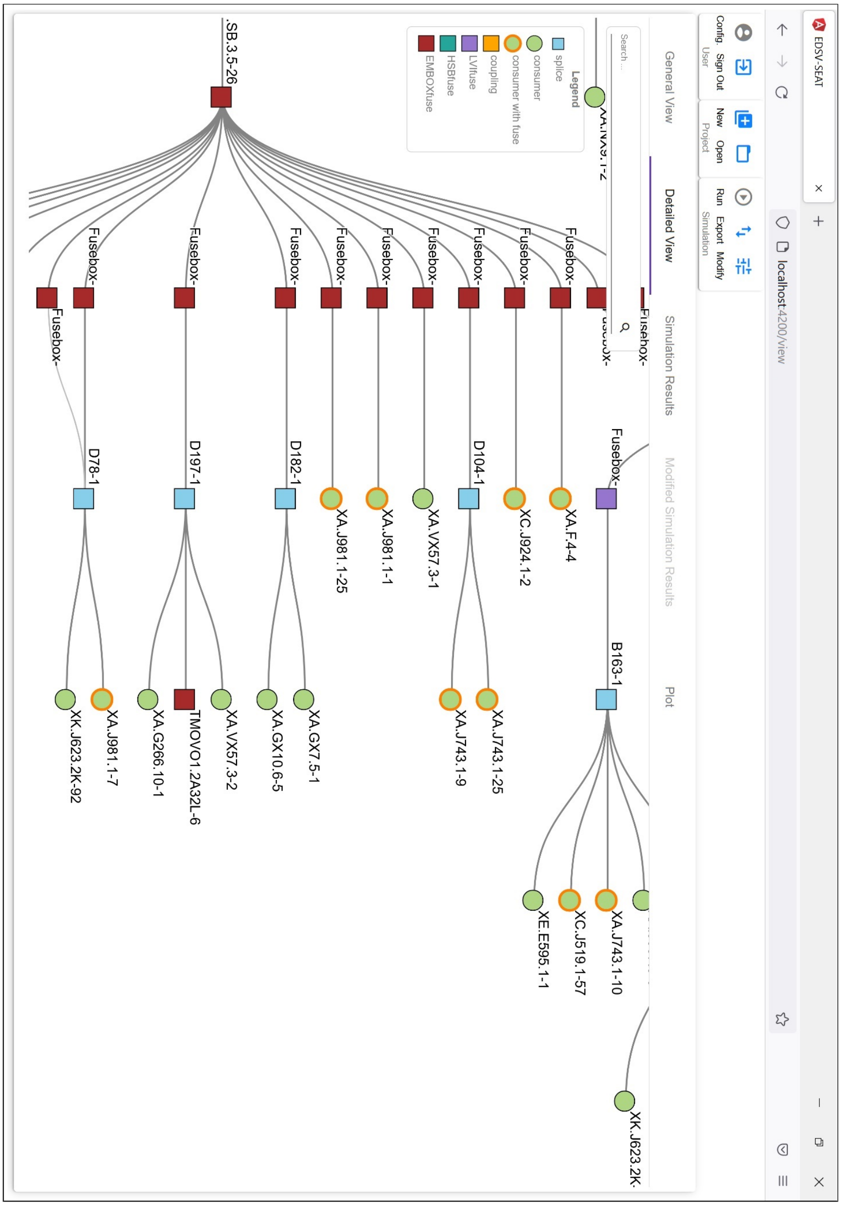


Figure 5.17: Overall interface of the deployed software tool

5.3 Conclusions

- In this chapter, the different outcomes of the visualization and simulation functionalities have been illustrated taking as a reference the main harnesses from two SEAT car models, the Ibiza and the Leon vehicles. Those main harnesses by their own can supply energy to large parts of their respective vehicles, encompassing hundreds of electrical nodes and tens of power consumers. This was specially the case of the Ibiza model.

- The reported simulation workflow demonstrated flexibility and modularity by means of the mature 3-tier scheme which encompasses the web browser, the web server and the simulation engine. The roles and complete interaction between the 3-tier elements for a full user workflow were described in detail to favor readers with a concise understanding about the implementation of this strategy. Indeed, considering real main-harnesses from commercial SEAT sedan models, the exhibited workflow evidenced how the deployed software tool can leverage the design duties of VEDS and assist the identification of problematic conditions under different scenarios. Moreover, the user is able to perform network modification to then witness if the unwanted states were overcome and thus improving the robustness of the system.

- The use of tailored Python-based data preprocessing at the Back-End allowed to make electrical meaning from factory datasets that are not intuitive as they are mostly intended for manufacturing purposes. By doing so, the electrical network topology of the wire harness was inferred and conveniently organized into different CSV files considering typical data formats from the power systems field. These files were then employed for visualization purposes at the Front-End using the Angular framework for web interface development. When a simulation or further data treatment is demanded by the user, an HTTP request is assigned to the Back-End that again, with the use of the Node.js environment and Python scripts applies the necessary modeling and numerical methods to fulfill the specific user request. Then, a reply with the correlated data is created to update the interface in a useful manner. All this process was designed to support and enhance the user cognition about the corresponding state of the network in the simulates scenarios.

> ”There is no real ending. It’s just the place where you stop the story.”
>
> Frank Herbert - North-American writer, 1969

Chapter 6

Conclusions and future work

6.1 Conclusiones (Spanish)

- Esta tesis ha abordado la incorporación de Analítica Visual (VA) y estrategias de simulación para el análisis de Sistemas de Distribución Eléctrica de Vehículos (VEDS). Estas redes de a bordo son responsables de entregar el suministro eléctrico a los consumidores de energía de un vehículo, excepto aquellos relacionados con tracción eléctrica (por ejemplo, inversor) que son alimentados por una red distinta de mayor voltaje. Los VEDS son sistemas complejos, ya que en un solo vehículo abarcan comunmente miles de cables y uniones eléctricas, cientos de consumidores de energía y decenas de Unidades de Control Electrónico (ECU) y elementos de protección; mismos que están interconectados con intrincadas configuraciones de cableado. Además, su complejidad ha aumentado en los últimos años debido a nuevas regulaciones, las tendencias de electrificación y mayores demandas de servicios por parte de los usuarios. Por lo dicho, el diseño de VEDS es una etapa desafiante en el proceso de desarrollo de un vehículo moderno.
- Tomando en cuenta todo el proceso recomendado por VA para amplificar la cognición y la comprensión de los usuarios que interactúan con VEDS,

la plataforma de software aquí implementada incluye el preprocesamiento de datos de la industria automotriz, permite una adecuada visualización de la red, mejora la percepción del usuario sobre el estado de esta, incluye funcionalidades de interacción y actualiza la plataforma en consecuencia. En este sentido, este trabajo ha evidenciado los beneficios de VA para integrar el tratamiento de datos de VEDS en una sola herramienta informática capaz de realizar simulaciones de flujo de potencia y facilitar la interacción del usuario con la información.

- A pesar de que una revisión sistemática de la literatura mostró que existe un empleo significativo de VA en los sistemas eléctricos, todas las contribuciones encontradas se realizaron en el campo de los sistemas de potencia. De manera similar, una revisión detallada del uso de VA en la industria automotriz reveló la falta de plataformas de software que permitan el análisis y la simulación de VEDS, incluyendo las características específicas de fábrica para los cables, fusibles, consumidores, ECUs y otros componentes. Sin embargo, esta investigación del estado del arte fue de gran relevancia para inferir los desafíos y beneficios de VA en dominios más amplios. Estas premisas generales y buenas prácticas se adaptaron luego a las necesidades particulares de visualización y simulación de VEDS.

- Hoy en día, la simulación por computadora es de suma importancia en la industria automotriz ya que permite la reducción de prototipos y un mayor análisis y robustez de componentes. A diferencia de otros sistemas de vehículos a bordo, el uso de herramientas de simulación aún no es una rutina extendida en el diseño de VEDS. La inclusión de plataformas de simulación a medida para estos sistemas, como la reportada en este trabajo, permite analizar diferentes arquitecturas y configuraciones de cableado bajo diferentes escenarios. Por lo tanto, las inconsistencias de diseño que puedan conducir a caídas de voltaje no deseadas, sobrecargas, selección inapropiada de fusibles o sobre temperaturas pueden anticiparse en una etapa rápida del proceso de diseño.

- El empleo de métodos de flujo de potencia Meshed-Network Backward/Forward Sweep (MN-BFS) y de Inyección de Corriente (CI) superaron a los enfoques tradicionales (como Newton-Raphson y Gauss-Seidel) en materia de intensidad computacional en circuitos de prueba DC radiales ligeramente mallados. Sin embargo, a diferencia del enfoque MN-BFS, no se requieren modificaciones topológicas y algoritmos de compensación cuando se utiliza la táctica de CI. Esto se tradujo en una reducción de tres veces en el tiempo de cálculo cuando se usa CI en lugar de la técnica MN-BFS en una red DC de prueba de tamaño medio que estuvo sujeta a diferentes condiciones de carga. Además, como el método CI es adecuado para estudios de flujo de potencia bidireccionales, este es el enfoque aquí empleado pues también favorecerá el análisis de futuras redes eléctricas de vehículos de a bordo que probablemente incluirán la cooperación entre VEDS de bajo voltaje y la red de mayor voltaje encargada del sistema de tracción.

- Para hacer frente a la complejidad de VEDS y favorecer la rápida creación y mantenimiento de prototipos de software, la metodología aquí presentada para implementar una plataforma de software para la visualización y simulación de VEDS, se basa en seis fundamentos clave: preprocesamiento de datos a medida, adecuada simulación del flujo de potencia, desarrollo ágil de software, uso exclusivo de herramientas de código abierto, arquitectura de software web e incorporación de estrategias de Analítica Visual. La practicidad y versatilidad del esquema propuesto hace que la plataforma desarrollada sea fácilmente escalable a otros entornos de ingeniería basados en la web que requieran simulación por computadora.

- Para proporcionar pautas específicas relacionadas a la implementación de la herramienta computacional expuesta, se han presentado flujos de trabajo de simulación completos considerando como casos de estudio dos mazos eléctricos principales de vehículos comerciales. La comprensión visual de estos mazos se facilitó con la generación automática de diagramas personalizados de nivel amplio (vista general) y de nivel cable por cable (vista detallada). La vista general se asemeja a la configuración física del mazo en el vehículo, en una disposición de vista superior; mientras que la vista detallada favoreció la visualización de la conectividad en los elementos del sistema de manera jerárquica como en los diagramas unifilares tradicionales. Además, para entregar información de una manera estética y útil, y mejorar la experiencia del usuario, se emplearon códigos de colores y símbolos para representar los diferentes elementos y facilitar su reconocimiento. El usuario puede arrastrar los nodos en la pantalla para obtener una visualización de red más limpia de ser necesario. La inclusión de tooltips, menús contextuales, leyendas interactivas, cajas de búsqueda, entre otras herramientas, permitieron de manera útil la entrega de información al usuario. Información que se deriva del modelado y simulación de los que consta la plataforma informática desarrollada. De hecho, las condiciones de la red encontradas mediante simulación son convenientemente comunicadas y resaltadas al usuario mediante la coloración de elementos para estados problemáticos, oportunos mensajes informativos emergentes, tablas con los resultados eléctricos y gráficos temporales. Además, el usuario puede realizar simulaciones con modificaciones de los parámetros de cables y tener una rápida retroalimentación sobre los efectos de esas nuevas condiciones en la red y, por lo tanto, mejorar sus diseños.

6.2 Conclusions

- This thesis has addressed the incorporation of Visual Analytics (VA) and simulation strategies for the analysis of Vehicle Electrical Distribution Systems (VEDS). These on-board networks are responsible for delivering energy to the different power consumers within a vehicle, except by those related with electrified traction (e.g. inverter) which in contrast are fed by a separate higher-voltage network. VEDS are intricate systems as in a single vehicle they typically encompass thousands of wires and electrical joints, hundreds of power consumers and tens of Electronic Control Units (ECUs) and protection elements that are all interconnected with intricate wiring path configurations. Moreover, their complexity has increased in the last years due to new regulations, electrification trends and higher user demands. Therefore, VEDS design is a greatly demanding stage in the product development process of a modern vehicle.

- Considering the entire sense making process recommended by VA in order to amplify users' cognition and understanding of VEDS, the here deployed software platform includes data pre-processing of automotive industry datasets, permits adequate network visualization, enhances user perception about the network state, includes interaction functionalities and updates the platform accordingly. In this regard, this work has evidenced the benefits of VA to integrate all the necessary VEDS data treatment in a single computer tool able to perform power flow simulations and facilitate human-information interaction.

- Despite the fact that a systematic literature review exhibited a significant employment of VA in electrical systems, all the contributions were in the power systems field. Similarly, a detailed survey of VA use in the automotive industry revealed the lack of software platforms permitting the analysis and simulation of in-car electrical network models including the specific factory features of wires, fuses, loads, ECUs and other components. Nevertheless, the aforementioned research was of high relevance to infer the challenges and benefits of VA in broader domains. Those general premises and good practices were adapted to the particular needs of VEDS visualization and simulation.

- Nowadays, computer simulation is of paramount relevance in the automotive industry as it permits prototyping reduction and higher components analysis and robustness. Unlike other on-board vehicle systems, the use of simulation tools is not yet an extended routine in VEDS design. The inclusion of tailored simulation platforms for these systems, like the one reported in this work, permits the testing of different wiring architectures and configurations under different scenarios. Therefore, design inadequacies that may lead to unwanted voltage drops, overloads, fuses mismatches or over temperatures can be anticipated in a prompt stage of the design process.

- The Meshed-Network Backward/Forward Sweep (MN-BFS) and the Current Injection (CI) power flow methods outperformed traditional approaches (such as Newton–Raphson and Gauss–Seidel) in the matter of computational intensity in radial or slightly meshed DC test networks. Nevertheless, in contrast to the MN-BFS approach, topological modifications and compensation algorithms are not demanded when using the CI tactic. This translated to three-fold reduction in computing time when using CI instead of the MN-BFS technique in a mid-sized test DC network subject to different load conditions. Additionally, as the CI method is suitable for bidirectional power flow studies, this is the here employed approach given that also will favor the analysis of future on-board vehicle networks that will likely include cooperation between low-voltage VEDS and high-voltage vehicle traction systems.

- To face the intricacy of VEDS and promote rapid software prototyping and maintenance, the presented methodology to deploy a software platform for the visualization and simulation of VEDS is based in six key foundations: tailored data pre-processing, convenient power flow simulation, agile software development, sole use of open-source tools, web-based software framework and incorporation of Visual Analytics strategies. The practicality and versatility of the proposed architecture makes the exhibited platform readily scalable to other engineering web-based environments that require computer simulation.

- To provide specific guidelines about the implementation of the exhibited computer tool, full simulation workflows have been presented considering as case studies two main wire harnesses from commercial vehicles. The visual understanding of these harnesses was fostered with the automatic generation of custom-made broad level (General View) and wire-by-wire level diagrams (Detailed View). The General View resembled the physical configuration of the harness in a vehicle, in a top-view disposition; while the Detailed View favored the visualization of the connectivity in the elements of the system in a hierarchical manner like in traditional one-line diagrams. In addition, to deliver information in a aesthetic useful manner and enhance user experience, different color and symbol codes are employed to represent the different elements and ease their recognition. The user is able to drag the nodes in the screen to procure a cleaner network visualization if needed. Mouse-over tooltips, contextual menus, interactive legends, search-box elements among other tools, allowed to provide the user with helpful information derived from the modeling and simulation embedded in the computer platform. Indeed, the network conditions encountered via simulation are conveniently remarked and provided to the user by means of elements coloring for problematic states, opportune pop-up informative messages, tables with the electrical data results and time plots. In addition, the user can perform further simulations with wire parameters modifications and have rapid feedback about the effects of those new conditions in the network and therefore improve his designs.

6.3 Future work

- As discussed in Chapter 2, Data Analytics (DA) is an optional step of the overall Visual Analytics (VA) process that may bring some benefits to VEDS analysis. Given the reduced observability of VEDS in modern vehicles, DA is still a pending task in these networks. To prioritize robustness, electrical wiring in VEDS may be oversized. Or in contrast, for unexpected scenarios it may be the case that some network elements are smaller than really needed. The use of DA in VEDS may permit to have a greater understanding about the degree of utilization and performance of the different electrical elements in the network, and therefore optimize their sizing and functionalities based on real performance data. To do so, as an initial step, novel VEDS instrumentation and communication strategies could be deployed in some test vehicles in order to have sufficient datasets with detailed records of the electrical variables in the system. This may permit the consequent DA deployment and knowledge extraction that may lead to optimized designs of these networks.

- In relation to the present project and as described in [191], four stages were set to validate the deployed simulation strategies. These steps started with a wire harness alone test bench. Then in this test bench, typical power consumers were added. After that, the essays moved to real wire harnesses from a commercial vehicle, beginning with a secondary harness, the one related with a driver-door. Finally, a group of selected wires from a main harness were instrumented to then compare the measures with the simulation data. Successful results and very high correlation were encountered. Nonetheless, to pave the way towards nearly zero-prototyping of VEDS in the automotive industry, further research, hardware tests and software user experience studies are needed to attain the expected robustness, reliability and user acceptance on the computer platform. Besides the Ibiza and Leon car vehicles architectures, greater tests and software development have to be now conducted for other vehicle models and harnesses to attain enough maturity and begin assisting the VEDS design of vehicle models that are still in the product development stage.

- One of the benefits of the presented computer tool, is the possibility to conduct studies in VEDS under different scenarios and conditions that are difficult to be reproduced in real prototyping. Besides the steady-state estimation of wires temperatures, to increase the simulation robustness and permit an advanced assessment that considers transient conditions, further work is needed to develop wire thermal models that takes into account for instance the transient evolution of peak currents. By doing so, complex scenarios could be reliably recreated beyond to what is feasible through real prototyping or on-the-road characterization.

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Appendices

Appendix A

Journal publications

A.1 Web-Based Simulation Environment for Vehicular Electrical Networks

Dominguez, X.; Mantilla-Pérez, P.; Gimenez, N.; El-Sayed, I.; Díaz Millán, M.A.; Arboleya, P. Web-Based Simulation Environment for Vehicular Electrical Networks. Energies 2021, 14, 6087, `https://doi.org/10.3390/en14196087`

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Article

Web-Based Simulation Environment for Vehicular Electrical Networks

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Abstract: For the validation of vehicular Electrical Distribution Systems (EDS), engineers are currently required to analyze disperse information regarding technical requirements, standards and datasheets. Moreover, an enormous effort takes place to elaborate testing plans that are representative for most EDS possible configurations. These experiments are followed by laborious data analysis. To diminish this workload and the need for physical resources, this work reports a simulation platform that centralizes the tasks for testing different EDS configurations and assists the early detection of inadequacies in the design process. A specific procedure is provided to develop a software tool intended for this aim. Moreover, the described functionalities are exemplified considering as a case study the main wire harness from a commercial vehicle. A web-based architecture has been employed in alignment with the ongoing software development revolution and thus provides flexibility for both, developers and users. Due to its scalability, the proposed software scheme can be extended to other web-based simulation applications. Furthermore, the automatic generation of electrical layouts for EDS is addressed to favor an intuitive understanding of the network. To favor human–information interaction, utilized visual analytics strategies are also discussed. Finally, full simulation workflows are exposed to provide further insights on the deployment of this type of computer platforms.

Keywords: power system simulation; road vehicle power systems; simulation software; system analysis and design

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1. Introduction

As part of product design in the industry, computer simulation nowadays plays a major role given its benefits such as high analysis capacity, prototyping reduction, improved product quality and attractive cost-efficiency [1]. This is the case of automotive manufacturing where specialized simulation platforms are being employed to meet current performance standards, newest environmental policies, superior product reliability and higher user demands. Conventionally, the majority of simulation tools in this sector have mostly focused in aerodynamics, computed-aided design, vehicle collision, autonomous driving, communication systems, electric drive-train and energy management [2]. The latest simulation trends in automotive systems deal with advanced functionalities such as scalable models for autonomous-driving cars [3], energy-efficient networking for electric vehicles networks [4] and internet of vehicles for automation and orchestration [5]. However, regarding the on-board Electrical Distribution Systems (EDS), which are responsible for delivering power supply to the different consumers within a vehicle, only few commercial tools (such as Harness Studio and Saber RD) and a few sustained research related to tailored simulation platforms have been exposed [2,6,7]. Vehicular EDS (in blue color in Figure 1) are intricate networks composed of a vast number of protections, splices, couplings, Electronic Control Units (ECUs) and loads that are interconnected with several wire harnesses enclosing thousands of cables, representing up to 3 km of cabling [7]. Every wire harness, hereafter only referred as harness for simplicity, is basically an assembly of bundled cables protected by tapes, fittings and plastic coatings capable to maintain safe electrical operation of the network for the demanding conditions that may exist in the surroundings. Independently of the type of vehicle (e.g., Internal Combustion Engine (ICE) propelled, hybrid, electric or other), on-board EDS are deployed in a similar manner. This is interconnecting different harnesses intended to supply energy to the different consumers within a vehicle, except by those related with electrified traction (e.g., inverter), which in turn are fed by a separate higher-voltage network having its own battery. Therefore, the approach proposed here to analyze in-car EDS can be applied to all kind of vehicle. Owing to assembling requirements, the entire on-board EDS are typically formed by a primary harness which delivers, through couplings, power supply as well as communication and control signals to different secondary harnesses such as those related with the bumpers, doors, seats or engine.

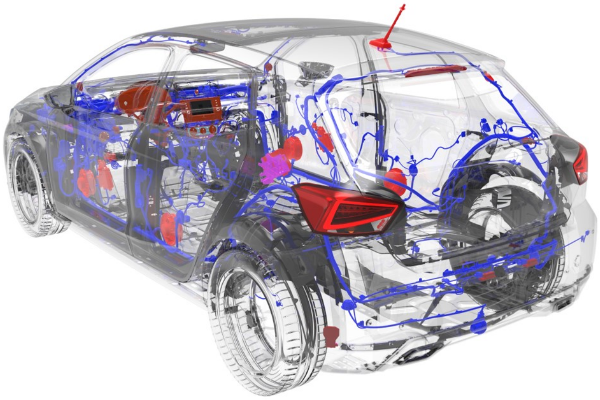


Figure 1. Vehicular EDS of the SEAT Ibiza car model.

Considering all the aforesaid, the design and prototyping of the vehicular electrical network represent a highly defiant stage in a car model development process. To cope these challenges and permit vehicle design engineers an early detection of unsuitable configurations, such as those leading to undesired voltage drops, excessive temperatures or mistaken components sizing, the development of versatile simulation methods and platforms is compelling. In this respect, recent research has proposed frameworks to perform EDS power flow simulations considering the specific data format employed in the automotive industry and using algorithms based on backward/forward sweep [6] and current-injections methods [8]. In [2], the relevancy to include Visual Analytics tactics in EDS simulation environments is highlighted to facilitate human–data interaction. Additionally, relevant software development cornerstones to deploy EDS visualization and simulation is exhibited in [7]. On this issue, when talking about key pillars that can significantly enhance the capabilities of simulation tools, web and cloud-based architectures are currently an accelerating trend given their capacity to boost collaboration, increase flexibility and tackle complex product-oriented designs [9]. Moreover, these web-based deployments present advantages not only for end users, but also for applications developers given the convenience of remote access, usage of any operative system and simplified software installation and upgrading. Therefore, web and cloud-based computing have been recognized as the third revolution in the Information Technology (IT) industry [10]. Due to these benefits, in the last years different simulation tools from the electrical engineering field have been developed or updated to include web-based functionalities. This tendency has been applied with varying architecture complexity depending on the magnitude of the projects, going from electric-electronic circuits schematics [11–14] and arriving to power system analysis, cost optimization and state estimation as reference [15] elaborates. This gives us an insight of the relevance of web-based technologies to develop a flexible, scalable, collaborative and easy-to-maintain simulation tools to face the challenging design demands of vehicular EDS.

Within this context, to complement the aforementioned vehicle EDS research and also propose a functional architecture for other industry web-based simulation environments, the main contribution of this work is the development of a methodology to deploy an industry-oriented web-based computer platform intended for the visualization and simulation of in-car EDS. This kind of initiative represents a novelty contribution for the automotive sector to the best of the authors' knowledge. Moreover, the functionality of the implemented software environment has been validated considering a real electrical harnesses from a commercial vehicle. In this respect, Section 2 elaborates on the proposed web-based computational architecture along with the required data preprocessing. Hereafter in the document, the implementation of the presented functionalities is discussed and then exemplified considering the main harness of the SEAT Ibiza car model as a case study. Specifically, Section 3 addresses the automatic generation of electrical diagrams for EDS interfaces. Satisfactory harness and wire-by-wire schematics are accomplished to support an intuitive understanding of the vehicular electrical network. To increase user experience and enhance human–information interaction, tailored functionalities and Visual Analytics strategies have been included, these are mentioned in Section 4. Then, Section 5 exhibits in detail the complete simulation workflow for typical user duties in a step-by-step manner. Section 6 makes a concise discussion about the visualization and simulation outcomes that were attained in the previous sections given the considered case study. Finally, some conclusions are exhibited in Section 7.

2. Simulation Engine Architecture

2.1. Web-Based Framework

In the conventional paradigm of traditional simulation tools, each user has an individual software copy installed in his own computer. Under this approach, the software and the computing resources are confined and scalability is not possible. On the other hand, in cloud and web schemes, an IT service provider supplies computing resources to clients on-demand. This allows the stringent modeling and simulation tasks to run on robust vendor servers (Back-End) while the clients' workstation (Front-End) mainly focuses on the user input and the interface display duties. This alleviates hardware upgrading in final users who are only required modest computational capabilities and a rapid reliable Internet or proprietary network connection which is becoming easier and more affordable day by day. Therefore, users and programmers can remotely access the application for its use or debug, respectively, and thus simplifying software licensing, maintenance and updating [16].

Taking advantage of the former benefits, web-based simulation software and research have been carried out to conduct electrical network studies. Most of these initiatives have primarily focused within the power systems analysis scope. In this field, some open source and commercial tools have reported to include web-based architectures. For instance, we have InterPSS [17], MatPower [18], Neplan [19] and Simulink from Matlab [20]. With respect to web/cloud-based research in this ambit, a few works have been reported. The initial contributions dealt with power flow and contingency examinations [21], dynamic transient assessment [22], distributed generation allocation and dispatch [23], cost optimization by the use of cloud-computing [24] and PMU-based estate estimation [25]. On the other hand, the latest studies are associated with a PHP-language application library [26], planning analysis for the ISO New England system operator [27,28] and a hybrid AC/CD network cloud-based simulation [29].

The most common architecture in the aforesaid web-based simulation platforms is a 3-tier scheme (web browser, web server and simulation engine). Given its maturity [26], this was also the architecture implemented in the present project as Figure 2 exhibits. Note that only open-source web development tools have been employed to do so. At the client side, the user access the application with a web browser. Here, the Front-End interface was deployed using the Angular framework [30]. The latter permits a rapid and well-documented design of aesthetic, dynamic, single-page applications by means of hierarchically integrated components, templates and services [31]. Additionally, Javascript-based D3 library [32] has been used to generate customized Scalable Vector Graphics (SVGs) for the interface. When the client inserts the corresponding URL, the browser requests the page (via HTTP) from the web server that hosts the page. Then, using the Node.js environment [33], the server returns the page to the requesting IP address so that the browser renders and displays the interface. Later, when computing intense data preprocessing or simulation is needed by the user at the Front-End, a new particular request is made again to the web server which now passes this specific petition to the simulation engine. In this work, this latter is settled on the same Back-End server but it can be hosted in another remote server if needed. It was deployed using Python language given its convenient libraries for data preprocessing and development of custom-made power flow analysis. In this stage, the simulation engine executes the necessary scripts and returns the corresponding data to the Front-End via the web server. For further insights on the entire process, a complete simulation workflow is exhibited in Section 5.

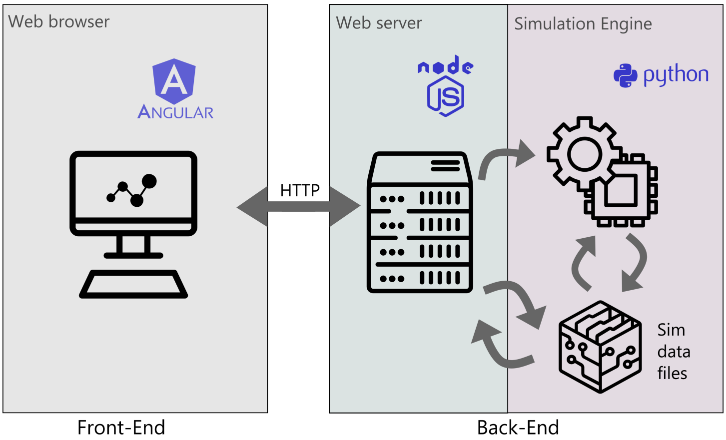


Figure 2. Web-based environment architecture.

2.2. Data Preprocessing

Prior to the visualization and simulation of the on-board electrical system, a preprocessing stage over different input data files is needed as Figure 3 exhibits. As a first step, the user inserts the following input information in the Front-End via the web browser: (i) the factory wire harness .XML data container which is different for every harness in the vehicle according to its corresponding car model; (ii) input variables values such as the nominal voltage of the battery, the ambient temperature, the need to perform static or time-profiles simulation, the type of car harness under study (main or secondary) among others; (iii) time-current profiles of the loads; (iv) the vehicle equipment configuration; (v) the fuse boxes internal connectivity; and (vi) the parameters of the different wires in the harness such as their cross section area, thermal conductivity and maximum/minimum temperature. Then, at the Back-End, by means of Python scripts, the simulation engine conveniently extracts, arranges and correlates all the required electrical information from the nodes and lines in the network. Now, the execution of visualization and simulation duties are possible as the information is suitably organized in a set of Comma-separated Values (.CSV) files (e.g., *Gendata*, *Linecode*, *Linedata*, *Nodedata*, *Segmentsdata* and *Loaddata*) having a data structure similar than the one employed in [34] which is common within the power systems domain to perform power flow studies. Further details on the aforementioned process are described in reference [8].

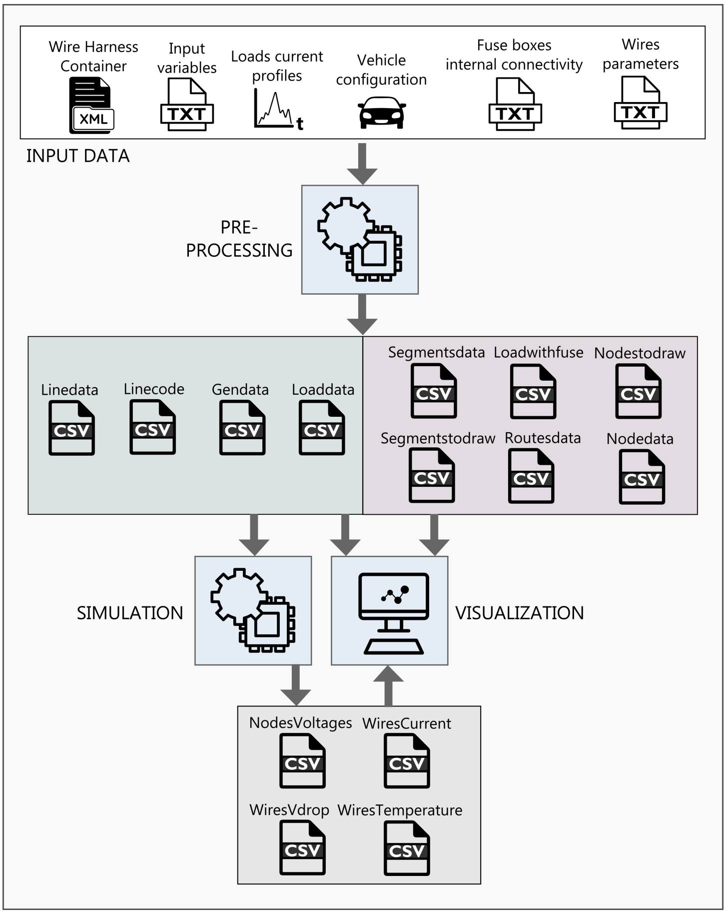


Figure 3. Data generation workflow.

3. Automatic Generation of Electrical Layouts for Vehicular EDS

For a proper representation of the electrical network under study, two types of visual schematics have been implemented: the General View and the Detailed View. Before elaborating on this schematics, note that hereafter in this document, the implementation of the presented functionalities are discussed and then exemplified considering as a case study the main harness from an ICE-propelled sedan car; the SEAT Ibiza model. To provide an idea about the characteristics of this harness, Table 1 details its attributes such as the number of nodes, lines and consumers.

Table 1. Network characteristics of the studied harness.

Feature	Number
Mechanical and electrical nodes	732
Electrical nodes	175
Harness segments	369
Lines	180
Consumers	46
Fuses	25

3.1. The General View

This view presents a broad level outlook of the nodes and the harness segments that interconnect them. These segments are drawn according to their from-to nodes that were previously tabulated in the *Segmentsdata*. Not all the nodes are related to electrical needs. That is the case of mechanical fixations, which stand for a high number of nodes that are relevant for the harness construction but negligible for the power flow simulation. It also must be noticed that every segment represents a bundle section containing different cables whose characteristics are defined in the *Linecode*. Therefore, a single wire may have a number of segments from one edge to the other. To correlate the specific path of every cable in the *Linedata*, the *Routesdata* file contains for each wire the different segments it goes through. For the General View, the positioning of the elements is obtained scaling down the XY coordinates of the *Nodedata* according to the available screen size in pixels. To facilitate a cleaner visualization, only the electrical nodes and segments present in the studied vehicle configuration are shown, leaving aside the nodes related to mechanical events. This is achieved by means of the *Nodestodraw* and *Segmentstodraw* files. Among the type of electrical nodes, we have (i) battery, (ii) main fuse box (HSBfuse), (iii) interior fuse box (EMBOXfuse), (iv) engine fuse box (LVIfuse), (v) coupling, (vi) splice and (vii) consumer. The power characteristics and the description/protection of the consumers are inferred from the *Loaddata* and *Loadwithfuse*, correspondingly. The pseudocode in Algorithm 1 elaborates on the overall process to create the broad General View and the wire-by-wire Detailed View. As it can be seen, both views share the initial stages and the last coding phase which are related to make meaning of the .CSV files and setup the interface functionalities, respectively. There, the description of selected power consumers has been added. It also can be observed that the XY factory assembling coordinates of the nodes and segments are evidenced as the generated layout can be associated to a top-view of the vehicle, where in the left side of the graph, we have the front headlights, and in the most-right part, we have the coupling to a secondary harness related to the bumper.

3.2. The Detailed View

Regarding the second view type, the Detailed View, it aims to create a hierarchically wire-by-wire representation of the network to easily understand its connectivity. In on-board EDS, the power distribution is mostly radial, beginning from the battery and passing downstream through various electrical elements (e.g., fuses, splices, ECUs and switches) to finally arrive to the consumers. This scheme is represented in a simplified manner in Figure 4. This path, from the battery to a load, can be accomplished with the main harness itself or, in turn, using a coupling to add a secondary harness. Nevertheless, discarding elements related to communication and instrumentation purposes, hundreds of electrical nodes and lines are commonly present in a main harness. Additionally, making electrical meaning from manufacturing data that is not designed for electrical studies also represents a challenge. These factors add complexity to the creation of an algorithm that is able to automatically position all the nodes in a coherent manner to then create aesthetic wire routing paths favoring a clean, intuitive scheme of the electrical network.

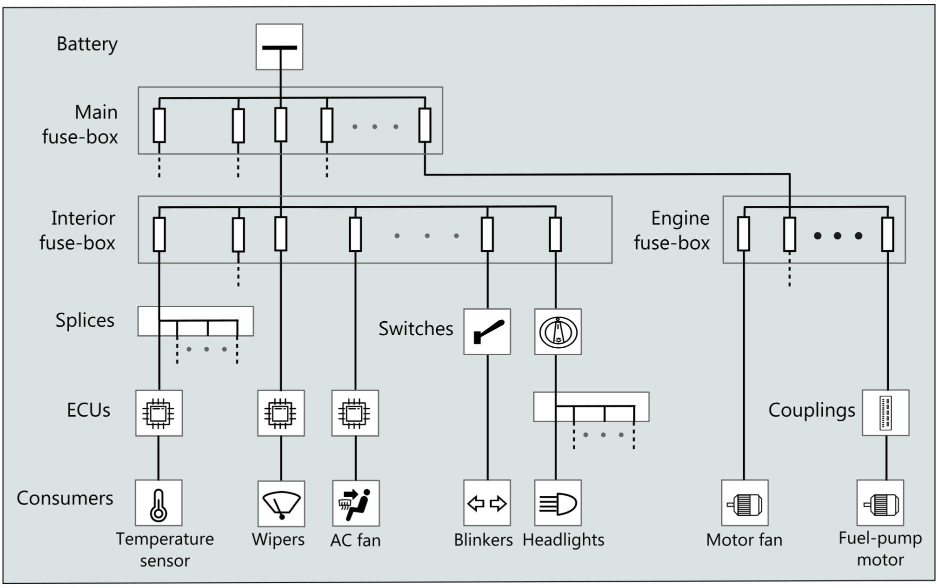


Figure 4. Simplified electrical topology of vehicular EDS.

In the literature, a few works report research on the automatic generation of electrical diagrams [2]. These are encompassed in the power systems domain. Some references address one-line diagrams creation considering XY coordinate constraints related to the nodes geographic information [35,36], while in other references restrictions in the nodes positioning are not a requirement [37,38]. In the case of vehicular EDS, the factory XY coordinates of the nodes are not determinant for a proper wire-by-wire hierarchical understanding of the network. Therefore, an ad hoc approach based on a tree-like scheme was implemented for satisfactory forming aesthetically functional drawings. This was achieved using as a base the Javascript-powered *D3.tree* library which generates node-link diagrams that lay out the connectivity between nodes in a parent–child correlation considering the tree representation algorithm exhibited in [39]. Under this approach, every child element is expected to have only one parent element. However, as earlier mentioned, on-board

EDS are not purely radial but slightly meshed and some cross-feedings may exist in some cases to procure supply redundancy. Therefore, redundant links existing when a child node has two or more parent nodes are detected and individually generated. The stages for the creation of this wire-by-wire representation are presented in Algorithm 1. On the other hand, Figures 5 and 6 present the resulting General View and Detailed View for the main harness of the SEAT Ibiza car model, respectively. In the Detailed View, to procure easier user navigation in the diagram, the nodes hierarchy is displayed horizontally, from left to right.

Algorithm 1: General and Detailed Views Generation

```
Require: .CSV files resulting from the preprocessing stage (e.g.: Gendata, Nodedata,
    Nodestodraw, Segmentsdata, Loaddata, Linedata ...)
Ensure: Harness General and Detailed Views
 1. Create the web-interface elements and components
    using the Angular framework
 2. Parse input .CSV files
 3. Convert input files into data objects (e.g.:
    NodedataObj, LinedataObj, SegmentsdataObj... )
 4. Correlate nodes with consumers and their protection fuses matching
    LoaddataObj, LoadtitlewithfuseObj and NodedataObj
 5. Correlate harness segments with the wires and their routing using
    SegmentsdataObj, RoutesdataObj and LinedataObj
 6. Infer nodes and segments to draw considering NodestodrawObj and
    SegmentstodrawObj
 7. Create the SVG containers and configure their functionalities such as zoom and
    panning
 8. if The General View is required then
 9.   Scale down the XY positioning of nodes from NodedataObj considering
      the available screen size
10.   Use D3 library to draw nodes, segments, patterns, texts and others
11. end if
12. if The Detailed View is required then
13.   Infer child-parent correlation in LinedafirstneighObj for main harnesses
      and LinedaObj for secondary harnesses
14.   Use D3.tree to give tree-hierarchy structure to the
      data
15.   Use base D3 library to draw nodes, links, texts and others
16.   Detect and individually draw redundant links
17. end if
18. Assign colors and styles to the different elements
19. Create and setup additional elements and interface functionalities (e.g.:
    interactive legend, tooltips, mouse-over highlighting, elements search-box,
    contextual menus, draggable nodes, correlation between views,
    simulation results export)
```

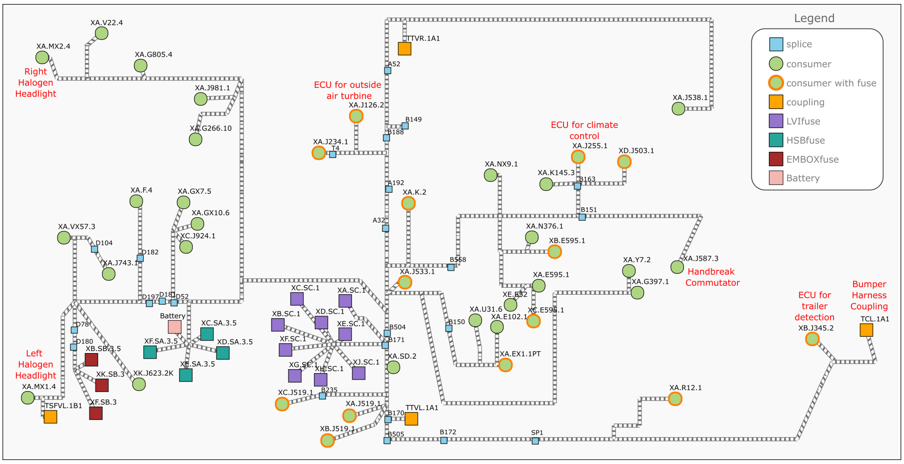


Figure 5. General View for the main harness of the SEAT Ibiza car model.

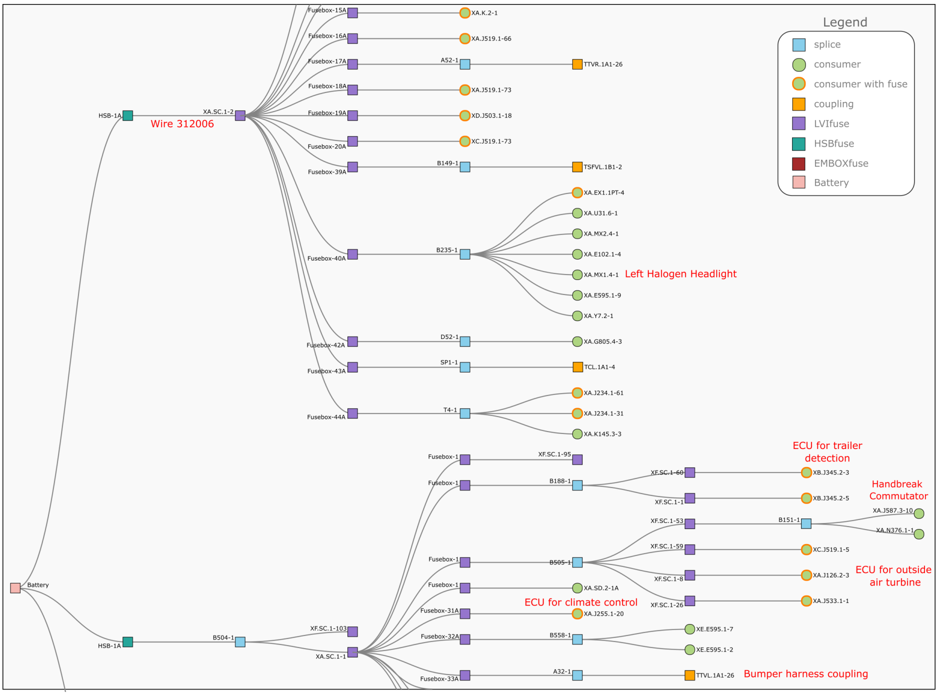


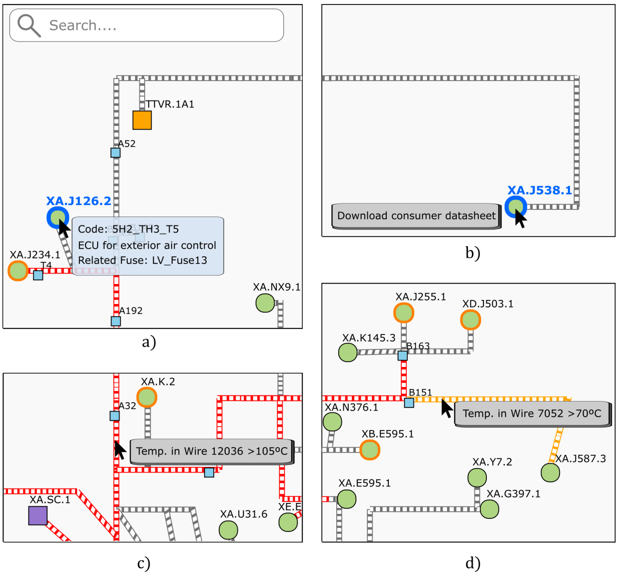
Figure 6. Extract of the Detailed View for the main harness of the SEAT Ibiza car model.

4. Visual Analytics Strategies

To improve user experience and ease human–information interaction, visual analytics (VA) strategies have been enclosed into the implemented web-based simulation environment. The VA precept lies in "combining automated analysis with interactive visualizations for effective understanding, reasoning and decision-making on the basis of a very large and complex datasets" [40]. Similarly to other engineering fields, VA has been also denoted as a relevant tool for software deployment in the transportation and automotive sectors for applications related to urban mobility patterns inference [41], urban congestion control [42] and in-car communication networks [43,44]. To adjust on-board EDS designs, engineers are nowadays demanded to consider isolated pieces of information related to construction guides, standards, electrical layouts and elements datasheets. Thus, some software platforms are typically used in parallel and thus further increasing the design complexity of EDS which are already complex systems. Under this approach, understand the network topology and infer the consequences in the modification of components and their sizing exhibits a significant challenge.

1. Automate the integration of all the necessary information. Once the user inserts the necessary factory input data files, the platform preprocess, derives and organizes all the information required for visualization and electrical simulation of the harness as the previous section elaborated.
2. Provide the user with a functional user-friendly interface. This was fulfilled by means of the following features:
    - (2a) Intuitive electrical diagrams via the already mentioned broad (General View) and wire-by-wire (Detailed View) schematics.
    - (2b) Elements highlighting and tooltips on mouse-over actions to ease the visualization and understanding of the selected items.
    - (2c) Interactive nodes legend to highlight in the schematic all the elements of the selected node type.
    - (2d) Preprocessing and simulation pop-up messages to keep the user informed along the process.
    - (2e) Pan and zoom options for a proper navigation into the electrical diagrams.
    - (2f) Shape and color coding of nodes, wires and harness segments to favor a prompt distinction of elements and risky simulation outcomes such as excessive temperatures.
    - (2g) Elements search box to rapidly locate specific wires and nodes in the network. When the desired element is found, it is highlighted and the screen is zoomed close to it.
    - (2h) Contextual menus via right-click over elements to download datasheets (consumers) or see troublesome temperature conditions after simulation (harness segments). On the latter, once the user clicks the contextual menu related to the problematic wire in the General View, the tool automatically shifts to the Detailed View to represent the risky condition in a wire-by-wire basis.
    - (2i) Draggable consumer nodes in the General View to permit the user a cleaner visualization of the network.
    - (2j) Option to export simulation results in a spreadsheet.

    Some of the above functionalities have been exemplified in Figure 7 as well as in Figures 5 and 6.



Code: 5H2_TH3_T5
ECU for exterior air control
Related Fuse: LV_Fuse13

Temp. in Wire 12036 >105ºC

Temp. in Wire 7052 >70ºC

a) b) c) d)

Figure 7. Examples of VA-based features. (**a**) Elements search box and tooltip on mouse-over. Contextual menus on right-click: (**b**) Download consumer datasheet, (**c**) Harness with wire having temperature>105 ºC and (**d**) Harness with wire having temperature>70 ºC.

3. Facilitate the understanding of the electrical behavior of the network via simulation, including the following:
   - (3a) Static or time-dependent power flow simulations where the user can add personalized current profiles for the loads.
   - (3b) Simulation logs exposing undesired conditions (wires over temperatures and fuses mismatches) as well as different tables detailing all the simulation results regarding voltages, currents and temperatures in wires.
   - (3c) Simulations with parameters variations where the user can modify the length, section and ambient temperature of wires.
   - (3d) Time plots to visualize electrical variables when consumers current profiles are inserted.

5. Simulation Workflow

This section elaborates on the entire workflow to perform a power flow simulation for the main harness of the commercial vehicle that has been considered so far, the SEAT Ibiza model. The full on-board EDS of the SEAT Ibiza vehicle is deployed using one main harness that feeds four secondary harnesses by means of couplings. The simulation has been devised to take place in single harnesses. Therefore, if the user assigns a current profile to a consumer present in a secondary harness, it is first required to perform a simulation in this harness in order to obtain the corresponding current consumption for each pin of the coupling as this element would be assumed as a load when simulating the main harness. A detailed explanation regarding the simulation numerical methods, considerations and algorithms can be found in [8]. There, simulation results are compared against experimental data in a real test scenario, exposing satisfactory results.

The simulation process (see Figure 8) and the execution of basic functionalities of the platform are described below.

(1a) The user inserts the corresponding input data files as specified in Section 3, for this case study this is the data related to the SEAT Ibiza main harness. As a time-dependent simulation will be conducted, the consumers have been assigned different time-varying current profiles.
(1b) The web-browser packs the information and send it to the Back-End attached to the HTTP request.
(1c) As detailed in Section 3, the preprocessing takes place over the input data executing different Python scripts that extract and arrange the electrical information in CSV files. The latter are now sent to the Front-End via an HTTP response.
(1d) The General View is generated as in Algorithm 1 and the user can interact with it.

Now, to perform the power flow analysis, these are the necessary steps:

(2a) The user clicks the corresponding simulation button.
(2b) An HTTP request is sent to the Back-End with the simulation demand.
(2c) A first stage of the power flow simulation, related to connectivity analysis, takes place. As in some cases the use of the input data itself is not enough to determine all the connection paths lying downstream from the main fusebox, the possible connectivity options for the isolated nodes are sent to the Front-End.
(2d) The interface displays a pop-up dialog that lists the connectivity alternatives.
(2e) The user chooses the corresponding connectivity options for the isolated nodes.
(2f) The interface sends the selected items to the Back-End.
(2g) The second part of the power flow algorithm is executed. The simulation results are organized in different CSV files, some of these are related to voltages and currents in the consumers, while the others are associated to the nodes and lines in the network. The latter (see Figure 3) are sent to the Front-End.
(2h) The interface shows a pop-up dialog exposing the simulation log where troublesome conditions (such as fuses mismatches and over temperatures in wires) are highlighted. The new incoming files are then processed to create the Detailed View and an additional tab containing all the simulation results related to voltages in nodes as well as currents, voltage drops and temperatures in wires.

To assist the user to fine-tune vehicle EDS designs, there is an specific option to perform power flow simulation including modifications in length, section and ambient temperature of wires. In this respect, note the following.

(3a) The required modifications are selected by the user in a tab designed for this purpose.
(3b) The modifications list is sent to the Back-End.
(3c) The entire power flow simulation takes place as the main fusebox connectivity was already given by the user in the former process. The new simulation files are issued to the Front-End.
(3d) The electrical schematics and tables are updated according to the new incoming files.

To favor the visual comprehension of the behavior of the electrical variables in the network, time plots can be displayed. To do so, note the following.

(4a) In the corresponding tab, the user selects the variables to plot for the consumers (voltage, current, power) as well as for the wires (voltage drop, current).
(4b) The list of variables to plot are sent to the Back-End.
(4c) The server sends back the simulation files related to the selected variables. This approach was employed to make the process more fluid by delivering on-demand only the desired simulation results. Given the large amount of electrical variables that can exist in a harness simulation, delivering all the results at once would be counterproductive.

(4d) At the web-browser, after parsing the received files, time-plots like in Figure 9 are generated using the D3 library. There we can see, for a given simulation scenario, that when the Left Halogen Headlight (see down-left part of Figure 5) is demanding power according to a profile predefined by the user, its voltage correlates with the current flow in an upstream cable that feeds this consumer's branch, namely wire 312006 (see top-left part of Figure 6).

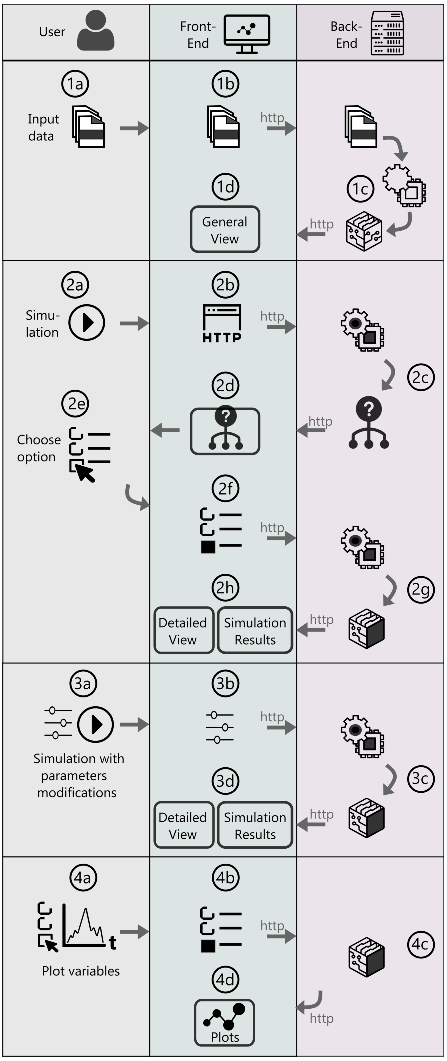


Figure 8. Simulation workflow.

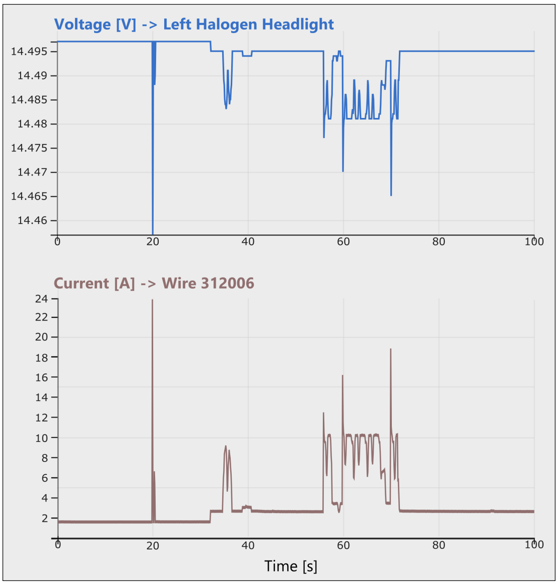


Figure 9. Simulation time-plots examples.

6. Case Study Discussion

In the previous sections, the different outcomes of the visualization and simulation functionalities have been illustrated taking as a reference the main harness from the SEAT Ibiza car model which encompasses hundreds of electrical nodes and tens of power consumers. Those results are now concisely discussed. The visual understanding of the harness network was fostered with the automatic generation of custom-made broad level (General View) and single-line level diagrams (Detailed View). The General View resembled the physical configuration of a harness in a vehicle, in a top-view disposition; while the Detailed View favored the visualization of the connectivity in the elements of the system in a hierarchical manner like in traditional one-line diagrams. Aesthetic yet interactive representations of the network were accomplished considering Visual Analytics strategies. For instance, different colors and symbols were employed to represent the different elements and ease their recognition. Moreover, the user is able to drag the nodes in the screen to procure a cleaner network visualization if needed. Mouse-over tooltips, contextual menus, interactive legends, search-box elements among other tools, permitted to provide the user with helpful information derived from the modeling and simulation embedded in the computer platform. Indeed, the network conditions encountered via simulation are conveniently remarked and provided to the user by means of elements coloring for unwanted states, opportune pop-up informative messages, tables with the electrical variables and time plots. In addition, the user can perform further simulations with wire parameters modifications and witness the effects in the network for those new conditions.

Last, the reported simulation workflow demonstrated flexibility and modularity by means of the mature 3-tier scheme which encompasses the web browser, the web server and the simulation engine. The roles and complete interaction between the 3-tier elements was described in detail to favor a concise understanding about the implementation of this strategy. The use of tailored Python-based data preprocessing at the Back-End allowed to make electrical meaning from factory datasets that are not intuitive as they are mostly intended for manufacturing purposes. By doing so, the electrical network topology of the wire harness was inferred and conveniently organized into different CSV files considering typical data formats from the power systems field. These files were then employed for visualization purposes at the Front-End using the Angular framework for web interface development. When a simulation or further data treatment is demanded by the user, an http request is assigned to the Back-End that again, with the use of the Node.js environment and Python scripts applies the necessary modeling and numerical methods to fulfill the specific user request. Then, a reply with the correlated data is created to update the interface in a useful manner. All this process was designed to enhance the user cognition about the corresponding state of the network in the analyzed scenarios.

7. Conclusions

Computer simulation has been permeating the industry as it contributes to higher system analysis, greater robustness, prototyping reduction and economic savings. This has been the case of some vehicular systems such as aerodynamics, autonomous driving, energy management and electrified traction. However, only lately some sustained research has exposed the use of tailored simulation tactics for on-board Electrical Distribution Systems (EDS), which are responsible for delivering power supply to the equipment within a vehicle. In this regard, this work has reported the development of a web-based simulation platform intended to reduce physical experimentation needs and thus pave the way towards zero-prototyping in vehicular EDS. Considering visual analytics-based precepts to boost user productivity, features such as data preprocessing, visualization, simulation and reporting have been incorporated in a single computer tool for this aim. On the other hand, an intuitive visual understanding of the electrical network was achieved by means of tailored broad level and single-line level schematics. The deployed software functionalities were validated considering a real harness from a commercial vehicle. The practicality and versatility of the proposed architecture, added to the sole use of open-source tools, makes the exhibited platform readily scalable to other automotive or transportation web-based environments that require computer simulation.

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A.2 Development of a Computer Platform for Visualisation and Simulation of Vehicular Distribution Systems

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Development of a computer platform for visualisation and simulation of vehicular DC distribution systems

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Abstract: Contrary to other in-car engineering systems where the use of simulation tools is highly extended prior to a prototyping stage, the simulation of vehicular electrical distribution systems (EDSs) is not still a common practice as manufacturers so far have mainly relied on laborious empirical procedures for technical validation. However, to provide flexibility in EDS design and procure even faster endorsement, the development of computation tools on this subject is compelling considering the intricacy of these networks. To face this challenge, this work provides guidelines and experiences to develop a customised platform for EDS visualisation and simulation within the automotive industry context. The use of agile techniques for software development, visual analytics, and tailored power flow methods is highlighted among other aspects. Realistic case studies are presented to discuss the attributes of the implemented computational tool. To also provide relevant perspectives on how future EDS visualisation and simulation platforms will be developed, the latest research is discussed in topics such as new electric/electronic architectures, electro-thermal analysis, electronic fuses, mild hybrid power trains, hardware in the loop, and high-voltage networks.

1 Introduction

The complexity in electrical distribution systems (EDSs) of vehicles has significantly increased in the last few years due to the use of new electronic devices and sensors, advanced safety functionalities, higher user needs, superior efficiency demands and the continuous electrification of traditional mechanical functions including the insertion of electrically-powered traction systems. Moreover, to ensure reliability, wires in automobiles are usually oversized to avoid temperature increase so that insulation integrity is maintained, and also to warrant an acceptable mechanical resistance to withstand the manufacturing process [1]. For these reasons, more and bigger power supplies, electronic control units (ECUs) and wires are required. This raise in system intricacy and weight provokes more time spending and energy in the manufacturing process as well as efficiency reduction in daily fuel or battery consumption [2]. On the other hand, the amount of information that planning engineers must handle is huge as today's vehicles may contain hundreds of power consumers, up to 10,000 possible wiring combinations and more than 1000 wires having a total extension close to 3 km and weight above 50 kg [3, 4]. Consequently, these networks (see Fig. 1) demand a variety of protections, harnesses, ECUs, and splices to properly transmit signals or power supply to the different components.

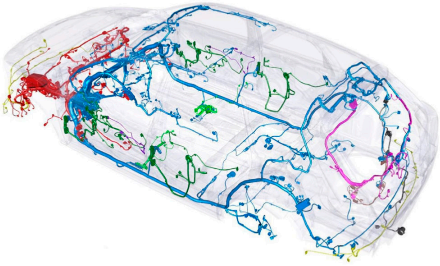


Fig. 1 *Electrical network harnesses of a vehicle, adapted from [1]*

Despite the aforementioned requirements, these electrical networks are not only intended to be flexible and robust but also they are expected to be aligned to fulfil efficiency standards [5, 6], design challenges [7], and emerging environmental policies on greenhouse gases reduction [8]. Besides, the pursue of original equipment manufacturers (OEMs) to add augmented comfort and customised options to consumers has provoked a significant increase in assembly logistics due to the great amount of possible harnesses architectures. To overcome these augmented demands, the use of software platforms at the design stage to suitably visualise, simulate, and analyse the vehicular DC distribution systems is crucial. In this respect, a variety of visualisation and simulation tools exist for the majority of other systems in modern vehicles such as chassis, air conditioning, engine, power train, or electrical drive. The use of simulation tools at the design stage enhances productivity and reduces prototyping costs in these systems. However, this is not the case of EDS in automobiles, where in most cases real prototyping exists at early stages and thus increasing time-to-market. This is a consequence of three main factors: (i) the massive amount of electrical components and wiring harnesses paths and configurations, (ii) the large complexity on integrating disperses and vast data from automotive manufacturers and their suppliers and (iii) the lack of tailored software tools able to carry out a user-friendly yet reliable power flow simulations.

To overcome this information overload, facilitate human–information interaction, and permit the electrical simulation of vehicular EDS, the development of versatile computational platforms is compelling to face these demands. In this regard, software tools such as Power Net Simulation and Simulink permit to examine overall energy optimisation strategies considering general models for the battery and the loads but lack on analysing in detail the on-board EDS in full network models containing all wires, fuses, ECUs, loads, and other components. Other tools such as EBCable, Vesys, Eplan Harness proD, and LDorado are commonly employed in the automotive industry but only permit automobile EDS design. Beyond the design tasks, other software such as Harness Studio, Siemens Solid Edge, and Saber RD have recently included additional modules to perform EDS simulation. However, the latter computational packages do not provide detailed information regarding those add-ons, they neither specify the modelling parameterisation of the different components and the included numerical methods to perform power flow analysis.

To address the aforesaid challenges, in previous work from the authors, the automobile wiring design process, the required manufacturing data preprocessing, and a detailed methodology to perform power flow analysis were presented [9]. Also, in the context of vehicular EDS simulation, the main contributions of this work deal with the aspects of software development, user interface, and visualisation. To contextualise, Section 2 exposes the characteristics inherent to these networks from the automotive product development viewpoint and contrasts their peculiarities with those from conventional power distribution systems. Afterward, Sections 3 and 4 dive into the proposed software development techniques. The first details the guidelines and experiences to deploy a computer platform for the visualisation and simulation of on-board EDS, where the automotive industry framework conditions the particularities of the selected approach. The latter exposes examples of visual representations and simulation results based on realistic vehicular electrical harnesses. Elements to enhance the user experience are discussed all along. Section 5 elaborates on future research and its impact on prospect visualisation and simulation platforms, while Section 6 gathers the conclusions drawn from the work.

2 Vehicular EDS characteristics

In the automotive industry organisation, all the wires and different components (electrical and mechanical) that allow energising every single consumer within the vehicle are considered as part of the EDS. Additionally, from a product development point of view inside an OEM, vehicular EDS does not include the battery and alternator as these elements are regarded as subjects of the energy systems division. Sizing of the energy systems is performed on a previous stage based on the technical concept design of the vehicle. The on-board EDS, similar to any other kind of electrical network, is dimensioned as a function of the allocated loads. Thus, a starting point for planning the EDS is the study of the current consumption of every load, which is then documented and stored in a database saving primarily the average and peak current values under nominal voltage conditions. Then, the EDS design takes into consideration several aspects such as optimisation of cable lengths, integrity of the wiring harnesses, electromagnetic compatibility, and risk prevention. These aspects condition the peculiarities of the electrical network, for instance, the quantity and location of fuse boxes inside the vehicle, the type of protection that should be used on the harnesses depending on temperature, humidity, and friction, among others. To establish a trustworthy operation of the vehicular EDS components, standards with clear specifications are also considered, i.e. the case of the ISO 8820, which details the general test requirements for fuse-links in the DC electrical network of road vehicles. Being fuses the key protective elements, their proper selection is of main importance for a fail-safe operation of the system. Their main function is to protect the wiring. Automotive fuses evolved from glass tube fuses to the current common blade fuses and slow blow fuses among others. In particular, blade fuses usage is widespread in the industry due to their compact size, lightweight, and durability.

The EDS itself has to respond to the activation and deactivation of the power consumers depending on the many functions that are available within the vehicle and are triggered either automatically or manually by the driver. Nowadays, a vehicle can register around 300 functions. This introduces the need for intermediate control devices that coordinate and extend the right signals' shapes to the different components. Such intermediate control devices are the ECUs. Moreover, the power delivery in ECUs must be guaranteed to also provide a physical-media fail-safe communication in all data buses. EDS as of today connects many decentralised ECUs that manage the operation of specific systems. Almost for every particular system that we can identify in a vehicle, there is a primary ECU managing the corresponding functions. For instance, for the window motor, the battery charging, the lighting, braking system, transmission motor, acclimatisation, and so on.

In urban networks, the concept of EDSs usually includes substations, transformers, protections, feeders, and consumers. Although vehicle EDS are appreciably smaller than metropolitan urban grids, they are representative of what one typically finds. There is: (i) the main energy supply, in this case, a battery, (ii) electro-mechanical protection devices (fuses and relays) safeguarding the integrity of the system, (iii) elaborated wiring paths to efficiently transport energy to loads within a range of acceptable voltage levels for variable current consumption and (iv) there might be DC energy conversion stages between high and low voltages as in the case of electric and hybrid vehicles. Validation of the components' quality and the correct network design is cyclically addressed all along the vehicle EDS development process and includes a set of experimental procedures on real prototypes. Contrary, experimentation within the development of metropolitan electrical networks to guarantee their correct operation is inherently difficult. Typically, once the infrastructure in these grids is deployed, they are expected to be immediately 'plugged' and launched to favour immediate energy supply for a given community. Therefore, simulation is a mandatory step for urban electrical networks. In this regard, power flow numerical methods are widely used tools to calculate the electrical variables all along with the network, anticipate proper energy balance and quality assurance of the voltage feed and identify the conditions deriving to instabilities in the system.

In turn, simulation in vehicular EDS is still not a common practice as manufacturers so far have usually relied on empirical procedures with step-by-step regulation guides to size cables, select protections, and estimate voltage drops assuming mainly steady-state conditions. The inclusion of simulation in EDS would be of high significance to test different architectures and configurations, anticipate unwanted voltage drops, and detect design failures in an early stage of the design process. Hence, the prototyping phase would just be focused to validate the optimised EDS design earlier attained via simulation. This design includes the correct selection and dimension of all the wires, protections, and auxiliary coupling elements. Beyond the electrical aspects, the thermal response of the wires and electrical components becomes of paramount importance. As an example, a wire should never reach temperatures leading to the melting of the isolation. Hence, to properly assist EDS designers, it is particularly relevant to the development of a computer tool able to infer temperatures from the estimated electrical parameters and thus assist the appropriate match between a fuse with its wire-load combination. To analyse this match it is not enough to rely on standards but to take into account the maximum peak energy that the fuse has to withstand during its operation. To evaluate this, it is necessary to have the amplitude and duration of peak currents for loads presenting this behaviour. As an example, every time a motor axis is blocked, its current experience peaks. For instance, a scenario could be the case of a driver in a highway under heavy rain or snow and thus using the wipers. Owing to the freeze on the windshield, the current consumption of the wiper motor will be higher than under regular conditions. The deployment of a tailored simulation tool would allow the verification of the previous scenario and many others, beyond what is feasible through on-the-road characterisation.

3 Software development

To develop a tailored EDS visualisation and simulation platform, six main pillars (represented in Fig. 2) have been considered. These foundations benefited: (i) rapid software prototyping (Agile methodologies, user-centred design (UCD), open-source tools), (ii) a clean and intuitive visualisation [visual analytics (VA)] and the incorporation of numerical methods (data pre/post-processing, power flow simulation). These guidelines are described hereafter.

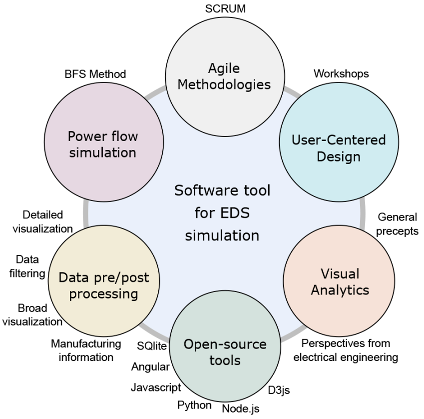


Fig. 2 *Developed computer tool foundations*

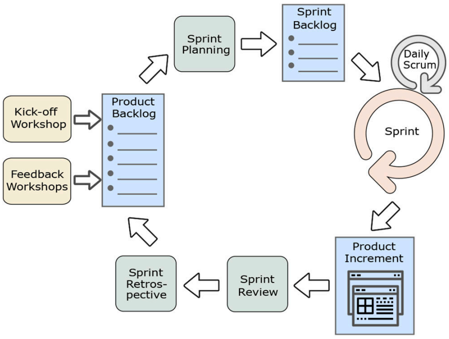


Fig. 3 *SCRUM process*

3.1 Agile methodologies

Plan-driven traditional software development, where sequential and rigid temporal stages exist for the different phases of the process, has been reported to present some drawbacks such as focusing on goals rather than teamwork, delayed working versions, and reduced adaptability to rapid-changing requirements [10, 11]. Based on these pieces of evidence and the aim to develop a rapid-testing yet robust computational tool to be used on a daily basis by engineers related to on-board EDS, Agile methodologies [12] were considered as a cornerstone to leverage team productivity and collaboration. Moreover, these approaches have proved to shorten the process in automotive software development [13]. For these reasons, in the present work, the targeted Scrum agile tactic framework [14] was chosen and adapted according to the time-constraints and profile of the personnel assigned to this project. Nevertheless, the Scrum methodology premises were tried to be satisfied as much as possible to take advantage of its benefits. In this regard, the Scrum Team consisted of a small, multi-disciplinary group of researchers and software developers organised in different roles:

- The product owner decided what was required to be done and prioritised the product backlog which is an ever-evolving list containing all the software requirements.
- The Scrum master removed impediments, facilitated meetings, and guaranteed that Scrum practices were satisfied.
- A development team that generated product increments.

Scrum splits a project into cyclical increments named as sprints. For medium–high complexity projects, a two-week sprint is suggested to procure rapid iteration and incorporation of new functionalities. Depending on the scrum team members' availability, the so-called daily scrum meetings were conducted onsite or remotely to review the advancements (activities are done or in progress), comment any obstacles, find solutions, and share future planned work. In every first daily scrum, the sprint planning took place to socialise the sprint backlog, being this set of product backlog items (user stories) chosen for the sprint. For every item, the corresponding daily activities were listed in a spread sheet that served as the scrum board. In the last daily scrum of the sprint, the results of the work were evaluated and accepted if they fulfilled the expectations; this as part of the sprint review. Finally, a sprint retrospective took place when needed to propose improvements in the scrum process. All the previously described scrum methodology is exposed in Fig. 3.

3.2 User-centred design (UCD)

To enhance intrinsic knowledge from experts and design software for a very specific target group, UCD [15] perspectives were incorporated into the scrum methodology as suggested in [16]. Therefore, to develop a functional tailored software by means of a proper understanding of the nature of the problem, workshops were carried out to gather all the user needs, suggestions, and perspectives concerning the computational tool. The kick-off workshop took place prior to the beginning of the scrum process and gathered potential users and engineers related to vehicular EDS design and testing. In this meeting, some context on the project was initially exposed by the scrum team to the assistants regarding the time planning, development software tools, the need for users involvement, and expected outcomes in virtue of preceding related work, among others. Then, a simple software process-flow [17] was conducted to propose a basic procedure to upload, visualise, and simulate electrical harnesses. This was achieved by means of low-fidelity prototypes (wireframes) [18], which are graphical representations (layouts) of the computer tool containing the most relevant interface elements and content. After this, comments from the participants were received regarding their impressions and suggestions on the process flow, the wireframes, and the corresponding interface elements. This was highly useful as it permitted to understand the users' needs and therefore make a proper initial definition and item prioritisation of the product backlog (see Fig. 3).

Also, regular feedback workshops were organised to receive opinions and validation of the interface process-flow and the proposed (general and detailed) EDS graphical representations. On this, for the general illustration (harness level visualisation), it was agreed to exhibit schemes familiar to other software tools commonly employed by EDS engineers. On the other hand, for the detailed representation (wire-by-wire visualisation), the regularly used electrical layouts were not considered as a starting point as they did not permit and straightforward understanding of the electrical routes and connections.

3.3 Visual analytics (VA)

As denoted by Sedlmair *et al*. [19], 'large companies provide a lot of interesting challenges and complex real-world datasets for information visualisation research'. This statement and the needs of this project motivated the inclusion of VA precepts. Moreover, VA has been remarked as a useful framework for software development in the automotive industry [20]. Indeed, it is a multidisciplinary field that merges different research areas such as visualisation, data analysis, data mining, human–computer interaction, data processing, geo-spatial analytics, statistics, and others [21]. Despite the fact that user experience and efficient human–machine interfaces are of great significance in the automotive industry, only a few academic attempts to use VA in varying depth exist. So far they have been mostly engaged in the domain of computer-aided-design [22], artificial vision [23], vehicle collision [24, 25], engine multibody dynamics [26], virtual reality [27], aerodynamics [28], sensor data [29], and electric

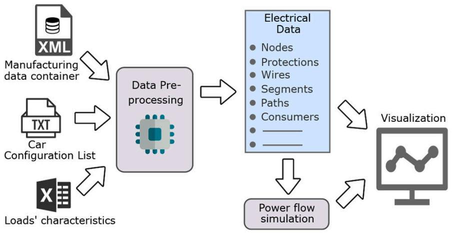


Fig. 4 *Input data for visualisation*

```
Input: Preprocessed electrical data
Output: Branch currents and node voltages
Network components categorization in correspondence to the type and identifier related to their pins
Partitioning of the network into a "positive" and "negative" grid to face complex paths to ground and improve the model accuracy
Incidence matrix creation. Rows represent branches while columns outline to nodes
Determination of the "cut" an "non-cut" branches
Calculation of the branch resistances matrix considering possible temperature variations
Computation of the Thevenin resistances in the "cut" branches by means of a unitary current sequential injection tactic
In view of the incidence matrix, withdrawal of unneeded branches having loops in the "positive" and "negative" grid
for $i = 1$ : Max. number of iterations do
    Calculation of the "non-cut" branches currents as the nodal currents are already defined
    Determination of the node voltages utilizing the "non-cut" branches resistances and the branch currents
    Obtention of the voltage drops in the "cut" branches considering the node voltages
    Obtention of the voltage drops in the "cut" branches considering the branch currents and the "cut" branches resistances
    if The computed voltage drops from the previous two approaches are close enough then
        Include a compensation algorithm based on the Thevenin equivalent resistance to improve the accuracy of the "cut" branches currents
        Break
    else
        Compute the new "cut" branches currents employing the new voltage profile
    end if
end for
```

Fig. 5 *Algorithm 1: pseudocode of the implemented BFS method*

vehicle (EV) charging analysis [30]. Additionally to the previous references, it is worth highlighting the contributions performed in [20] regarding the systematic deployment of visualisation systems for vehicle communication networks in a large automotive company. In the present work, attributes such as proper manufacturing data preprocessing, colour coding, clear appearance, easy navigation, zooming and panning, boxes for elements search, interactive data visualisation, and simulation results tabulation have been incorporated.

3.4 Open-source libraries and database managers

Well supported programming languages (Javascript, Python), robust database managers (SQlite [31]), and open-source and specialised libraries and frameworks (D3 Data-Driven Documents [32], Node.js [33], Angular) have been used in this project. Furthermore, Javascript-based library D3 is being highly employed in a broad variety of information visualisation projects as it permits with ease to add interaction and animation to complex datasets by using scalable vector graphics. Recently, D3 has even been used to increase the awareness of power distribution infrastructure [34]. Despite the fact that the deployed software platform is oriented to local execution, it could easily be upgraded in the future to operate in a cloud computing environment. This may represent an effective alternative to minimise costs, increase accessibility, provide flexibility to customer's demands, and promote resource sharing and agile development [35].

3.5 Data pre-processing and post-processing

In the automotive industry, there is a systematic process to create a file container having all the possible electrical configurations for a particular car model [9]. This container has an extensible mark-up language extension (.xml) and it was mainly designed for automotive industries and suppliers to share manufacturing data. To obtain from these .xml files all the required electrical information for visualisation and power flow studies, laborious data preprocessing is firstly needed to extract the identifiers and characteristics from wires (sections, paths, lengths, insulators), protections, ECUs (topologies, input/output pins) and splices (solder joints). To filter the data and derive the electrical elements present in a particular car configuration, an extensive list (containing the arrangements of the different components) is also required. Additionally, the ratings and pattern consumption of the loads are obtained from components databases. The data pre-processing has a double purpose. On the one hand, it prepares the information to arrange it in the necessary form to deploy a power flow simulator, and on the other hand, it outputs part of the information required for visualisation. In the first stage, for the broad level visualisation, a nodes map is constructed. Every node has associated an x–y coordinate and identifying information. The nodes are interconnected by harness segments. In the second stage, for the detailed wire-by-wire representation, all the wires in the harness are given their source and destination nodes along with the length, section, path, and resistance. Once the power flow algorithm is executed and successfully achieves convergence, the third stage of visualisation takes the results and integrates them into the already developed harness representations. The workflow indicating the data processing for visualisation is sketched in Fig. 4.

3.6 Power flow simulation

To allow a rapid and reliable power flow simulation for the particular characteristics of vehicular EDS (complex weakly-meshed low-voltage DC networks), the backward/forward sweep (BFS) method [36] was chosen as it has been exposed to outperform traditional approaches such as Newton–Raphson and Gauss–Seidel in terms of computational intensity in radial or slightly meshed systems [37]. Additionally, the mathematical formulation for these kinds of networks is more straightforward when BFS is employed. This method relies on the iterative use of Kirchhoff's current and voltage laws. Algorithm 1 summarises the implemented BFS strategy. However, a detailed explanation can be found in [9] (Fig. 5).

4 Interface visualisation and simulation

This section exposes visual representations and simulation results attained with the implemented software tool. Realistic vehicular electrical harnesses have been considered for this purpose. Owing to assembling requirements, vehicular EDS might be formed by the main harness (blue in Fig. 1) which delivers power supply as well as communication and control signals to different secondary harnesses (non-blue harnesses in Fig. 1) such as those related with the bumpers, doors or engine. Bearing this in mind, the general representation (broad level visualisation) of the main harness for a particular car model can be seen in Fig. 6. There, the description of selected power consumers is shown. This harness contains several nodes consisting of different components such as the battery, main and secondary fuse boxes, coupling connectors, ground plates, splices, and power consumers. The main harness is connected to secondary harnesses by means of coupling connectors. For

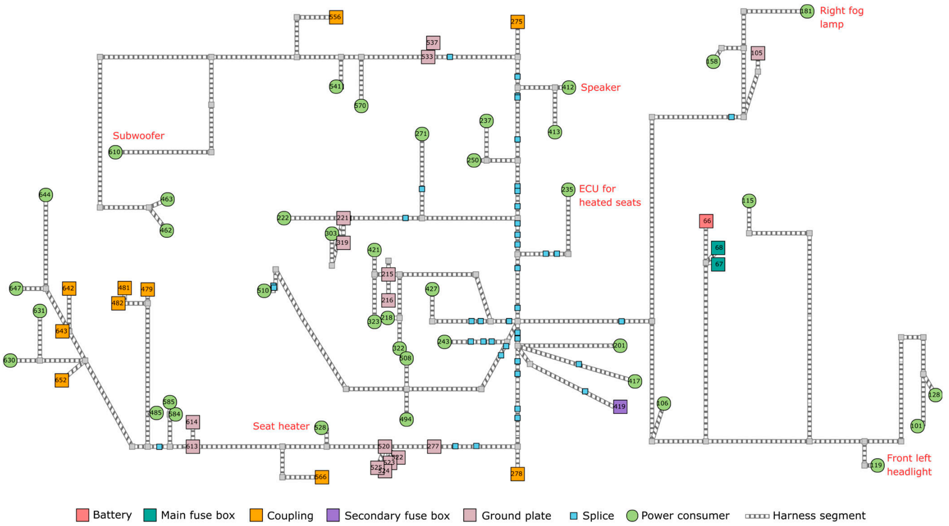


Fig. 6 *Main harness general representation*

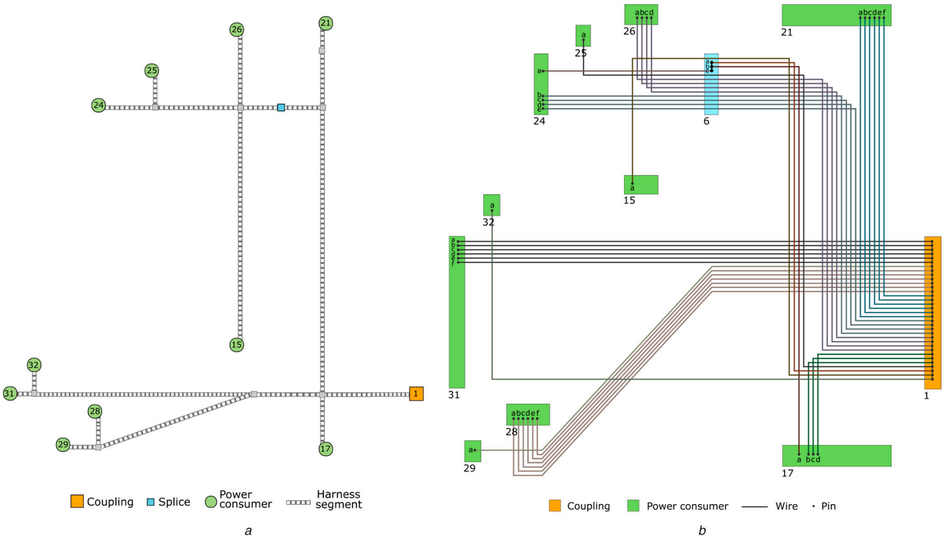


Fig. 7 *Secondary harness*
(a) General representation, ***(b)*** Detailed representation

instance, node 278 in the lower-middle part of Fig. 6 presents a coupling to a secondary harness. The general representation of this secondary harness can be observed in Fig. 7*a* where the aforementioned node 278 has now been named as node 1 for didactic purposes. Besides, Fig. 7*b* exhibits the detailed (wire-by-wire) representation of this secondary harness. The detailed layout was designed to provide the user with an intuitive understanding of the network by resembling the general scheme. To add interactivity and easy navigation to the interface, mouse over highlighting and tooltips, element search boxes, responsive legends as well as zooming and panning options have been included.

Regarding the power flow simulation, Table 1 details the voltage and current calculated for the different consumers in the secondary harness given a predefined power consumption and also considering node 1 having 14.5 V in all its pins. The consumers can be predefined in an active or inactive state. Consumers in nodes 15 and 24 have been deactivated for this test. Voltage drops exist due to the physical characteristics of the lines (length, section, material, temperature) that are extracted and organised in the pre-processing stage and calculated during the power flow simulation. A single consumer may function as a multi-load element, demanding current from different pins. For instance, a headlight

Table 1 Voltage and current in the consumers' loads

Node pin	Power, W	Voltage, V	Current, A
15a	0	14.5	0
17a	1.16	14.4938	0.08
17b	26.1	14.469	1.8
17c	1.45	14.4983	0.1
17d	0.72	14.4988	0.05
21a	29	14.4857	2
21b	29	14.4912	2
24a	0	14.5	0
24b	0	14.5	0
24c	0	14.5	0
24d	0	14.5	0
24e	0	14.5	0
25a	0.43	14.4983	0.03
26a	391.5	14.289	27.4
26b	391.5	14.289	27.4
26c	391.5	14.289	27.4
26d	391.5	14.289	27.4
28a	2.9	14.4903	0.2
28b	2.9	14.4903	0.2
28c	2.9	14.4903	0.2
28d	29	14.4028	2.01
28e	116	14.103	8.23
28f	87	14.2044	6.12
29a	0.29	14.499	0.02
31a	2.9	14.4893	0.2
31b	2.9	14.4893	0.2
31c	2.9	14.4893	0.2
31d	29	14.3923	2.01
31e	116	14.0589	8.25
31f	87	14.1718	6.14
32a	0.29	14.4989	0.02

Table 2 Line currents

From node pin	To node pin	Voltage drop, mV	Current, A
1	6a	3.71	0.08
24a	6c	0	0
1	15a	0	0
6b	17a	2.48	0.08
1	17b	30.96	1.804
1	17c	1.2	0.05
1	17d	1.72	0.1
1	21a	14.26	0.776
1	21b	8.84	0.481
1	21c	14.26	1.226
1	21d	8.84	0.76
1	21e	0	0
1	21f	8.84	0.76
1	24b	0	0
1	24c	0	0
1	24d	0	0
1	24e	0	0
1	25a	1.67	0.03
1	26a	210.97	27.398
1	26b	210.97	27.398
1	26c	210.97	27.398
1	26d	210.97	27.398
1	28a	9.66	0.2
1	28b	9.66	0.2
1	28c	9.66	0.2
1	28d	396.97	8.225
1	28e	295.6	6.125
1	28f	97.18	2.013
1	29a	0.96	0.02
1	31a	10.7	0.2
1	31b	10.7	0.2
1	31c	10.7	0.2
1	31d	441.07	8.251
1	31e	328.17	6.139
1	31f	107.71	2.015
1	32a	1.07	0.02

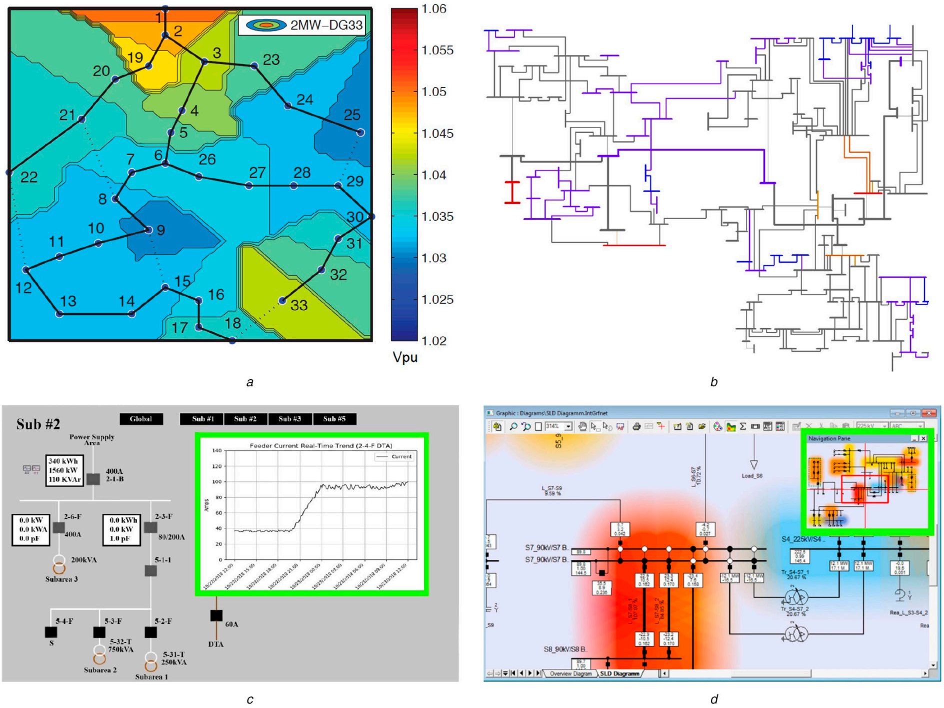
can have three loads associated: one for the blinker, one for the high beam, and another for the dimmed beam. Additionally, Table 2 exhibits the line currents and voltage drops. As can be seen, the results are coherent all along with the network for the assumed power demands in the consumers' loads validating the implemented BFS power flow algorithm. The visualisation and power flow analysis aforementioned described can be extended to other vehicle harnesses having their particular network topologies.

5 Future research and trends on vehicular EDS

This section begins exposing future software functionalities and research regarding the inclusion of VA from the power engineering experience. On this, some context is provided to then comment on possible forthcoming developments from these perspectives. Next, the analysis and visualisation of thermal conditions are discussed. Later on, to also provide the reader with some insights and trends that will play a significant role in future on-board EDS and the way in which simulation platforms are developed for these systems, topics such as new electric/electronic (E/E) architectures, electronic-fuses (e-fuses), hardware in the loop (HiL), mild hybrid power trains, high-voltage networks, and power converters are discussed as well.

5.1 Tailored VA

Bearing in mind that VA techniques permit the user to rapidly and intuitively obtain insights and sufficient understanding of the electrical network in the study, the adaptation of well-proven visualisation precepts from power systems will be highly relevant. In this respect, colour contouring [38, 39] (see Fig. 8*a*) would enhance visual EDS diagnosis as colour serves as an effective highlighting feature allowing a rapid localisation of problematic zones or elements in large and complex networks [40]. Under this approach, nodes voltages and branch currents are usually employed to build the corresponding background colour grid. A similar tactic to this strategy is colour coding [41] where transmission lines or buses themselves are represented with discrete colours according to their voltage or current levels (see Fig. 8*b*). On the other hand, the incorporation of time plots will permit us to observe the evolution of varying data (voltage, current, power) over time once the temporal simulation is included in the software (see Fig. 8*c*). Additionally, as in vehicular-DC networks, there is a vast amount of components, wires, and paths; the automatic one-line diagrams generation [42–45] added to the inclusion of navigation panes (see Fig. 8*d*) will be beneficial. In these on-line layouts, the inclusion of animations representing the system power flow will emphasise the energy delivery correlation between the different elements. Taking into account that in on-board EDS the geographic or coordinate position of nodes is not compulsory for visualising and understanding the network, the use of force directed graphs [46] to avoid overlapping of lines or the adoption of multi-dimensional scaling with 'electrical distances' [47, 48] to infer electrical connectivity, could represent valid alternatives to be taken into account when analysing troublesome or critical conditions. Nevertheless, all these aforesaid visualisation techniques should be handled with care and given on-demand. Otherwise, the user could be overwhelmed with the amount of information visually given [40].



a

b

c

d

Fig. 8 *VA techniques from power systems*
(a) Colour contouring taken from [49], ***(b)*** Discrete buses colouring (blue ≤0.96 pu and red ≥1.04 pu), taken from [41], ***(c)*** Time plot, adapted from [50], ***(d)*** Navigation pane, adapted from [50]

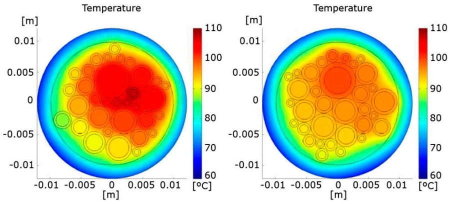


Fig. 9 *Thermal response for two different wire bundles configuration, adapted from [1]*

5.2 Thermal analysis

The electrical simulation of vehicular EDS is closely tied to the inner thermal characteristics of the electrical components but also to the corresponding elements and environments surrounding them. For instance, the wires resistance can be linearly correlated with the temperature as in (1), being T the ambient temperature and α the temperature coefficient of resistance. This was the approach employed in this work to relate the electro-thermal interaction in wires

$$R(T) = R(T_0)[1 + \alpha(T - T_0)] \qquad (1)$$

However, to achieve more accurate power flow simulations, there is room for future research regarding an improved estimation of the wires' isolation temperature. Nonetheless, as wires in bundles transmit heat between each other, all the wires in their particular harness segment should be also taken into account. Indeed, the wires' temperature inference is not trivial given [51]: (i) the great number of wiring harness paths and combinations, (ii) the random distribution of wires in bundles as they are manually assembled, (iii) the presence of wires carrying only control or communication signals, (iv) the non-uniform heat dissipation along the wire's section and length, and (v) the difficulty to infer neighbouring temperatures due to the thermal particularities of the different vehicle car compartments such as those which house the motor, doors, bumper, roof, or base platform. As a starting point, to simulate the thermal response in wire bundles in nominal conditions and during short-circuits, the use of finite element analysis has been presented as a reliable tool [1] suited to enhance user experience and understanding. For instance, Fig. 9 exhibits the radial thermal behaviour in a harness for two different wire bundles configuration. This figure provides a brief insight into the complexity to perform accurate electro-thermal simulation when different elements and thermal environments are involved. However, the extension of this tactic to EDS zones or complete harnesses would provide the user with valuable information and intuitive representations of troublesome thermal areas, paths or elements in the electrical network given certain conditions or scenarios.

5.3 New E/E architectures and e-fuses

Contrary to isolated hardware-oriented architectures, future E/E systems will be designed to integrally merge the vehicle hardware (ECUs, sensors, actuators, loads, protections, wires, communication, and connecting devices) by means of a central computing platform and a unified software. In this respect, on-board EDSs are moving towards standardisation and scalability. To do so, the incorporation of robust power devices and a new conception of vehicular e-fuses is required [52]. Indeed, e-fuses will dramatically outperform typical electromechanical protection devices (fuses and relays) given their controlled short-circuit current, rapid precise reaction-time, and fault-tolerance capability. For instance, specialised EDS software could permit engineers an intelligent parameterisation of time-current curves for the different e-fuses in the network, allowing robust protection coordination. Moreover, some work has been proposed towards enhanced reliability functions by means of safety mechanisms at device and system levels [52] and decentralised modular architectures [53]. Under this last approach, smart distributed power devices can be achieved with different DC/DC converters where conditions such as over-temperature and overcurrent are constantly informed to master control. Despite some efforts on the initial development of e-fuses some years ago [54–56], it must be mentioned the lack of academic research regarding the integration of smart e-fuses into on-board EDS. Relevant information on this topic can be mainly found in manufacturers or vehicles' societies websites as in [53, 57, 58].

In this context towards a paradigm shift favouring universal E/E architectures, significant efforts must be devoted to the development of modular software packages having combined design environments. This will permit us to analyse the interaction and avoid conflicts between different vehicular subsystems which are currently designed independently such as the EDS, the high-voltage power conversion system, electric charging, communications network, battery energy management, and electro-mechanical traction. This convergence will be reflected in improved system reliability, programmability, and coordination.

5.4 Mild hybrid EVs (MHEVs)

In 2019, the amount of fully EVs, hybrid EVs (HEVs) and plug-in HEVs (PHEVs) sold worldwide (around 2.2 million) represented a 2.5% market share over all vehicle sales [59]. However, by 2030, it is expected to rise to a 30% share [60]. Hence, until HEVs and EVs get consolidated in the market, sustained efforts are taking place to improve the conventional internal combustion engine (ICE) technology and fulfil European regulations such as the limit of 95 g/km of carbon-dioxide emissions in new passengers cars [61]. In this respect, the incorporation of mild-hybrid powertrains has been exposed as a convenient approach to improve fuel efficiency up to 20% with reduced costs [62]. It consists of adding to the conventional 12 V battery system, an additional 48 V supply. This higher voltage availability in MHEVs permits the extraction of sufficient power to use a small electric motor/generator intended only to assist and act as a power booster for the ICE. By doing so, no insulation upgrades are required and the fuel consumption is reduced by decreasing the engine idling time when the vehicle is stopping, braking, or cruising. Moreover, the electric motor can guide the ICE to efficient operating points and even accomplish partial regenerative braking [63]. Given these benefits, automakers are showing high interest in mild hybrid technology. This is evidenced by some international industrially oriented conferences and expositions that have been taking place in the last few years with the aim of consolidating the 48 V power supply systems [64].

From the software design point of view, simulation capabilities can be leveraged by considering recent related academic contributions. Between these we have optimal hybrid energy management [63], low-cost 48 V switched reluctance drive [64], DC/DC converter architectures [65, 66], hybridisation degree levels [67], motor-inverter power module for electric compressor [68], modelling and validation of lithium-ion battery packs [69], and integrated converters for mild hybrid starter-generators [70, 71].

5.5 Vehicular high-voltage networks and power converters

In the last few years, as the literature reveals, most of the academic efforts related to electrical systems in vehicles have been devoted to the development of new power conversion and charging systems towards electrified traction. On this subject, towards electric mobility, two main scenarios are being witnessed: (i) the short-term migration from ICE vehicles (ICEVs) to MHEVs, already contextualised in the previous subsection and (ii) the progressive strengthening of PHEVs and EVs in the market. For this second scenario to promptly unfold, the design of future on-board E/E architectures and powertrains must be reformulated to suitably integrate high-voltage machines (beyond 200 V) requiring high torque and power densities such as those based on permanent magnet materials [72]. The DC-link voltage is nowadays normally designed around 400 V but it is expected to rise up to 800 V where wide-band gaps or silicon-carbide devices are used on the power inverters [73]. Furthermore, automotive manufacturers have started integrating into common enclosures the inverter with the other vehicular power electronics systems to minimise connections, reduce size and weight, and reuse common functionalities [73]. Additionally, the use of multi-phase and multi-level drivers has been exhibited as an attractive solution to improve torque-density and handle DC-link voltages >800 V, respectively [74]. On the other hand, regarding the energy storage in batteries and their charging systems, consistent work has been exposed towards fast and wireless charging [75, 76] and flexible vehicle/grid interaction [72]. As the actual lithium-ion-based technologies are arriving at their theoretical specific energy limits, some research on the use of solid-electrolyte-based lithium batteries and hybrid energy storage systems (including supercapacitors or fuel cells) has been proposed to favour longer operating cycles, improve power density and increase lifetime [77]. It is also noteworthy that the relevance of battery management systems (BMSs) to monitor and control proper states of charge and state of health in the battery packs [77]. In future vehicular EDS, the BMS will be required to be a functional aspect of a universal software able to monitor and control all the relevant low- and high-voltage electrical components and systems part of the entire E/E architecture. Finally, to enhance resiliency on vehicular EDS, some efforts have been proposed to achieve energy assistance from the high-voltage to the low-voltage side during normal operation modes [78, 79]. Nevertheless, these approaches should be extended to critic or extreme conditions.

5.6 Hardware in the loop (HiL)

On-board EDS design and simulation platforms can also take significant advantage from HiL systems to attain accurate dynamic models for the different electrical elements, emulate if needed some system components (sensors, ECUs, actuators, mechanical parts) and thus refine and validate the numerical methods. To do so, some HiL experiences in vehicles should be considered and adapted. For instance, HiL has been employed to emulate vehicular ECUs, improve plant models, facilitate rapid-prototyping, and perform standardised tests [80, 81]. Research on the use of HiL for assisted and autonomous driving has also been presented [82–84]. An analysis of mechanical–electrical traction shift in HEVs is exhibited in [85]. Additionally, an internet-based HiL testbed for HEVs, able to integrate distributed vehicular subsystems can be found in [86].

6 Conclusions

As a consequence of new regulations, novel electrification trends, and higher user demands, the complexity in vehicular EDS has significantly increased in the last few years. Hence, EDS design represents a highly demanding stage in the automotive industry manufacturing. In this respect, EDS conception should incorporate versatile interfaces to test different architectures and configurations, anticipate unwanted voltage drops, and detect design failures in a prompt stage of the design process. Moreover, computational platforms would permit the analysis of demanding EDS scenarios, beyond what is feasible through prototyping or on-the-road characterisation. This paper has reported strategies and experiences to develop a specialised computer tool for EDS visualisation and simulation. Regarding the software development methodology, some cornerstones such as the SCRUM agile framework, UCD, and open-source libraries have been exposed to leverage teamwork productivity and facilitate rapid software prototyping. By means of the implemented computer tool, broad and detailed level visual representations have been exhibited for realistic EDS harnesses. Consistent power flow simulation results have also been presented given predefined power demand in the consumers. On the other hand, VA has been exposed as a promising research field able to enhance the user experience by means of aesthetic yet functional interfaces. Besides, the adaptation of well-proven VA techniques from conventional power systems represent promising alternatives to permit users a rapid and intuitive understanding of the on-board electrical network. As has been elaborated in virtue of recent research, future simulation and visualisation platforms for EDS must be developed to face new challenging technological trends being witnessed by the automotive industry.

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A.3 Toward Smart Vehicular DC Networks in the Automotive Industry: Process, computational tools, and trends in the design and simulation of vehicle electrical distribution systems

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Toward Smart Vehicular dc Networks in the Automotive Industry

BACKGROUND ©ISTOCKPHOTO/COMICSANS

Process, computational tools, and trends in the design and simulation of vehicle electrical distribution systems.

THE AUTOMOTIVE INDUSTRY IS EXPERIencing unprecedented requirements to fulfill higher expectations from customers and include new functionalities in vehicles, such as driving assistance, gadget connectivity, sharing capabilities, and electrified traction. The electrical network is currently one of the most challenging onboard systems to be designed and prototyped because these demands add to its intrinsic complexity.

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 of more than 50 kg. As a consequence,

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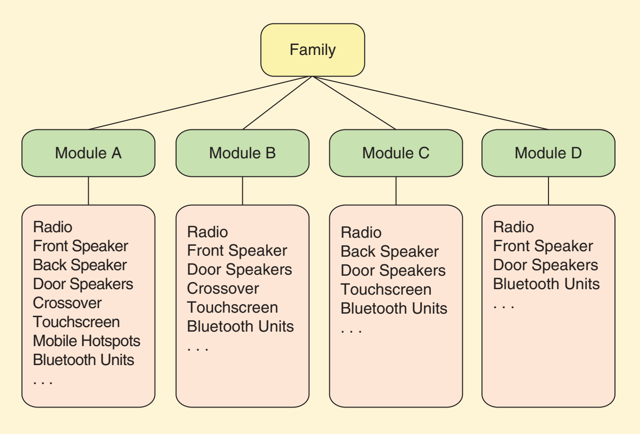


Figure 1. There may be some module options to fulfill a specific vehicle functionality (family).

Figure 2. The complete EDS of a vehicle can be composed by a set of different wire harnesses. (Source: SEAT S.A.; used with permission.)

there may be up to 10^{10} possible wiring architectures, which requires a great logistics effort to integrate, disperse, and store data from manufacturers and suppliers. The development of software platforms must suitably visualize, analyze, and simulate these intricate vehicular electrical networks in multiple possible configurations and scenarios.

The prompt detection of failures in the electrical distribution system (EDS), such as unwanted voltage drops or erroneous components sizing, can be achieved only by means of versatile power-flow simulation. Hence, those configurations not complying with operational and safety requirements could be dismissed in an early project stage. With a simulation phase evaluating many architectures within the EDS design, the prototyping stage could simply be used to endorse the results previously attained with numerical methods. Therefore, the time to market may be shortened, as the required number of prototypes could be potentially reduced.

To enhance 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 designers with analytical reasoning by means of interactive interfaces. To realize this, it is crucial for these tools to include perspectives from visual analytics (VA), a multidisciplinary field that has gained significant attention in recent years because it facilitates human–information interaction and intuitive understanding of complex systems with large data sets, as in the case of vehicle EDSs.

The Wiring Design Process in Vehicles

Currently, most manufacturers offer selectable functionalities to customers for a particular car model, even if this greatly increases the logistics complexity of the development process. A modularity strategy is used to allow this customization while ensuring proper electrical operation in all of the configurations. This approach is based on the use of families and modules. A family consists of a group of elements able to perform a specific function, such as the sound system, which is made up of different components, including the radio, front speakers, back speakers, touchscreen, and so on. The components, in turn, are organized inside modules. With this technique, a family can be formed by different modules, each composed by predefined components, that might represent a different level of complexity of the required functionality (Figure 1). In the example of the sound system family, possible configurations could include modules A and B. Module A could represent a better-equipped sound system compared to module B.

The elements in a specific family include not only electrical (fuses, wires, relays, connectors, and loads [i.e., the speakers 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 selections, the complete EDS of a vehicle can be composed of a set of different wire harnesses (such as that 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 types of loads included in the harness have a significant impact on the selection of its wiring cross section and electrical protections. The final product of this stage is the complete description of the wiring harnesses as they would be installed inside the vehicle, maintaining the modularity information. Figure 3 shows the scheme of all of 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), which includes diagrams of the logical connections among all of the components inside the full onboard EDS. The WS shows 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, in what is referred as *wiring plans* (WP), the numbering of the cables, wiring cross sections, couplings, and other physical characteristics are added to the WS.

The elaboration of the routing files for the wires takes place simultaneously with the development of the WS and WP files. Here, all of the wire paths between components are designed, with the mechanical constraints considered, and then traced into 3D CAD files. Similar to the case of the WS and WP, there is a database containing the graphical information of every component. After this, the WP files are combined with the routing diagrams to generate a full graphical description of the wiring harness, which also contains the cable-length information. From this merge, a file from the German “Kabel Baum Liste” (“Cable Tree List” in English) [referred to as *KBL (Kabel Baum Liste)*] with an XML extension is created. The KBL file embeds all of the required manufacturing information of a wiring harness and also contains 3D information that can be later represented in elaborated 2D WS layouts known as *full-wiring drawings*. There is a KBL file for each harness in a vehicle. The process is shown in Figure 4.

To complete the database creation process, two Excel files are automatically generated from the KBL file: the wire list (WL) and bill of materials (BOM). The WL includes a numbered list of all of the wires present in the harness, along with information, such as the identification tag, origin and destination node with pin information, total length, cross section, color, and insulation type, among others, together with the family and module to which each cable belongs. This list is critical because it contains all of the connections performed with wires. On the other hand, the BOM file lists electrical components that are not wires, including not only fuses and relays but also

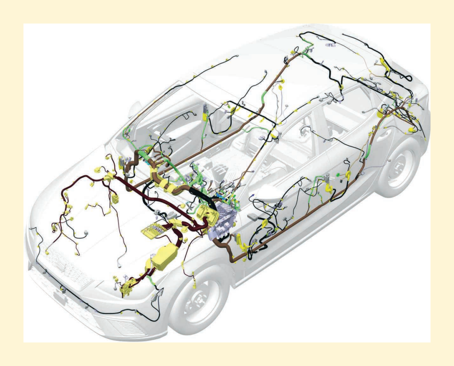


Figure 3. All of the wiring harnesses present in a car. (Source: SEAT S.A.; used with permission.)

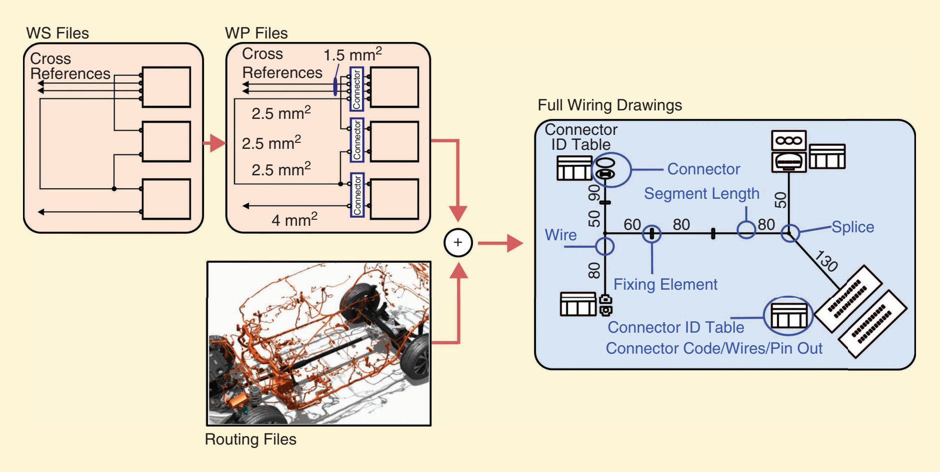


Figure 4. The full-wiring drawings’ design process.

elements from the wire harness that have only mechanical purposes (such as fixings, wire guides, and so on), specifying the module and family for each one.

Computational Tools for the Simulation of Onboard EDSs

Simulation in automotive engineering was first used in the domains of aerodynamics, vehicle collision, and engine multibody dynamics. In recent years, these efforts have expanded to areas such as artificial vision, virtual reality, network communications, energy balance, electrical traction, and charging systems. However, as a consequence of the largely dispersed factory information and sharp intricacy of vehicular EDSs, only a few commercial platforms and even fewer academic efforts have proposed computational tools able to perform a detailed simulation of these systems, considering the necessary manufacturing data preprocessing, complex wiring, and different electrical components forming the harnesses.

Commercial tools (such as EB Cable, Vesys, and EPLAN Harness proD) permit only design duties but are not suited for simulation. Meanwhile, platforms (e.g., Power Net Simulation by Bosch and Simulink from MATLAB) mainly allow simulation of the overall energy balance, employing general models for the battery, alternator, and loads, all operating under selected scenarios and driving conditions. Finally, software tools (for instance, Harness Studio, Siemens Solid Edge, and Saber RD) have typically assisted in harness design but, recently, 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 establishment of a benchmarking between them. The next section details an entire procedure for successfully performing a reliable power-flow simulation for onboard EDSs, taking into account the available automotive-factory data formats.

Tailored Power-Flow Simulation for Smart Vehicular Electrical Networks

Data Preprocessing

The data containers with the most 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 were not conceived for electrical simulation. In addition, they do not contain all of the necessary data, such as time-current characteristics of fuses, the temperature class of each cable, or pin-out information of the consumers, among others. Therefore, to create a proper data container intended for power-flow studies, in addition to including the WL and BOM archives as inputs, a customized multidimensional data structure has been created, referred to as QT. This is an Excel file having condensed information from the automatically generated BOM and WL but complemented with the aforementioned missing data, which have been taken from other dispersed databases.

As the XML files were originally designed to contain all of the possible modules that exist for a given family within a car model, the newly generated data container provides, by default, the full module information. In practice, a specific vehicle is described by the selection of only one module per family; thus, its simulation requires filtering of the data container. To achieve this, the user introduces 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 preprocessing algorithm removes the unnecessary information. Finally, the filtered data are used forward as input for the power-flow solver. Figure 5 sketches the overall data preprocessing process.

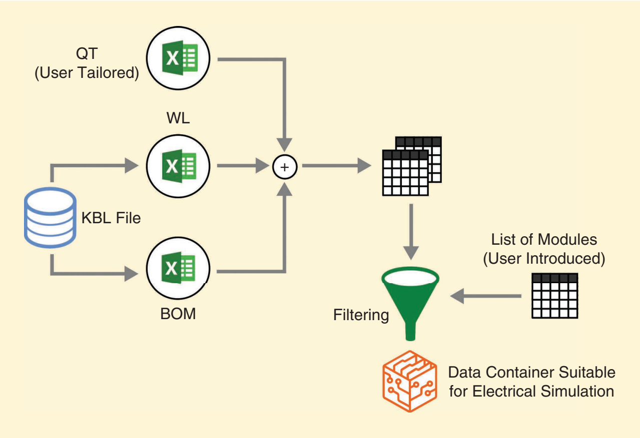


Figure 5. The overall data preprocessing process.

Tailored Power-Flow Simulation

Traditionally, the algorithm most used for solving power-flow studies in conventional electrical systems relies on the Newton–Raphson criteria. However, the algorithm chosen for vehicular EDS features is the method known as *backward/forward sweep* (BFS). This method uses the Kirchhoff's current and voltage laws (Kirchhoff's current law and Kirchhoff's voltage law) iteratively. It was selected mainly for the following reasons.

- The formulation for this specific application case is simpler.
- The convergence speed of these BFS methods has proven to be better than that of the Newton-based tactics in radial or slightly meshed systems.

To provide some insights into the tailored developed algorithm to perform power-flow simulation for the vehicular EDS, the main highlights of the procedure are listed as follows.

1) The network components are classified as consumers or source, according to the type and number of their pins.
2) The interface between the positive and negative grids is determined. The onboard EDS has been considered as having a positive and negative grid. The former refers to all of the nodes and segments connecting the positive terminal of the battery to components and between them, whereas 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 separate 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. In addition, it has been verified that this approach benefits the accuracy of the model.
3) The incidence matrix providing the connections data, where each row represents a branch of the system and each column a node, is formed. The cut and noncut branches are also defined.
4) The branch resistance matrix is obtained by using information about wire length between the 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) All of the Thevenin resistances of the cut branches are calculated by using a unitary-current sequential-injection method, in which 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 ECUs, the procedure is exactly the other way around: the current associated with a ground pin is split among its associated input pins.
6) The branches that define loops in both the positive and negative grids are removed by analyzing the incidence matrix. Hence, a compensation technique will be included afterward 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 noncut branches are calculated directly 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 by making use of the branch currents and resistances of the noncut branches. At this stage, the voltage drop in the cut branches can be calculated using two different approaches.
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) With the second method, the branch currents and resistance of the cut branches are used to calculate the voltage drop.
12) If the voltage drop error is lower than a predefined threshold, the calculated voltage drops are analyzed to determine if they are consistent.
13) Both described approaches must match when the algorithm convergence is achieved. If not, the second method is used to update the branch currents, as in step 8, and a new iteration is launched. A detailed explanation of the entire previous methodology can be found in Mantilla-Perez et al.

Case Study

The aforementioned methodology is quite simple but sufficiently robust and efficient to tackle the challenges involved in the EDSs of vehicles, as this section illustrates 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 the prefix "F"). The nodes identified with the prefix "Sp" are splices nodes; splices represent ultrasonic soldered connections of multiple wires. Consumers have been named with the prefix "C," while couplings and ECUs have the prefixes "K" and "E," respectively. The numeration is not exactly consecutive to represent the fact that, given the modules selected, certain components were filtered out in the data preprocessing stage.

Component E1 is an ECU, classified as "source." It has four pins: pins 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 interconnected through the vehicle body itself. The battery ground or negative terminal is identified with the code gr00.1. Figure 6 shows the different node voltages and branch currents. Voltage drops are encountered in the lines as a result of the calculated line resistances, given their physical characteristics. Nominal node voltages decrease following the power flow, as expected. In addition, the voltage drop in fuses depends on their type, and

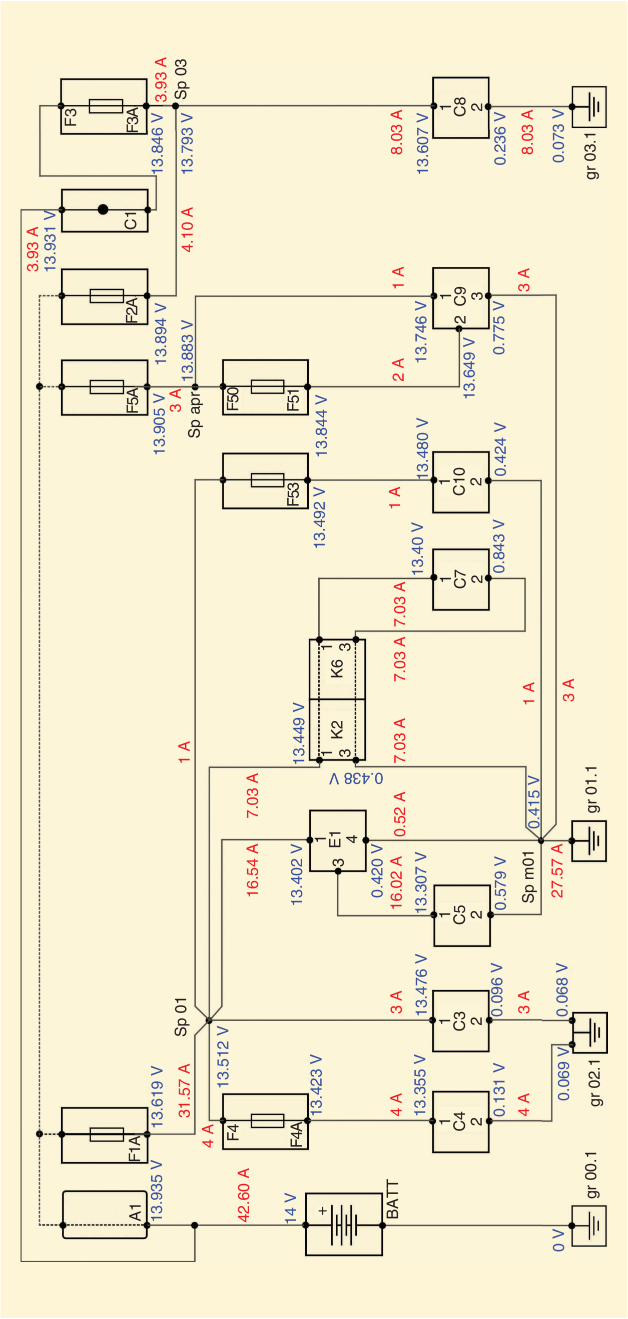


Figure 6. A sample network showing different node voltages and branch currents.

the calculated branch currents are consistent all along the circuit.

Future Research and Trends Toward Smart EDS

Proper results were attained in the case study given a simplified network. Furthermore, the proposed simulation strategy is able to individually analyze the different harnesses in the onboard EDS. In addition, the described methodology may also serve as a referential framework to begin including other functionalities and ongoing trends procuring the development of smart vehicular EDSs, some of which are described in the following sections.

Thermal Studies

The inclusion of heat thermal analysis is of high relevance and may allow the study of the thermal behavior of automobile cable harnesses in the steady and transient states, 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 predefined scenarios. In this regard, some advances have been proposed by Rius, although, in that case, the modeling is limited to the simulation of single wires or bundles but not applied to the entire EDS.

HiL

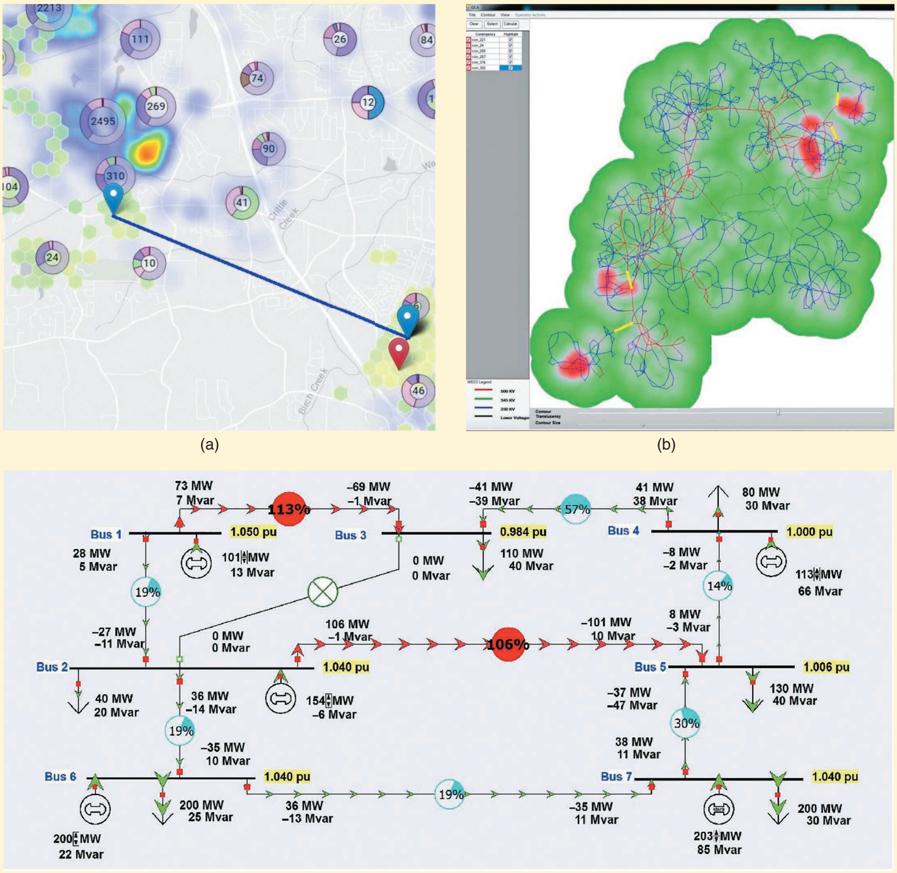
The role of HiL is becoming more significant in the automotive industry, as it provides an efficient alternative for performing trustworthy simulations and developing robust control strategies for complex and challenging applications, such as autonomous driving or electrical–mechanical traction shift in hybrid electric vehicles. For the case of onboard EDSs, the use of HiL would permit the development of accurate dynamic models and analysis of the real-time transient and steady-state responses 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 offline simulations will be enhanced to exhibit highly accurate results. This will provide EDS designers with sufficient industrial reliability to promptly endorse or discard different network topologies and configurations at an early stage.

Automobile High-Voltage Networks, Power Converters, and Smart Energy Systems

Electric and hybrid vehicles sales are growing exponentially; therefore, for reliability purposes, it is necessary to enhance the interaction between the high-voltage (HV) power conversion stage and the low-voltage EDS. Despite the fact that both systems are now intended to exchange energy in normal operation modes, under extreme conditions, the onboard EDS should be resilient and flexible enough to receive energy from the HV battery to maintain the proper supply of critical loads. In addition, the EDS could be designed to provide the user with warnings and messages related to early fault detection and the status of the ongoing system performance.

VA

VA has emerged as a promising multidisciplinary field that encompasses different research areas, including



(a)

(b)

(c)

Figure 7. VA techniques have been used in electrical networks for other applications such as (a) distribution system metering visualization and contingency analysis in (b) multiple or (c) single scenarios. [(a) Source: Lawanson et al. 2018; used with permission.] [(b) Source: Wong et al. 2014.] [(c) Source: Overbye and Weber 2015; used with permission.]

visualization, data analysis, data mining, and human–computer interaction, among others. It has been employed in different disciplines to gain knowledge, amplify cognition, and get insights from large and complex data sets. In electrical systems, some contributions have been made by means of VA; however, all of them focused only on power systems, not on extensive, weakly meshed, and structurally complex low-voltage dc distribution networks, as in the case of vehicles. The inclusion of VA precepts and tools in onboard EDS simulation platforms would be of high significance, as it may permit the development of aesthetic yet functional interfaces, enhance intrinsic knowledge from designers, improve the visualization of electrical parameters, determine risky or unsuitable electrical configurations, and perform batch simulation and data mining, among others. Many possibilities appear just by adding some interactive techniques, such as color contouring, animation, data aggregation, and automatic layout generation, are included. Figure 7 exemplifies the use of those techniques in interfaces for electrical networks of other ambits. However, the reader can infer an idea of the possibilities for VA practices to leverage interactivity, assist knowledge acquisition, enhance user experience, and achieve the visualization needs of the intricated EDSs 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 huge numbers of possible wiring paths, configurations, and components. This necessitates 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 onboard EDS has been justified in this article. These computational tools can be of great significance to help engineers study the network under various conditions and topologies before a prototyping stage. Therefore, inappropriate configurations may be promptly discarded, thus shortening the design process.

To perform numerical simulation in the onboard EDS, a data preprocessing stage is first needed to collect the required electrical information from different manufacturing data files. To perform a power-flow analysis, the 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 on and results of the custom-developed power-flow algorithm have been provided. The proposed case study exhibits consistency in the attained voltage drops and branch currents throughout all of the elements.

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

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A.4 Vehicular Electrical Distribution System Simulation Employing a Current-Injection Algorithm

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Vehicular Electrical Distribution System Simulation Employing a Current-injection Algorithm

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***Abstract*—Modeling and simulation have been permeating all development areas within the automotive industry such as structural simulation, powertrain, engine, thermal management, electronics and also the electrical distribution system (EDS) design. Rapid adoption of simulation techniques has the potential of reducing prototype manufacturing and thus vehicle time-to-market. This paper provides a methodology towards vehicle EDS simulation based on the Current-injection algorithm to calculate electrical variables within the network and detect early phase design problems. This algorithm allows for a high convergence speed of the computed results and is applicable to combustion vehicles, hybrids or full electrical vehicles (EVs). We compare the simulated results with the measurements on a test bench of a real automotive wire harness and a vehicle prototype to validate the calculated results.**

***Index terms*— Automotive modularity, vehicle electrical distribution system, DC power flow, Backward/Forward Sweep.**

I. INTRODUCTION

As vehicular electronics gain in scope and variety of functionalities, so does the importance of reliability within vehicular Electrical Distribution Systems (EDS). The vehicle EDS supports the operation of an increasing amount of critical safety functions towards highly automated vehicles. Moreover, in this days warranty of continuous energy supply and communications data are mandatory for a trust-worthy operation of fully autonomous vehicles. In a first stage, attention has been given to integrated electrical vehicle (EV) energy management systems, such as reviewed in [1] and [2]. However, most of the recent works on power flow simulation related with automobiles refer to the relation between the distribution network and the EV as a dynamic element, absorbing or delivering power to the network [3]–[5]. The different articles employ diverse strategies towards minimization of both battery charging/discharging and degradation cost due to vehicle-to-grid (V2G) operation. In [6], a flexible day-ahead optimal control (DAOC) model based on the three-phase power flow and sensitivity analysis is described to manage the available EV battery capacity. A new research field known as Deep Reinforcement Learning (DRL) is implemented by [7] in stochastic EV charging navigation, to extract information such as charging prices and waiting time at charging stations and thus minimize total travel time and charging cost. On the other hand, introduction of optimization schemes using photovoltaic-powered charging stations are presented in [8], [9]. The work by [10] analyses a series of charging cost minimization algorithms applied to the problem of one vehicle associated to one house. Regarding multiple target optimization, according to [11] it is possible to achieve a globally optimal solution that fits a sustainable EV charging scheduling together with minimization of the cost of power generation. As seen, there is a wide amount of works devoted to the aforementioned topic, however literature related with vehicular electrical distribution systems (EDS) simulation is scarce. In previous articles, the authors introduced a review of the state of the art in EDS simulation [12] while a general overview of the EDS characteristics is also given in [13]. Analysis of the vehicular EDS itself, even if not widespread, should be kept in focus and not treated as a fully solved topic. Nowadays, the automotive industry is experiencing an enormous pressure to update the current wiring harness development processes in order to comply with stricter regulations [14] such as Functional Safety for Road Vehicles ISO 26262 [15]. The introduction of ISO 26262 within the wire harness development is not straight forward. Since 2015 there exists an industrial work group that is exclusively dedicated to the topic of evaluating risk failure of the wire harness components [16]. Technical limitations that will affect manufacturing will have to be addressed, but also other aspects are to be covered such as a stricter changes management, traceability and consistency [16]. The final goal is to ensure an intrinsically safe EDS. From the authors' perspective, one key to support such required process re-invention is the introduction of simulation schemes within EDS deployment.

In this regard, the main contribution of this work is the demonstration of an improved simulation procedure applied to the electrical distribution system of a vehicle and its validation against experimental data. The simulation is enabled by a pre-processing stage of the existent vehicular EDS information and further launched using a modified Current-injection based algorithm. The latter represents an evolution

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over a previous proposal by the authors [12], reaching a three-fold reduction in calculation time and enhanced robustness. While it is true that the current-injection tactic is well-known and commonly employed in the literature, its adaptation and experimental validation according to the particular requirements of on-board vehicular DC networks is novel to the best author's knowledge. Moreover, the here proposed simulation methodology allows a simpler execution flow with a more intuitive input data structure, thus facilitating its establishment within the industrial development process of the electrical distribution system in vehicles.

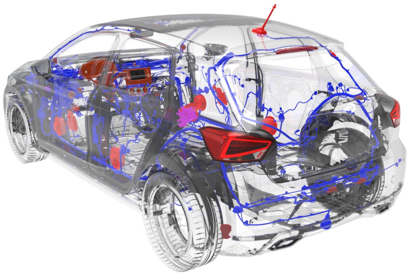

Fig. 1. Wire harnesses inside a SEAT Ibiza.

II. APPROACH TO VEHICULAR EDS

One of the main characteristics from the simulation tool described in this work relies on its capability to adapt to the formats in which the automotive industry manage the EDS information. This adaptation permits the semi-automation of the simulation workflow as for a complex harness containing dozens of consumers, the network configuration might be directly imported without requiring an additional step from the user. For instance, manual introduction of electrical components and circuit drawing required in most of electrical simulation tools would not be necessary.

In Figure 1 are shown in blue color the wire harnesses inside a vehicle. The whole electrical distribution system is built upon an interconnection of wire harnesses. One possible configuration is to have a primary harness that connects directly to the vehicle battery through the fuse boxes and feed the secondary harnesses by means of couplings located at different parts of the vehicle. Examples of such secondary harnesses could be the doors wire harnesses, the bumper harness or the tailgate harness. Those might also be fed by electronic control units (ECUs) that hang directly from the primary harness. The elements that are fed directly with wires connected to the fuses are treated as ”upstream” representing a first level hierarchy. In this sense, the upstream elements are consumers electrically closer to the slack node, in this case the battery. Many ECUs and high current-consumption devices as the motor fan or PTC (Positive Thermal Coefficient) heaters are inside this group. The current interruption elements that allow or block the power flow in accordance to the user requirements also belong to the first level hierarchy. There are a huge variety of these elements inside the vehicle such as press buttons, joysticks and selectors. These elements allow the activation and deactivation of selected consumers. Even though they are not the consumers themselves, in this approach they inherit the current consumption from its associated load for the power flow analysis. Couplings that connect a primary harness to a secondary harness are also considered first level elements. As the simulation was designed to perform in single harnesses, for a full vehicle EDS, a current consumption for each pin of the couplings should be given. These currents might be calculated in a previous step simulation of the associated secondary harness, considering the coupling as a slack node itself. On the other hand, connections of the secondary harnesses couplings carrying control or activation signals in a forward or reverse direction (upstream) are neglected due to their low power consumption.

A second level hierarchy is formed by the many sensors and actuators that feed from the ECUs. Within those elements, there are consumers of diverse amperage. Such consumers don't have a fuse directly associated and are considered ”downstream”. ECUs play the role of local sources of power and feed the consumers through their corresponding wires. There are not protective fuses for the wires that connect ECUs with the downstream devices or second level hierarchy as output energy control mechanisms are already embedded within the ECUs.

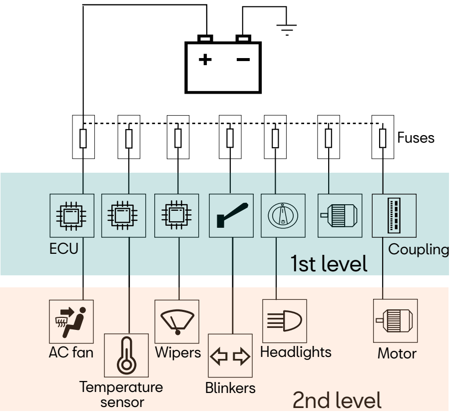

Fig. 2. Hierarchy of consumers within a primary wire harness.

Considering these first and second hierarchy levels, Figure 2 shows a simple representation applicable to a main wire harness. The current from the battery or slack node is distributed through a set of fuses to different elements such as 3 ECUs on the left, 2 activators, a motor and a coupling. These elements are the first level consumers in the power

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flow. At the bottom in the second level, there are a set of consumers such as an air conditioner fan, temperature sensor, wiper motor, blinker, headlight and generic motor. As already discussed, the main simulation is performed through the first level components. For this to work properly, their input current should already account for all the secondary consumers that feed from them. Knowing that the consumption of first level elements such as ECUs depend on the amount of activated second level consumers, typical current load profiles are taken that represent realistic operation of the vehicles or if required, to take worst-case situations data. Within the vehicle EDS there might appear cross-connectivity of power activation lines between consumers of the first level hierarchy. These lines are neglected for the power flow analysis, and similarly to the case of the second level consumers, the delivered power between consumers is taken into account within the overall power consumption of the element that acts as a source.

It is possible, for a very accurate simulation, to consider the positive and ground conductors as two separate circuits. This is, however, computationally more demanding [17]. Therefore, for this simulation grounding wires are filtered out and every first level consumer is assumed to be grounded, by principle.

III. DATA PRE-PROCESSING

The wire harnesses information for a given vehicle is typically given in a set of XML data containers per harness. As detailed in [12] each of these files provides the information regarding connectivity and properties of the EDS components within the specified harness. The connectivity is described by means of a categorization of nodes and segments. A simple wire may have several number of segments from one extremity to the other. The segments represents connections between nodes. Not all nodes are associated with electrical events, such as a soldered junction or a connector, but they might represent mechanical fixations as well. Every node has a Cartesian coordinate associated to represent the 2D electrical full wiring drawing (FWD). In the case of the connectors, they are assigned to one single node despite containing multiple pins. Given that the node's information as received from the XML can't be directly used to run the simulation, it is necessary to establish a categorization which ignores non-electrical nodes and assigns a node to each single Connector-pin relation. Specifically, a load with a connector having a single node associated and n power activation pins is treated as n single loads, each associated to a node. The convention taken for the electrical node definition is then to assign an electrical node to the tandem Node_number-pin. In the special case of the battery, the node name is only Node_B.

Correlation within harnesses are given by the couplings information and the names assigned to the power signals that flow through the wires, which are kept constant all along the XML files.

The XML from the main or primary harness is the source of the information about the fuses distribution. These elements are of extreme importance within the EDS because they allow a safe operation of the wires. All the connectivity of the fuses to the first level consumers is encircled in the primary harness. With the data pre-processing of both main harness and secondary harness, it is possible to link the fuses to consumers in the secondary harnesses (second level consumers) when it is needed. The aforementioned situation is shown in Figure 2 for the last fuse in the right, where a motor is powered through the scheme fuse-coupling-motor and not directly as fuse-motor. In this example, the main harness information would end up in the coupling, while the motor information would be part of a secondary harness file. This means that if there is not a combined analysis of the main harness and secondary harness, it would not be possible to make the match between the motor and its corresponding fuse. In addition, the information of the wires that connects the battery to the main fusebox is not contained in the main harness, neither is the battery itself. It is then necessary that the pre-processing stage automatically adds data related to the connectivity between the battery and main fusebox in the main harness. Otherwise, the whole EDS to simulate would be disconnected from the slack node.

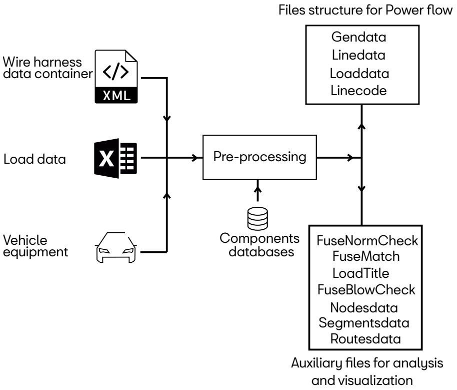

Fig. 3. Inputs and outputs of the pre-processing process.

The programming language used at all stages of the simulation is Python. Using the library xml.etree.ElementTree [18] every wire harness container can be fully parsed, thus allowing to display and extract the required information out of the xml tree architecture.

As shown in Figure 3, the pre-processing stage takes as inputs the wire harness data container in the form of the XML file together with load data and the vehicle configuration equipment. The load data is taken only from components databases in the case of static simulation or might be completed by the consumers current profiles for the case of time-dependent simulation. The consumers databases indicate the pin-out of each consumer with their respective average and peak current consumption. On the other hand, the vehicle equipment is a file that allows the reduction of the XML file such that it represents a specific vehicle configuration. The reason for that is that the XML wire harness information contains all the existent variations for every possible element.

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For instance, if a customer selects a vehicle with a given functionality such as the seated heats, the affected wire harness in this vehicle will be different than the case of another which doesn't have the function. The XML wire harness container will have the information of both cases, even if in the real situation only one remains. By including the vehicle equipment as input, the algorithm reduces the information to the one associated with the simulated vehicle only. In [12] this is further explained within the concept of modularity. The components database input accounts for technical components information needed for the simulation. That includes data from loads, wires and fuses. For example, in the wire harness data container it is clearly specified the references of all the wires, the connectivity among elements, their length, the references for the connectors, the fuses and every component of the EDS. However, the technical characteristics associated to those references are not always included and are taken from the databases, such as: wires section, wires resistivity, fuses nominal melting (i^2t) term [19] and fuses rate. Some of the tasks performed by the pre-processing algorithms are intended for visualization purposes and are not strictly required for the execution of the power flow.

In comparison to the work presented in [12], the pre-processing stage is highly automated and avoids the creation of specific excel input files, that could be a labour-intensive task. The pseudo-code in Algorithm 1 shows the workflow of the pre-processing stage.

```
Input: Wire Harness data container as XML file, Vehicle
    equipment as .txt file, load data and components
    databases
Output: Gendata, Linedata, Loaddata, Linecode,
    FuseNormCheck, FuseMatch, LoadTitle,
    Nodesdata,Segmentsdata,Routesdata
1. Extract and save into variables the lists of fuses, wires,
   connectors
2. Filter out elements depending on the vehicle
   configuration and write new reduced XML
3. Filter out wires that carry digital signals or ground
   signals
4. Categorize the nodes depending on the original nodes
   name. The possible categories are: fuse node, junction
   node, battery node, coupling node and consumer node
5. Expand list of fuses with their technical information
6. Match each fuse with the wire it is protecting
7. Extract load description data (visualization)
8. Extract list of nodes with their Cartesian coordinates
   (visualization)
9. Generate the four main files for the power flow
   simulation: Gendata, Linedata, Loaddata and Linecode
```

Algorithm 1: Pre-processing

The pre-processing obtained outputs are a set of organized files that serve as inputs for the power flow. The selected file architecture is a simplified version of what has already been proposed in [20]. This is a widespread data structure within power systems simulation, however, to date, not implemented in simulation of vehicular EDS. Within this data structure the name *Gendata* comes from the generator information. In this case it refers to the battery data, as depicted in Table I. The first column is a counter field to specify the number of generator nodes. It is followed by the node name used for the positive terminal and the internal resistance, which enables the modeling of a non-ideal power source. Finally, the last column indicates the nominal voltage for the positive battery terminal. The *Linedata* provides information about the wires and their connectivity, such as indicated in Table II. The first field is a counter of wires, followed by the connected nodes. The wire number is used all along for a unique identification, while the part number might be common to several wires and it is correlated with a given technical description in the databases. The signal name is also a field description of the wires that identifies the potential. For instance, each wire connected 1 to 1 by a coupling has its own wire number, however, the signal name is kept equal. Finally, the fields named Location code with their corresponding pins, are related to the elements connected. Location code is also a unique identifier for couplings and consumers.

Counter	Node name	Internal resistance (Ohm)	Voltage (V)
1	Node_B	0	14.5

TABLE I: Example of Gendata.

The *Loaddata* has the information about the consumers. From left to right in Table III the initial fields include a load counter, the consumer node and part number similar to the case of the *Linedata*. Next, the nominal load power is given together with the constant impedance factor, constant current factor and constant power factor, which define the type of power load modeled according to the ZIP model [21]. The individual values should be in the range between 0 and 1 and the overall sum of the factors must add to 1. Depending on the type of simulation mode selected, whether if single time or from current-time profiles, the nominal load power field is addressed. When the simulation takes current-time profiles the nominal power field is not used and the initial power vector is calculated by multiplying the nominal battery voltage with the current for each time step. The *Linecode*, as shown in Table IV, contains the wire technical characteristics required to calculate the voltage drops.

IV. POWER FLOW SOLVER

Conventional electrical systems have mainly relied on the Newton-Raphson method to solve the power flow analysis. However, in very particular networks, the Backward/Forward Sweep (BFS) method demonstrated faster convergence. In [22] an in depth description of the methods can be found. Many authors have addressed the comparison between both methods [23]–[25], coinciding in the asseveration that BFS is less prone to divergence problems derived from high R/X ratio distribution networks. In addition, variations of the BFS have been proposed to enhance computation speed

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Counter	Source node_pin	Destination node_pin	Wire number	Length (mm)	Part number	Signal name	Src. Location code	Pin	Dst. Location code	Pin
1	Node_B	Node_7-1	145001	980	9930	Amplifier positive	A.170	1	K.2A1	11

TABLE II: Example of Linedata.

Counter	Node-pin	Part number	Nominal Power (W)	Constant impedance factor	Constant current factor	Constant power factor
1	Node_13-3	5F514	1.450	0	0	1

TABLE III: Example of Loaddata.

Counter	Part number	Area (mm2)	R20 (Ohm/m)	Tmin(°C)	Tmax(°C)
1	9930	0.5	37.1	-40	105

TABLE IV: Example of Linecode.

or to simplify its implementation [26], [27]. Moreover, as described in [17], methods such as the BFS as well as the Current-injection rely on an initial guess of the voltage profile to calculate the currents demanded or injected in the nodes. Then, a main algorithm based on the Kirchhoff Current and Voltage Laws is applied to update the voltage profiles. In this sense, the Current-injection algorithm shares with the BFS its robustness when solving networks with non-linear characteristics. Nevertheless, when it comes to meshed networks, the BFS algorithm might show convergence problems as it was mainly designed for fully radial networks. In such cases, it is necessary to perform a network topology modification removing the branches forming loops. Once the network in its radial form is solved, an additional formalism must be added to compensate for the effect of the removed branches. The procedure is described in detail in [28]. This branches removal and compensation process slows down the solving execution time and introduces convergence problems. In previous works by the authors [12], the above mentioned BFS modification was applied to vehicle sample networks. In addition, a detailed current return path network was considered. Even though this last approach outputs more accurate results, it requires longer execution times. As opposed to the BFS, the Current-injection method does not require any topological transformation of the network, and it can solve it in its original form. It has also been shown in [17] that a modification of the Current-injection algorithm make it suitable to be applied to networks with bidirectional power flow such as the case of DC Railway Networks. Although the here studied vehicle electrical networks are mostly radial and the power flow is unidirectional, the use of the Current-injection algorithm allows an easier implementation and faster adaptation to more complex study cases that would include bidirectional power flow, for instance, regenerative braking in hybrid and electrical vehicle networks. For the above mentioned reasons, in this work the power flow is calculated using the Current-injection algorithm as presented in [17] and neglecting the current return paths.

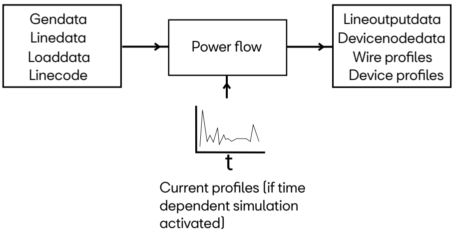

Fig. 4. Inputs and outputs of the power flow solver.

Algorithm 2 describes a series of preparation steps to put together the matrices necessary for the calculation of the power flow. These steps take as inputs the main files derived from the pre-processing stage. In the algorithm the expression 'devices' refers to the first level consumers. The operation varies whether the simulation is static or time-dependent. For the first case, the load nominal power is taken from the *Loaddata* while for the latter, it is imported from given profiles and a power matrix is created where there is a row per device and a column per time step.

Algorithm 3 takes as inputs matrices and vectors calculated in Algorithm 2. The incidence matrix Γ has a number of rows equal to the number of lines and a number of columns equal to the number of nodes. It is built according to the following rules:

1) $\Gamma_{ij} = 1$ when the tail of the edge i,is vertex j
2) $\Gamma_{ij} = -1$ when the head of the edge i,is vertex j

On the other hand, the matrix denominated $Device_{con}$ has as many rows as number of existing devices and as many columns as nodes. $Device_{con}(i, j)$ is 1 when $Device_i$ is connected to $Node_j$ and zero otherwise.

A maximum iteration number is defined to achieve convergence. The iterations occur for every time step defined in the current profiles. To start the first iteration in a given time step, a device voltage vector $Device\_V$ is obtained by multiplying $Device_{con}$ by V_s. It is to note that the voltage vector V has the voltages for every node in the network, while $Device\_V$ only for the nodes that have components connected. The device power and current vectors are calculated using the equations in Lines 3 and 4 of Algorithm 3. Line 6 represents the application of the Kirchoff Current Law (KCL), to compute the branch currents vector I_n which further multiplied by the inverse of the admittance matrix ${Y_N}^{-1}$ yields a new nodes voltage vector V_{new}. Establishing an error criteria between the previous and actual node voltages, the calculation is stopped or continued. If the difference between

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```
Input: Gendata, Linedata, Loaddata, Linecode
Output: $\Gamma$, $Device_{con}, Y_N, Y_s, I_s, V_s, K_p, K_i, K_z, P_{j,k}$
Get nominal battery voltage $V_s$ and nominal battery resistance $R_s$ from Gendata
Get wires resistance vector Line_R from Linedata and Linecode
Get loads ZIP model current factor vector $K_i$, impedance factor vector $K_z$ and power factor vector $K_p$ from Loaddata
if Simulation is static (single time) then
    Assign load nominal power vector $P_k$ from Loaddata
else
    for k=1:1:number of devices $Dev\_count$ do
        Import current profiles $I_k(t)$
        Calculate power vector $P_k(t)$ by multiplying $I_k(t)$ with $V_s$
        Create power matrix $P_{j,k}$ for each time step j by column stacking $P_k(t)$
    end for
    Create Incidence matrix $\Gamma$ from Linedata
    Calculate adjacency matrix $A_m$ using $\Gamma$
    Check connectivity of all nodes to battery using $A_m$
    Calculate lines admittance vector Line_Y as 1/Line_R
    Create devices connectivity matrix $Device_{con}$
    Obtain admittance matrix $Y_N$ excluding source
    Obtain admittance matrix $Y_s$ of the battery
    Calculate battery current vector $I_s$
end if
for j=1:1:number of time steps do
    Calculate power flow with Algorithm 3
end for
```

Algorithm 2: Matrices preparation

```
Input: $\Gamma, j, Iter_{max}, Device_{con}, Y_N, I_s, V_s, K_p, K_i, K_z$
    $P_{j,k}, \epsilon, D$
Output: $V_{out}, I_{out}, V_{devices}, I_{devices}$
Init. vector V to $V_s$
for it=1:1:max iteration number $Iter_{max}$ do
    $Device\_V = Device_{con} * V$
    $Device\_P = P_{j,k} * (K_p + K_i * Device\_V/V_s$
    $+K_z * (Device\_V)^2/V_s^2)$
    $Device\_I = Device\_P/Device\_V$
    $I_n = -I_s - (Device_{con})^T * Device\_I$
    $V_{new} = {Y_N}^{-1} \cdot I_n$
    $tol = norm(V - V_{new})$
    if tol< $\epsilon$ then
        break
    end if
    $V = D * V_{new} + (1 - D) * V$
    $V_o = V$
    $V_{drop} = \Gamma * V_o$
    $I_{line} = Y_N * V_{drop}$
end for
if j>0 then
    Column stack $V_{drop(j)}$ to get $V_{out}$
    Column stack $I_{line(j)}$ to get $I_{out}$
    Column stack Device_V to get $V_{devices}$
    Column stack Device_I to get $I_{devices}$
else
    $V_{out} = V_{drop(j)}$
    $I_{out} = I_{line(j)}$
    $V_{devices} = Device\_V$
    $I_{devices} = Device\_I$
end if
```

Algorithm 3: Power flow.

both voltages is still greater than the selected value the algorithm continues by using a damping factor D to obtain an updated voltage vector V. This strategy has proven effective in reaching a faster convergence [17]. The line voltage drops are then calculated using the incidence matrix Γ and the currents per line using the voltage drops multiplied by the admittance matrix. For each time step the output vectors are column-stacked to form matrices. The number of rows in V_{out} and I_{out} is equal to the number of nodes in the network while for $V_{devices}$ and $I_{devices}$ the number of rows is the number of connected devices. The number of columns is the amount of time steps for all the four matrices.

To compare performance of the algorithm in [12] against the current algorithm, a series of simulations were launched to calculate average execution times for a static simulation scenario. A conventional computer with an Intel(R) Core(TM) i7-4510U CPU @ 2GHz and 8GB of RAM processor was used. In a first stage, average time for 100 simulations at full load in a network of 44 nodes (100% node activation) was calculated. Then, the total of activated loads was reduced to 80%, 60%, 40% and 20%. For each load scenario, 100 simulations were run using randomly selected activation by means of a random binary vector used as multiplier to the input power vector P_k. Average times were then calculated. Using the algorithm in [12], three topologies were run 100 times each to obtain the average execution time. The topologies had a total of 14, 27 and 46 activated nodes.

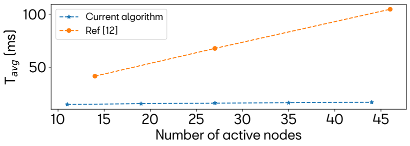

Fig. 5. Comparison of average execution times of the algorithm in [12] against this work.

As observed in Figure 5, as the number of active nodes increases, the improvement over the previous algorithm gains

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more relevance. For the last simulation point, the current algorithm is almost three times faster as [12].

V. CASE STUDIES

A test bench using a vehicle driver door was set up to verify the reliability of the developed tool, as shown in Figure 6. The analyzed consumers were the mirror blinker, mirror heater, door lock actuator, door open-close indicator LED, windows and mirrors control buttons lightning, electric window motor ECU and mirror movement motors regulator. Based on previous analysis performed on the loads, they were treated as constant current loads.

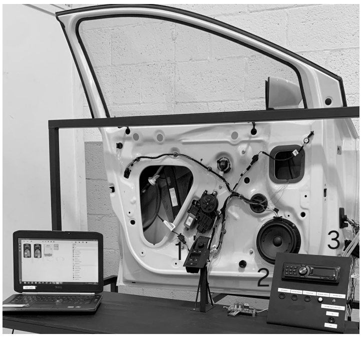

Fig. 6. Vehicle driver door test bench. 1) Windows and mirror control buttons 2) external control panel including the radio (dashboard) and 3) coupling position.

On the right side of the driver door (see 3 in Figure 6) there is a coupling that connects the door wire harness with the interior wire harness in the case of the assembled vehicle. To allow operation of the isolated door test bench it was necessary to employ a power source (Delta Elektronika SM66-AR-110) set at 14.5V together with a control panel for activation of the consumers (number 2 in Figure 6). The control panel is serially connected to a printed circuit board that emulates the outputs of the ECUs for the consumers that require it. The windows and mirrors control buttons are extracted from the door panel to allow visualization of the wire harness (number 1 in Figure 6). Figure 7 depicts the connectivity between all elements in the test bench, where continuous lines represent the positive voltage and dashed lines indicate the ground voltage.

Data acquisition was accomplished by means of a Yokogawa DL850EV scope-recorder with a 720221 Module (16 Ch Temp/Volt). Only wires carrying power were studied. Their voltage drops were measured by rolling up voltage probes to stripped areas of the wire extremes at around 4 cm from the end connectors to provide contact while the currents were measured by inserting high precision shunt resistors at the vehicle side of the coupling.

The consumers were manually activated and deactivated in an arbitrary sequence, described in Table V, with measurements being taken every 5 ms. The current load profiles were considered as inputs for the solver. These currents are then used to calculate a power matrix ($P_{j,k}$) employing the nominal battery voltage as indicated in Algorithm 2. For the particular case of an isolated driver-door harness, the network configuration resembles a pure radial configuration where the coupling point can be interpreted as the supply source (Battery node) and the rest of consumers are connected downstream. Therefore, the load profile currents that represent the input node currents for the algorithm match with the respective branch currents in this circuit. Validation of the pre-processing and power flow algorithms is performed through the voltage drops calculations.

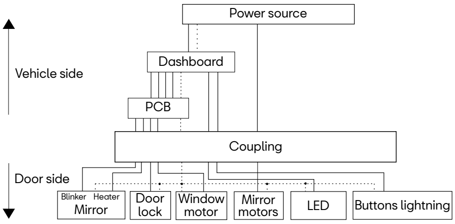

Fig. 7. Connections scheme of the door test bench.

Consumer	Activation (s)	Deactivation(s)
Mirror blinker	8.1	58.7
Mirror motors	12.3	30
Buttons lightning	2.8	37.5
LED	21.8	46.3
Window motor	38.8	44.7
Mirror heater	53.1	77.2
Door lock	32.5	35.8

TABLE V: Door test-bench consumers activation sequence.

Following the method shown in Figure 3, for simulation it was necessary to input the wire harness data container for the driver door together with the consumers currents profiles and the vehicle equipment. Once the simulation is succeeded all the different output files are available. The wires for the electric window motor and the mirror movement motors regulator have 7.5A protecting fuses each, which are correctly matched and evaluated showing no failure conditions. Figure 8 shows the voltage drop profiles in the wires connected to each door consumer, also named ”Wire profiles” in Figure 4. It can be observed that experimentally, some transient peaks which are not recorded in the current profiles are catched during the voltage drop measurements for the motors. As the input to the solver is the node current profile data, where the peaks are missing, those peaks are not reproduced in simulation. The voltage drop in the wire feeding the door lock actuator reflects a change of polarity representing its turn into a closed or an open position. Concerning the simulation errors, for the case of the electronics regulating the motors, the error in voltage drops is calculated by using the signals RMS values for the activation period neglecting the peaks, thus obtaining a relative error of maximum 5%. For the blinker and door lock the error

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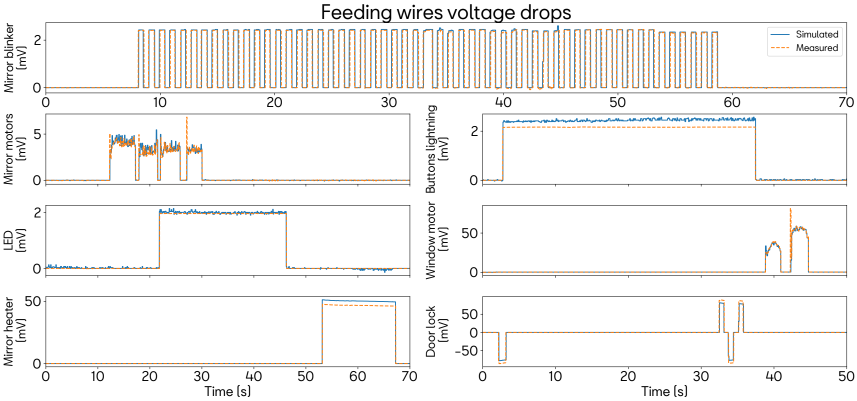

Fig. 8. Comparison between measured (dashed) and simulated (continuous) voltage drops for wires powering the door consumers.

is also evaluated using the RMS values, while for the rest of the consumers it is calculated by using the signals averages. The maximum error is 11.4% for the case of the door lock. It is desirable that the simulated values reflect worst case scenarios, however, this might not always be the case, as observed for the door lock.

To validate the approach further, static tests were also performed within a prototype vehicle. Measurements of currents and voltage drops were performed on main branches and the wires feeding the consumers. For the on-vehicle voltage drop measurements, perforation connectors were used to reach the conductors through the insulation. Currents were also measured by means of high precision shunt resistors as in the driver door test bench. A schematic with the representation of the power distribution inside the vehicle is observed in Figure 9.

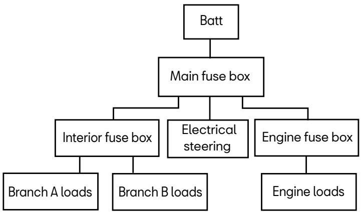

Fig. 9. Fuse boxes distribution scheme.

The battery is connected directly to the main fuse box (MFB) which in turn distributes the current through four fuses, namely, two connecting to the interior fuse box (IFB), one connecting the electrical steering and the last connecting the engine fuse box (EFB). The interior fuse box feeds most of the vehicle consumers by means of two separated fuse groups referred as Branch A and Branch B. This strategy follows operative safety issues and regulations. The engine fuse box feeds components in the engine surrounding, such as the electronic control unit for the motor, airbag, brakes, among others. A fuse with 80A rate in the main fuse box feeds directly the electrical steering due to its high current peaks.

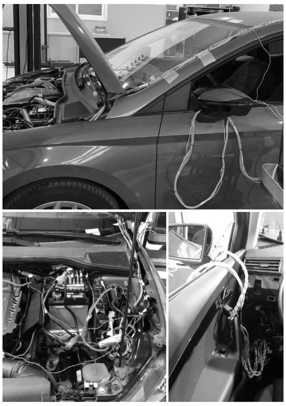

Fig. 10. Vehicle fuse boxes with measuring probes.

Current and voltage drops in the wires feeding the electronic control unit known as the Body Control Module (BCM) were

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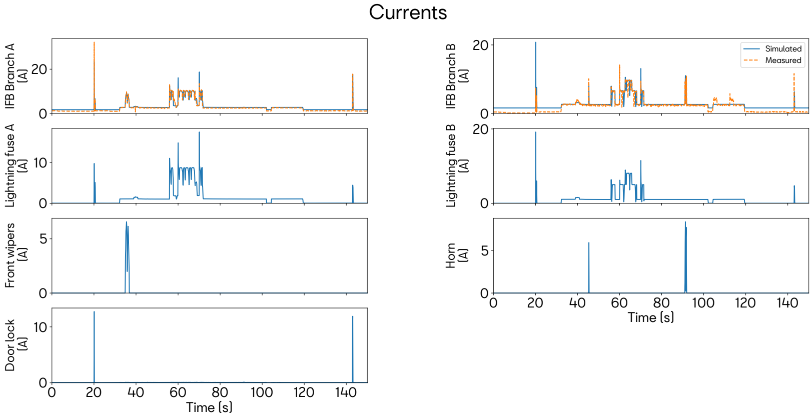

Fig. 11. Interior fuse box currents.

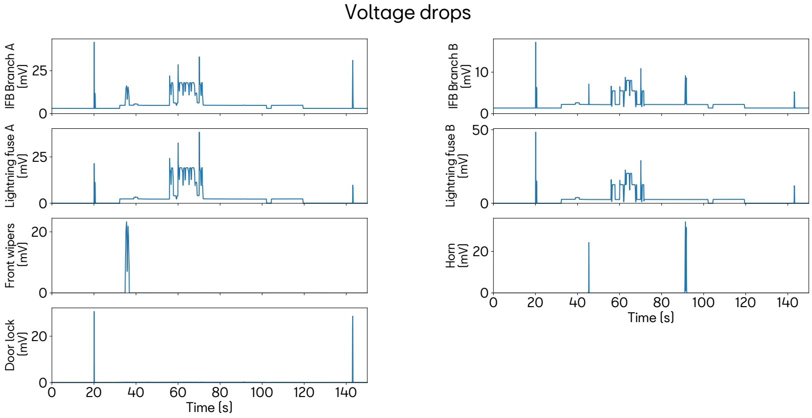

Fig. 12. Voltage drops in wires connecting to the interior fuse box.

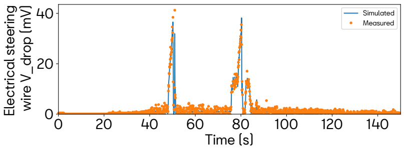

Fig. 13. Voltage drop in the electrical steering feeding wire.

measured. These were related to consumers such as the front headlamps, wipers, horn and door lock, that are all controlled by the BCM and considered as constant current loads for the solver. In addition, branch currents and voltage drops were also measured.

The activation sequence is described in Table VI. Figure 11 shows in the first column the currents associated to a group of consumers from Branch A, and in the second column the ones from Branch B. In the first row, the total branch currents are depicted comparing them with measured data (dashed lines). As expected, the calculated branch currents

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Consumer	Activation (s)	Deactivation(s)
Open door	20	–
Switch and daily running lights	32	119.3
Wipers	34.8	36.7
Ignition	38.9	102.2
Horn honk	45	45.4
Steering wheel fully to the left	48	51.2
Lights in AUTO mode	55.6	58
Full beam lights	60	67.5
Fog lights	62.7	65.9
Lights in AUTO mode	70	71.7
Steering wheel fully to the right	75.5	80.7
Steering wheel to center	81.6	87.4
Horn honk	91	91.9
Close door	143	–

TABLE VI: On vehicle activation sequence.

follow the activation of consumers powered from that branch. When opening the vehicle, lighting functions such as blinkers and interior lights activate, therefore there is a correlated peak between the lightning fuse A and the door lock. On the other hand, the starting switch activates and deactivates the daily running lights. This is shown in the current increase present at both lightning fuses at around 39 secs and its return to zero at around 120 secs, corresponding to the switch turning on and off. Constant parasitic currents for the consumers fed from the branches and not measured were taken from previous experimental factory data and used as inputs for the solver. In overall, there is a good agreement between simulated and measured data. A slight offset from the measured values is observed for the current in Branch B, thus suggesting that an improvement could be obtained by a deeper analysis and characterization of the parasitic current profiles.

Figure 13 shows as well a good agreement between simulated and measured values for the voltage drop in the electrical steering feeding wire, thus indicating a proper contrast between the theoretical data as given in the electrical diagrams and the wire harness construction.

It is worth mentioning that from a manufacturing perspective, the wires resistance per unit length at 20^{o}C (R_{20}) and wires length might vary to upper or lower values than the theoretical. Resistances are allowed to change in about +/-4% while manufacturing wire length tolerances can range up to +/-10% due to their manual assembly. These could bring differences between simulated and measured data such as the ones found for the experiments. However, for the purpose of the EDS validation, these errors are within an acceptable range and result useful to determine if design inconsistencies exist. In this sense, important differences would reflect problems such as a harness construction that is not following the theoretical data specified in the design, and the use of inappropriate or incomplete loads data (including stand-by currents for electronic control units). At a mature stage, a detailed virtual validation would replace most of the experimental work.

VI. CONCLUSIONS

This work introduces a method to simulate power flow within vehicular electrical wire harnesses starting from the original EDS factory data. The strategy in which the vehicular EDS is approached is described qualitatively. The pre-processing algorithms deliver a simpler data structure for simulation while the power flow, based on a Current-injection algorithm, represents an evolution over previous works showing remarkable improvement in workflow and convergence speed. The actual power flow implementation enables the use of temporal profiles if required by the user. Furthermore, the method is validated against experimental data taken from a door wire harness test bench and a prototype vehicle itself finding a proper match between simulated and measured data.

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A.5 Power Flow Simulation in the Product Development Process of Modern Vehicular DC Distribution Systems

P. Mantilla-Pérez, J. Pérez-Rúa, M. A. D. Millán, X. Domínguez and P. Arboleya, "Power Flow Simulation in the Product Development Process of Modern Vehicular DC Distribution Systems," in IEEE Transactions on Vehicular Technology, vol. 69, no. 5, pp. 5025-5040, May 2020, `https://doi.org/10.1109/TVT.2020.2983288`

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Power Flow Simulation in the Product Development Process of Modern Vehicular DC Distribution Systems

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***Abstract*—Nowadays, automakers face unprecedented requirements to comply and exceed quality standards while attending to consumer expectations. Among the challenges are the insertion of new functions for driving assistance towards highly automated vehicles, electrification and connectivity. Introduction of simulation – driven design in the broad wide disciplines involved within vehicles development yields significant savings in both costs and product release time. This paper introduces an approach to vehicle electrical distribution systems (EDS) simulation adapting the methods used conventionally in transmission and distribution systems to the special features found in the vehicle EDS. To this purpose, a procedure based on a backward/forward sweep (BFS) algorithm for solving power flows in weakly meshed dc traction networks is applied and described. An important part of the work has to do with the information pre-processing from the modular based format used in automotive industry into standard simulation matrices. Constant current load profiles are assumed for the consumers, while the electronic control units (ECU) are considered static power distribution boxes. The main outputs of the proposed methodology are nodal voltages, branch currents and differential voltages at components terminals in the vehicle EDS. The knowledge extracted from the simulation will help the designers during the dimensioning and validation process of modern vehicles EDS and will be a powerful tool to reach the zero-prototypes goal before the start of production.**

***Index Terms*—Automotive modularity, vehicle electrical distribution system, DC power flow, backward/forward sweep.**

NOMENCLATURE

Acronyms

ASDS	AllSeriesDataSets.
BFS	Backward-Forward Sweep.
BOM	Bill of Materials.
EDS	Electrical Distribution Systems.
ECU	Electronic Control Unit.
FAT	Research Association for Automotive Technology.
FWD	Full Wiring Drawings.
KBL	Automotive branch XML file.
KCL	Kirchhoff current law.
KVL	Kirchhoff voltage law.
MN-BFS	Meshed-Network Backward/Forward Sweep.
NR	Newton-Raphson.
OEM	Original Equipment Manufacturer.
QT	File condensing BOM,WL and loads information.
VDA	German Association of the Automotive Industry.
VHDL	Very High Speed Integrated Circuit Hardware. Description Language.
WHDP	Wiring Harness Development Process.
WL	Wirelist.
WP	Wiring Plans.
WS	Wiring Schematics.
XML	Extensible Markup Language.

Variables

I	Branch current.
n_N	Number of nodes.
S	Node apparent power.
T	Ambient temperature.
V	Node voltage.
Z	Branch impedance.
ϵ	Voltage drop error.

Vectors

$\boldsymbol{I}$	Branch currents vector.
$\boldsymbol{P}$	Nodes active power vector.
$\boldsymbol{Q}$	Nodes reactive power vector.
$\boldsymbol{V}$	Nodes voltage amplitude vector.
$\boldsymbol{\theta}$	Nodes voltage angle vector.

Matrices

$\boldsymbol{R_b}$	Branch resistances matrix.

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$\boldsymbol{\Gamma}$	Incidence matrix.
J	Jacobian Matrix.

Superscripts

^{k}	k_{th} iteration number.
TH	Thevenin.

Subscripts

$_c$	Cut branches.
$_i$	Node i.
$_j$	Node j.
$_n$	Negative grid.
$_{nc}$	Non-cut branches.
$_p$	Positive grid.

Operators

Δ	Incremental.
^{T}	Transpose.
$*$	Conjugate.

I. INTRODUCTION

IN THE last years, complexity of vehicle electrical distribution systems has considerably grown due to the aim of automotive OEMs (Original Equipment Manufacturer) to provide customization and advanced comfort, entertainment, and safety functions to users. Such trend imposes an increased amount of power consumers and wiring in vehicle EDS that reaches around 10^{10} possible architectures. It is only through the deployment of electrical simulation or equivalently, the construction of digital twins of the vehicle EDS that the multiple possible scenarios could be addressed and analyzed. Moreover, implementation of autonomous driving will add stricter demands on the fail-safe operation of every system and component within vehicles including its EDS. This turns EDS simulation into an imperative step inside the product development process. By means of computational simulation, early detection of possible electrical network failures can be done, such as excessive voltage drops or wrong components sizing for the whole range of feasible architectures, and consequently, to discard those ones which do not comply with operational and safety requirements in an early project stage. In addition, critical or damaging conditions could be safely reproduced in a virtual environment to observe the system response. With a simulation phase within the EDS design, the prototype phase would serve merely to corroborate the results already obtained by simulations, where naturally, a wider amount of architectures could be evaluated. As a consequence, the required number of prototypes could potentially be reduced through the use of virtual experimentation.

Although simulation-driven design is widely extended inside OEMs in areas such as vehicle crash and vehicle dynamics, it is not the case for vehicle EDS modeling. However, a few efforts have been devoted to it. Some commercial tools are available, such as the Power Net Simulation by Bosch [1] or SABER by Synopsys [2]. These tools are used to simulate a complete energy transfer system that include three major parts: the alternator, battery and the electrical loads, all operating under selected drive cycles or scenarios. These programs center their usefulness on an early phase of design to determine the correct dimensioning of the battery and alternator, given the required loads and the different driving scenarios. In these programs the characteristics of the EDS itself with all its connecting wires and flow control components such as fuses are not taken into account. On the other hand, commercial tools for the design of vehicles EDS like LDorado [3] or EBCable [4], which contain the detailed information of the full EDS are not suited for simulation. From these, important differences of the present work in comparison to the existing commercial tools are summarized as follows:

- The group of commercial software for simulation does not center its functionality in the vehicle EDS itself including the complex wiring and components forming the harnesses. Instead, the focus lies on the proper dimensioning of battery and alternator (energetic balance)
- The underlying simulation methods used in the commercial tools are not always known by the user
- The simulation oriented commercial tools are mainly thought for an user to insert every single functional box with its corresponding parameters, while in the present work, a great advantage is the possibility for the user to extract the information of a complete harness and connected loads from the factory data, as received, thus saving the amount of effort required from the user
- The existing commercial software tools for EDS design consider all the details of the EDS components but do not allow the option for electrical simulation

II. STATE OF THE ART IN EDS SIMULATION

Not many works have been published to introduce a complete methodology for power flow simulation in vehicle EDS. There are a few examples of related work such as the development of freely-distributed Very High Speed Integrated Circuit Hardware Description Language models (VHDL models) for different components by the Research Association for Automotive Technology (FAT) in the German Association of the Automotive Industry (VDA) [5]. Other reference is the work by Petit [6] which shows the modeling of an alternator, battery and light bulb using Matlab Simulink. In this work the transient behavior of the network is simulated and experimentally corroborated using detailed lumped parameter models. A similar work by Bilyi [7] uses a combination of analytical calculations, lumped parameter models of power components and SimPowerSystems-blocks in Matlab Simulink for the simulation of a 12 V vehicle electrical network containing an alternator, excitation current control, different types of loads and battery, showing a solid match with experimental data.

In [8] Ruf and coworkers combine a modified discrete Particle Swarm Optimization with a physical power net simulation to meet voltage stability requirements in transient behaviors. Such physical power net simulation is performed using a Dymola-based tool with the models implemented in Modelica language. The simulation includes the model of chassis ground, wiring harness, battery, alternator, loads, dc/dc converter and electric double layer capacitors. However, the importance is given to the description of the optimization algorithms to achieve a minimum network weight with voltage stabilization topology rather than to the power flow description itself. In a more recent work, Gorelik *et al.* [9] introduce a simulation model for energy management systems to perform analysis of power net designs taking into account the validation of safety requirements and the design of system fault reactions for automated driving applications. Simulation and optimization lie on the energy management, where under critical network conditions the degradation of loads will occur under a priority criteria where safety prevails over comfort. Similar to the work of [7] and [8], the wire harnesses are not object of study. On the other hand, the need for weight reduction has motivated the modeling and optimization of wire harnesses as described in [10], [11]. In these works, the authors have applied heat transfer equations to represent the thermal behavior of automobile cable harnesses in steady state and transient regime, under application of constant currents through the wires. The models have been validated against experimental data showing remarkable match. The modeling is, however, limited to the simulation of single wires or bundles but not applied to solution of full automotive electrical networks.

The related existing literature reports usually lack the methodic where it is clearly stated the step by step procedure employed to carry out the simulations of the power flow through the harnesses in the vehicle EDS. In particular, because the translation of the standard vehicle EDS information into a suitable input for a solver algorithm is challenging and secondly, in the existing works there is a scarce description of the methods employed to solve the equations derived from the network. In some cases, extremely detailed models are employed for each element in a Simulink or Modelica based approach which are hardly scalable to a more realistic network containing more than a hundred of power consumers. Although the power flow analysis of static networks such as transmission and distribution lines is a well-known topic within the power systems field, and it has been successfully employed in other applications like railways [12], [13], aircrafts [14]–[17] or ships [18]–[23], the application of such techniques for the vehicle EDS has been rarely addressed and needs to be adapted according to the complex structure of the vehicle and the available factory information. Typically, the information required to launch simulations is spread into different source files.

In this work, the authors propose a general procedure for simulating the complete electrical system of vehicles based in a modular wiring system design approach, as it is used within many European automotive OEMs. In addition, the application of an efficient and robust method for calculating the vehicle EDS based on a modified version of an algorithm used commonly for radial static distribution networks is demonstrated. The initial algorithm is known as Backward/Forward Sweep (BFS), and the cyclic-graph version as Meshed-Network Backward/Forward Sweep (MN-BFS).

The paper is structured as follows: in Section III the structure of the factory data is discussed together with the concept of modularity and the process of wire harness development, specifically, the vehicle EDS organization data is selected and grouped in three files which are subjected to pre-processing algorithms; Section IV describes the structure in which data is assembled in order to deliver it to the power flow solver, where the results from the pre-processing act as inputs for the power flow algorithms. In Section V the simulation strategy is explained including the treatment of the loads, and required inputs. Different power flow solvers are explained as the Newton-Raphson and the BFS including a performance comparison between them. The proposed power flow solution of the system assuming constant current consumption and applying the MN-BFS is described. At this point, the voltages and currents throughout the network are calculated. Section VI presents case studies based on two different vehicle sample networks that employ the described methodology to extract the node voltages and branch currents of the circuits. Finally, a set of conclusions are stated.

III. FACTORY DATA

Depending on the model, the full EDS of a vehicle can be composed by a set of different wire harnesses. 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 different harnesses are interconnected by means of couplings in specific parts of the vehicle. The present method is thought to be applied one by one in each of the different wire harnesses co-existing in a vehicle independently, to approximate the response of the full EDS. The most important source of factory information are the electrical schematics describing each single harness. There exists one data container file per each of the wire harnesses present in the vehicle. Such data container files are represented in the form of an Extensible Markup Language file (XML) denominated KBL, which was designed for the automotive branch. As described in [24], each KBL document has both a logical and a physical structure. Physically, the KBL document is composed of units called entities, in a tree-structure. A document begins in a *root* or document entity. For the automotive case, the KBL files contain electrical components data information and they can be represented as 2D schematics by the use of specific software. A description of the structure for the KBL files has been published by the German Association of the Automotive Industry VDA (Verband der Automobilindustrie) in [5].

One limitation within the use of the KBL files for simulation is that their structure and definitions are not conceived for electrical simulation. The data containers structure has been developed to facilitate exchange of product data between OEMs and wire-harness manufacturers mainly for production purposes. For instance, although a definition of nodes is present in the KBL, they do not correspond to what would be specified as an electrical node and instead are associated in many cases to constructional aspects of the wire harness. Another limitation lies in the need to extract additional information of the power consumers, electrical and wiring elements in external databases, given that not all the necessary information is contained in the KBL files. Examples of such information are the time-current characteristics of fuses, pin-out information of the different consumers, temperature class of each of the cables, among others. Apart from the challenges that arise from the available product data scheme in vehicle EDS, there are technical aspects

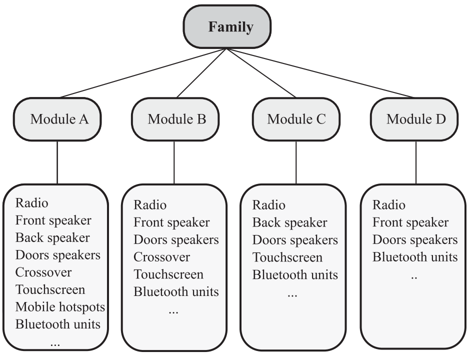

Fig. 1. Concept of modularity.

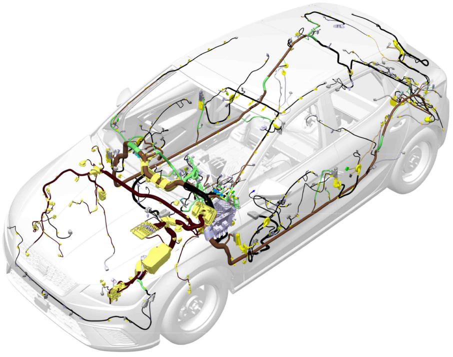

Fig. 2. Sketch of the wire harnesses inside a vehicle.

like the greater current densities, the presence of electronic loads and the generally weakly meshed characteristics of this kind of distribution systems which must be attended in order to develop a computational tool for calculating the electrical variables in the system.

There exist two important variants within OEMs that determine the way in which factory data is organized: the few variants model and the many variants model. In the first case, the OEMs offer a restricted amount of selectable options for a particular car model. On the contrary, in the latter, OEMs offer a vast range of selectable options to customers. This is an advantage from the customer point of view but it requires a strong logistic effort in order to provide fully-customized vehicles. The strategy behind the flexibility of a vehicle configuration lies in the concept of modularity.

Modularity is the strategy followed in the wiring harness development to allow full customization of electrical functions of vehicles. It operates by means of families and modules. A family represents a group of elements able to perform a specific function. This function can be, for instance, the lighting. The sound system is another functional system formed by the radio, front loudspeakers, back loudspeakers, touch screen, etc. To operate the lighting functionality of the vehicle there are units as the brake light, indicators, fog lights, head lights, rear lamps, among others. The components forming the families are in turn organized in modules. In this way a functional family can be formed by a certain group of modules, all of them capable of performing the function and where each module is composed by diverse parts and might represent a different level of complexity, as shown in Fig. 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 type of loudspeakers, which are loads in the vehicle electrical system, would also be classified according to modules. The reason is that the load characteristics have impact on the wiring harness components. For instance, a higher power loudspeaker would require a bigger wire cross-section. On the other hand, the elements in a specific family are not only electrical as fuses, wires, relays and connectors but also fixing and protective elements such as clips and tapes. Each single element in the vehicle wiring harness is associated to a module, which in turn is associated to a family. As a general rule, for each family in the vehicle only one module is present. Then, a full description of a specific and unique wiring harness configuration is based on a list where for each functional family defined there is a module selected.

The final product of the EDS wiring harness development is the full wiring harnesses description as they would be installed inside the vehicle, maintaining the modularity information all along. Fig. 2 shows the scheme of all the wiring harnesses present in a car for a given user-defined configuration and vehicle model.

Databases containing the electrical information and properties of all components to be used within the developed electrical network are built before hand and used all along the process.

The Wiring Harness Development Process (WHDP) then starts with the design of system schematics and ends with the actual development of the wiring harness inside the vehicle, going through different stages.

The first step for the wiring department is the creation of the system diagrams for a particular car model. These diagrams are general representations of the logical connections among all the components inside the on-board electrical network and will be referred to as wiring schematics WS. The components are sketched as boxes having a specific pin-out. In overall, the WS are a set of drawings that include clearly the electrical power distribution from the battery to the last of the consumers, indicating the connections through fuses, relays and other electrical elements and including cross-references between WS files. By employing the system diagrams it is possible to determine all the connections that occur inside the vehicle excluding the technical details such as type of wiring, wiring cross-section, couplings, among others.

The second step in the WHDP is the elaboration of the cable wiring plan, also described as WP files. Graphically, the wiring diagrams are similar to the WS files, except for the fact that they include the numbering of the cables together with the physical

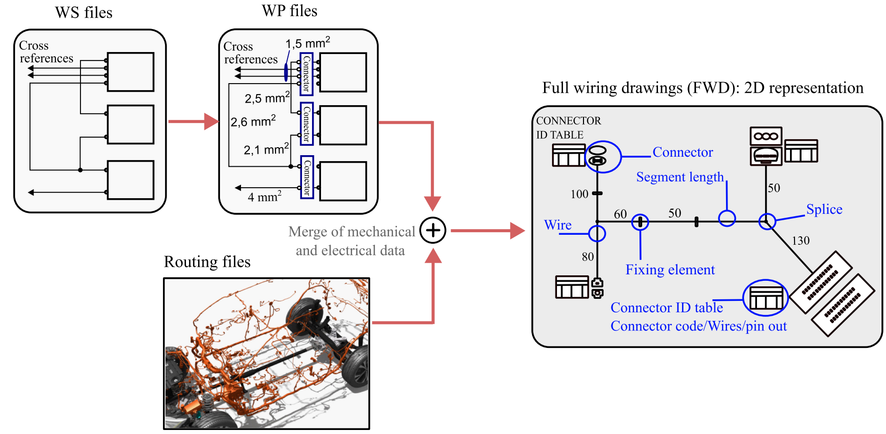

Fig. 3. Wiring Harness Development Process (WHDP).

characteristics of the cables holding the connections specified in the WS. Technical information such as cables type, cables cross-section and couplings are included in the WP.

Simultaneously to the development of the WS and WP files takes place the development of the routing files for the wires. All the wire paths which connect one component to another are designed taking mechanical considerations into account and saved into 3D CAD files. Similarly to the case of the WS and WP, there exists a database containing the graphical information of every component that can be reached through the CAD software.

A third step in the WHDP is the merging of the cable wiring plans WP with the routing diagrams to generate a full graphical description of the wiring harness containing also the cable lengths information. A KBL file type that contains the mixed mechanical representation of the wires and components and their electrical data is formed. The resulting KBL files contain 3D information that can be later represented into 2D schematics. Such are saved with XML extension. These elaborated 2D wiring drawings, which are the result of the WHDP contain all the relevant manufacturing information of the wiring harness and will be referred to as full wiring drawings FWD.

As the last step of the process, all the generated information is uploaded to specific databases. A scheme with the representation of the WHDP flow is shown in Fig. 3 including a section of a FWD.

Specific software tools allow the automatic generation of two files; namely, the Wirelist (WL) and the Bill of materials (BOM) for each of the KBL representing a wire harness. In the case of the Wirelist, this 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 because 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 functions such as fixings, clips, wire-guides, etc, specifying module and family for each one.

Both WL and BOM documents are excel files and are used without modifications for the pre-processing of the vehicle EDS data. However, a third file denominated QT must be manually designed for the design of a multi-dimensional data structure denominated dataContainer. The QT is an excel file with condensed information from the automatically generated BOM and Wirelist, but complemented with information about each electrical component in the network taken from the WHDP database. Examples of these components are sensors, sources, electronic control units, actuators and loads. As already mentioned, there is a WL and BOM for each wire harness to be simulated. If the simulation aims to calculate the operation of three wire harnesses, there would be 3 WLs and 3 BOMs, respectively. However, a unique QT is designed that merges the information for the different wire harnesses under study. A scheme with the factory data inputs is shown in Fig. 4.

The components information is extracted from the databases and include the pin diagram, the type of pin and also the current consumptions under different operational states (inrush current, minimum, normal and maximum regime currents). Each pin can be classified as input power pin, output power pin, ground connection, signal or coil connection. Loads current information are used to assign the input node currents for the MN-BFS algorithm. At the post-processing stage, a comparison between the calculated branch currents and the nominal maximum cable currents is performed, returning alarms and warnings in case the obtained currents exceed the nominal values.

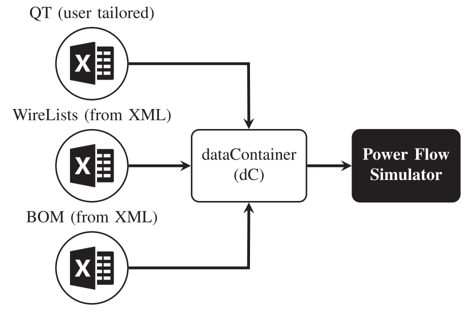

Fig. 4. Factory data inputs.

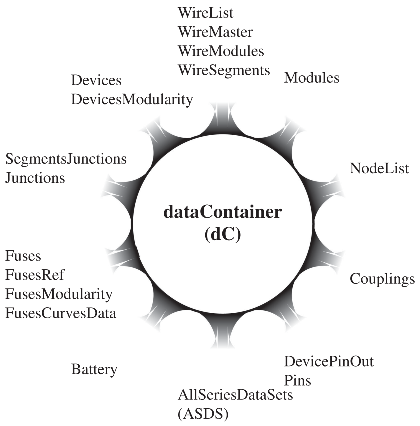

Fig. 5. Fields composing the data container.

IV. THE DATACONTAINER STRUCTURE

The files shown in Fig. 4 are used to create the structure denominated dataContainer in Matlab. The fields composing the dataContainer are shown in Fig. 5 and provide all the required information of the vehicle EDS. In many cases, the dataContainer copies directly the information from the input excel files, while in other occasions, operations are performed to associate together data from the three files to generate the dataContainer tables.

In the group of Wire related fields there are four tables, as seen in Fig. 5: WireList, WireMaster, WireModules and WireSegments. The WireList is a condensed version of the one obtained directly from the WHDP. It contains selected information such as: wire id, wire number, parent harness, source node, destination node, part number and length. Within the factory data it is common to have multiple identification tags associated to an element. Examples are the wire id, wire number and partnumber fields of the WireList. WireMaster is a table providing geometrical and materials information. In this file each row contains the wire partnumber together with the conductor material, isolation material, conductor cross section area, isolation cross section area in mm^2, specific weight (g/m) and specific resistance (Ω/m). The WireModules table contains a list of every single wire that can be present in the harness together with the logistics wire id, the module to which it belongs and the family. In this list there can be rows where the wire id repeats because a wire with a given id can be present in different modules. Likewise, WiresSegments contains a list of all the defined physical segments inside of a harness with their respective identification tags, describing the segments trajectory of each cable. Complementary, the table SegmentJunctions contains a list of each segment but instead of giving information about the parent wires, it provides the identification tags for the geometrical nodes interconnecting the segments inside of the parent harness and the ambient temperature. This is important given that all along a wire there might be segments exposed to different external temperatures (for instance those harnesses installed in the engine compartment are exposed to higher temperatures compared to those installed in the air-conditioner compartment).

TABLE I
IDENTIFIERS ASSIGNED TO THE DIFFERENT PART TYPES

Identifier	General	Specific
1	Node	Fuse box
2	Connector	Wire
3	Node	Soldered splice
4	Node	Coupling
5	Node	Device
6	Node	Ground bolt
7	Connector	Component internal
8	Connector	Coupling internal
9	Connector	Fuse
10	Node	Negative terminal
11	Node	Positive terminal
12	Connector	Plate
13	Connector	Relay coil
14	Connector	Relay switch
15	Node	Vehicle's body

The field of Fuses information contain the list of fuses with their identification tags and the specific input an output pins, while the FusesModularity provides the modularity information per fuse. The table of FuseRefs contains the list of product numbers of the existent fuses with their type and current rating. Finally, the fuses information is completed with the table FuseCurvesData which contains the tripping curves.

Table I shows a list of identifiers for the nodes and connectors. Depending on the element to which a node belongs or the type of connector, a different number is assigned. This should not be confused with the unique id that every node or element on the network has. Precisely, for this matter exists the NodeList. It contains a table of all the nodes, id tag, classification according to Table I and specific connection pin. From Table I Nodes of the type 5 are considered Device Nodes. A device or also called component is basically every unit that might consume energy, such as a load, or provide energy for loads such as an ECU. Apart from a part number and id, another identification for the devices is a concept denominated "location". For a particular device or component there can only exists one location associated.

TABLE II
EXAMPLE ROW OF AN ALL SERIES DATA SETS. TYPES TABLE

Node type	Connector type	Node type	Connector type	Node type	Connector type	Node type	Connector type	Node type	Connector type	Node type
11	2	1	9	1	2	5	7	5	2	10

TABLE III
EXAMPLE ROW OF AN ALLSERIESDATASETS.IDS TABLE

Node id	Connector id	Node id	Connector id	Node id	Connector id	Node id	Connector id	Node id	Connector id	Node id
1	1	3	1	4	2	5	1	6	3	2

The table of Devices contains a list of the components with an id and their location, and DevicesModularity contains the information of all elements categorized as components, fuse boxes, battery and couplings, by indicating their modularity, part numbers and location for the case of components. The table Pins contains all the elements categorized as components with their respective pin out and the type of pin. There are 7 defined pin types: signal, component power input, component power output, sink, switch power, switch coil or not connected. In addition, information of current consumption and current peaks is given in this table. For the calculations, as it will be explained in Section V, it is necessary to establish a relation of the input pins with correspondent output pins in the components. This is shown in the table DefInOut for every component. The pin out for the battery is given in the table Battery.

The tables Modules and Couplings are simply lists of modules with the families and the couplings with their id, respectively. Finally, the AllSeriesDataSets (ASDS) is a two-table structure containing all the possible current paths from the positive terminal of the battery to the negative terminal. The first table is the ASDS.types and is constructed by having a column with the Node type followed by the Connector type sequentially until it finishes with a column of Node type which is the negative terminal for the battery. In this way, the column connector type describes the type of connector used in between each two nodes. This type of connector, as shown in Table I, can be a wire, a component internal connection, an internal coupling, a fuse, a plate, a relay coil or a relay switch. The second table is the ASDS.ids which in turn contains unique ids of the elements. The id for an element is unique within its type classification. For instance, for the type wires (2), there is only a wire with wire id equal to 1. Similarly, for the type fuses (9) there is only a fuse with a fuse id equal to 1. An example of a row within the ASDS tables is shown in Tables II and III, corresponding to Fig. 6.

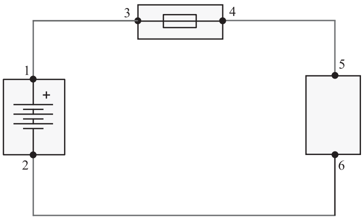

Fig. 6. Circuit represented by Table III.

Algorithm 1: Selecting Device Type.

```
Require: dataContainer as dC
Ensure: device type
  From dC.DevicesModularity extract a vector with all devices
  Count number of pins of the type 'Signal', 'Power in', 'Power out', 'Sink', 'Switch p', 'Switch coil' per each device
  Classify each component as 'Source' or 'Consumer' according with the number of pins of each type and save classification in the vector device type
```

Algorithm 1 reads the DeviceModularity information within the dataContainer and with this classifies a component or device as an ECU or as a consumer by analysing its pinout. A component is considered an ECU or "source" if and only if it has at least one *component power in* terminal and one *component power out* terminal. On the other hand, a component is allocated as Consumer if it has only pins of the type *Sink* or power inputs but without power output pins. Components containing only pins of the type *Signal* are neglected. Two situations lead to an inconclusive classification: a component without pins of the type *component power in* but at least one terminal *component power out*, and a component with *component power in* pins but none *component power out* or *sink* pins.

The WL and BOM as depicted in Fig. 4 contain the information directly from the XML. XML files are designed to contain all the possible modules that exist for a given family within a car model, therefore, the generated dataContainer 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 dataContainer. The way to achieve this is to allow for the user introduction of modules per family in the form of a table, corresponding to the car configuration to be studied. Once this table is introduced together with the dataContainer, a pre-processing algorithm removes unnecessary data. Filtered data is forward used as input for the power flow solver (see Fig. 7).

V. POWER FLOW SOLVER

Traditionally, the most used algorithm for solving the power flow problem in conventional electrical systems was the so called Newton-Raphson. For very specific networks, with very specific characteristics, the Backward/Forward Method proved to be faster. In the next subsections, a very brief description of both methods is going to be presented. A detailed analysis of them can be found in [25].

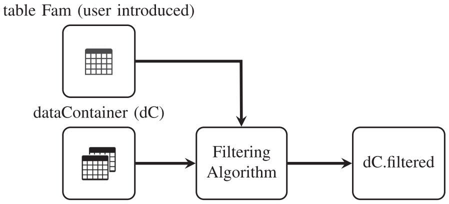

Fig. 7. Filtering process.

A. Conventional Power Flow Solvers

1) Newton-Raphson (NR) Method: The Newton-Raphson method is a derivative-based method in which a vector containing all the voltages amplitudes and angles in the nodes is initialised and updated according to:

$$\begin{bmatrix} \boldsymbol{V} \\ \boldsymbol{\theta} \end{bmatrix}^{k+1} = \begin{bmatrix} \boldsymbol{V} \\ \boldsymbol{\theta} \end{bmatrix}^{k} + \begin{bmatrix} \Delta\boldsymbol{V} \\ \Delta\boldsymbol{\theta} \end{bmatrix}^{k} \tag{1}$$

The voltage amplitude and angle increment vectors (ΔV and $\Delta\boldsymbol{\theta}$) can be obtained using the Jacobian matrix ($\boldsymbol{J}$) as follows:

$$\begin{bmatrix} \Delta\boldsymbol{V} \\ \Delta\boldsymbol{\theta} \end{bmatrix}^{k} = \begin{bmatrix} \Delta\boldsymbol{P} \\ \Delta\boldsymbol{Q} \end{bmatrix}^{k} \cdot \left(\begin{bmatrix} \boldsymbol{J} \end{bmatrix}^{k} \right)^{-1} \tag{2}$$

The active and the reactive power incrementals ($\Delta\boldsymbol{P}$ and $\Delta\boldsymbol{Q}$) represent, respectively, the error between the specified active and reactive powers in the nodes, and the ones calculated with the nodal voltages of the ongoing iteration. More information about the calculation of the Jacobian matrix can be obtained in Chapter 3, Section 3.5 of [25]. The convergence is achieved when all voltage increments are below a given threshold.

2) Backward-Forward Sweep (BFS): The BFS method assumes an initial voltage profile in all the nodes and it calculates the nodal current for each node according to the next expression:

$$I_i^k = \left(\frac{S_i^k}{V_i^k} \right)^{*} \tag{3}$$

where S represent the apparent power and V the nodal voltage. The subindex i represents the specific node and the superindex k the iteration number. Once the nodal voltages are obtained, the branch currents can be obtained in a backward way using the Kirchhoff Current Law (KCL) according to the following expression:

$$I_{ij}^k = I_j^k + \sum_{m \in j, m \neq i} I_{jm}^k \tag{4}$$

I_{ij} represents the branch currents connecting the nodes i and j. The branch currents are used to update the node voltages starting from the slack node and sweeping the network in forward direction according to:

$$V_j^{k+1} = V_i^{k+1} - Z_{ij} I_{ij} \tag{5}$$

where Z_{ij} represents the impedance between the nodes i and j. Once all the voltages are updated the next step is the calculation of the currents (see eq. (3)) until the convergence is achieved. Convergence is achieved when the difference between the voltage profiles in two successive iterations is below a given threshold.

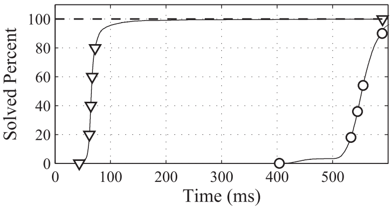

Fig. 8. Comparison of the speed of convergence of the conventional NR and BFS algorithms. ○ NR: Newton-Raphson algorithm. ▽ BFS: Backward/Forward Sweep algorithm.

TABLE IV
COMPARATIVE BEHAVIOUR OF THE ORIGINAL BFS AND NR ALGORITHMS

Selected algorithm	Min. time per case(s)	Max. time per case(s)	Mean. time per case(s)	Achieved converg.(%)
NR	0.403	2.524	0.563	100.0
BFS	0.043	0.916	0.071	100.0

3) Performance Comparison Between (NR) and (BFS): BFS method performs better in radial systems in terms of speed. The tests have been done with a fully radial DC system with 200 nodes, half of them loads and the other half generators. The authors generated a battery test of 10^4 random load cases solved in a conventional computer with a processor Intel(R) Core(TM) i7-2670QM CPU @ 2.20GHz and 4GB of RAM. The convergence achieved by both algorithms was 100%. But in terms of speed the BFS algorithm was nearly 8 times faster. In the Fig. 8 are shown the amount of solved cases in percentage versus the time invested per case. As it can be observed the BFS algorithm solve 80% of the cases investing less than 80 ms per case while the NR algorithm solve 80% of the cases in less than 570 ms per case. In Table IV, more details about the convergence speed can be found. The mean time for solving a case for the NR algorithm is 0.563 s, while the BFS invests as an average 0.071 s. In the table, it can be found also the minimum and the maximum time invested for solving a case for both algorithms.

B. Proposed Solver

The chosen algorithm to solve the vehicle EDS is the method known as Backward/Forward sweep. This algorithm uses the Kirchhoff current and voltage laws (KCL and KVL) iteratively instead of using the traditional power based formulation of the conventional Newton-based methods. This method has been selected for several reasons; 1) Obtaining the formulation for this specific case of application is much simpler; 2) The speed of convergence of these BFS methods has been proved to be higher

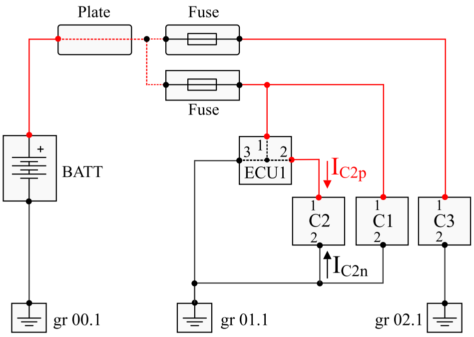

Fig. 9. Example network divided into positive grid (red) and negative grid (black).

than the Newton-based methods in radial or slightly meshed systems [26]. In the specific application of vehicle EDS the system cannot be purely radial, but slightly meshed, hence a Meshed Network BFS must be implemented. This algorithm is based on the conventional BFS, however, it includes minor modifications to deal with the existent loops that will be explained later on this section.

The vehicle EDS can be seen as a two-fold grid: the positive and 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. An illustration of a simple network with the two sub-grids is seen in Fig. 9, showing in red the wires and nodes of the positive grid and in black the ones of the negative grid. The three ground symbols represent ground bolts, interconnected between them through the vehicle body.

The strategy of studying the vehicle EDS as two separated networks is based on the fact that in such networks the path to ground or equivalently, the negative terminal of the battery, represents an intricate network itself. Typically, reaching the negative terminal involves passing through current splices and sequential ground bolts before reaching the main ground bolts in the vehicle body. The selected approach benefits the accuracy of the model. In addition, the MN-BFS adopts only one voltage as the nominal value required. Both the battery positive terminal voltage and negative terminal voltage can be interpreted as the nominal voltages for two different grids. The variable that connects the two networks is the battery current, in other words, the current that flows from the battery positive terminal must be equal to the one that flows into the negative terminal. With this approach, addition of current in the positive grid and negative grid at all branches is always equal to zero. Voltage drops in the network are easily addressed by subtracting node voltages of the respective nodes, ones calculated for the positive grid and the others for the negative grid.

In general, the following is applied: for black boxes behaving as consumers a number of loads appear equal to the number of relationships pin-pout associated to that component. These relationships are clearly stated in the QT file. The loads can be 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 order to guarantee the same total amount of current in the battery terminals, a distribution of current between the nodes need to be done. Considering the case of consumer C2 in Fig. 9, it is observed that there is only one relationship (1-2), where 1 is the input and 2 the output pin, therefore the nodal injection current in the node 1 or I_{C2p} (positive grid) and in the node 2 or I_{C2n} (negative grid) are equal. However, it would be possible to find two relationships inside of a component. That were the case for a C2 consumer with 3 pins, having for instance the pin relations (1-2) and (1-3), being pin 3 another output pin. In such an event, the current injections assigned to the nodes 2 and 3 (both belonging to the negative grid) were exactly the half of the current associated to the input pin 1. In the case of components classified as ECUs the procedure is exactly the other way around: the current associated to a ground pin is split among its associated input pins. Back to Fig. 9, as seen for ECU1, pin 1 is the only input pin linked to the ground pin 3, therefore there is only one current load per each of the grids inside of this component, equal to the current associated to the pin 3.

Algorithm 2 also denominated *Voltage Constructor* executes several tasks. It goes line by line through all of the possible current paths between the positive and negative terminal of the battery, taking into consideration that each odd column is a node and each even column is a connection. The tasks performed are, in order: classification of the elements as consumer or source using Algorithm 1, determination of the interface between the positive and the negative grid (stop node), calculation of the currents to inject in the stop node and neighbors or node current injection vector $\boldsymbol{I}_{np}$, formation of the incidence matrix $\boldsymbol{\Gamma}_p$, branch resistances matrix $\boldsymbol{R}_{bp}$, voltage node id vector $\boldsymbol{V}_{np}$ for the positive grid and their equivalent for the negative grid $\boldsymbol{\Gamma}_n$, $\boldsymbol{R}_{bg}$, $\boldsymbol{I}_{ng}$, $\boldsymbol{V}_{ng}$. Finally, the algorithm creates a pairing matrix which contains the information about the terminals of the components where it is required to obtain their differential voltage (between the inputs pins and output-grounded pins). For the example network in Fig. 9 one possible current path goes from the positive of the battery passing through ECU1, C2 and ending in the negative of the battery through ground bolt gr01.1. The stop node for this current path would be pin 2 of C2.

A set of rules are followed to determine the nodal injection currents $\boldsymbol{I_n}$. Namely:

1) if in a row there is only one element categorized as 'Consumer' through two nodes, the current of the input node belonging to the 'positive grid' is assigned according to the modules selected, and the current of the output node belonging to the 'negative grid' is equal to that of the input node divided over all its related output pins (ignoring the signals)
2) when an output pin is associated to more than one input node, then its current its calculated by adding up the currents that result from following Rule 1 for each of the input nodes

Algorithm 2: Voltage Constructor.

```
Require: dataContainer as dC with dC.ASDS Filtered
Ensure: $\boldsymbol{V}_{np}$, $\boldsymbol{I}_{np}$, $\boldsymbol{\Gamma}_p$, $\boldsymbol{R}_{bp}$, $\boldsymbol{V}_{ng}$, $\boldsymbol{\Gamma}_n$, $\boldsymbol{R}_{bg}$, Pairing matrix
pathsnumber=lengthrows(dC.ASDS.types)
for currentpath=1:1:pathsnumber do
    Create device type vector using Algorithm 1
    Find position of the input node of the last consumer connected to ground or Stop node
    Assign injection currents to nodes according to the Rules 1 to 6
    Create incidence matrix $I_{ncp}$
    Calculate branch resistances $R_{bp}$
    Repeat for the negative grid to get $V_{ng}$, $I_{ncg}$, $R_{bg}$
    Create the node pairs matrix or Pairing matrix
end for
```

3) the current of an input node is assigned only once. If the same input node appears in different rows forming new node pairs, the value of input node current will remain the first assigned while the second node gets the current of the input divided over all its related output pins (ignoring pins carrying communication signals)
4) for 2 or more consumers connected in series within a single row the minimum current among them is assigned to the input node of the consumer which is connected to ground
5) if in a row there is only one element categorized as 'Source' through two nodes, the current of the output node belonging to the 'negative grid' is assigned according to the modules selected, and the current of the input node belonging to the 'positive grid' is equal to that of the output node divided over all its related input pins (ignoring the signals)
6) when an input pin is associated to more than one output node, then its current is calculated by adding up the currents that result from following Rule 5 for each of the output nodes. Exactly the opposite to the case of the consumers

Figs. 10 and 11 are graphical representations of the aforementioned rules.

The incidence matrix $\boldsymbol{\Gamma}$ provides the connections data, where each row represents a branch of the system and each column a node. The construction of $\boldsymbol{\Gamma}$ is done following the next rules:

1) $\Gamma_{ij} = 1$ when the tail of the edge i,is vertex j
2) $\Gamma_{ij} = -1$ when the head of the edge i,is vertex j
3) $\Gamma_{ij} = 0$ Otherwise

The KCL and KVL can be expressed in matrix form using the incidence matrix, respectively:

$$\boldsymbol{\Gamma}^T \cdot \boldsymbol{I_B}^T + \boldsymbol{I_d} \cdot \boldsymbol{I_n}^T = 0 \tag{6}$$

$$\boldsymbol{\Gamma}^T \cdot \boldsymbol{V}^T - \boldsymbol{R_b} \cdot \boldsymbol{I_B}^T = 0 \tag{7}$$

where the newly introduced parameters are $\boldsymbol{I_B}$ which is a vector containing all the branch currents and $\boldsymbol{I_d}$ which is the identity matrix.

To calculate the branch resistances, the algorithm uses information of wire length between nodes given in the dataContainer, together with the selected conductor resistivity. The calculated resistance takes into account effects of temperature by means of the linear approximation of resistivity with temperature shown in equation 8, where T is the ambient temperature and α is the temperature coefficient of resistivity in K^{-1}.

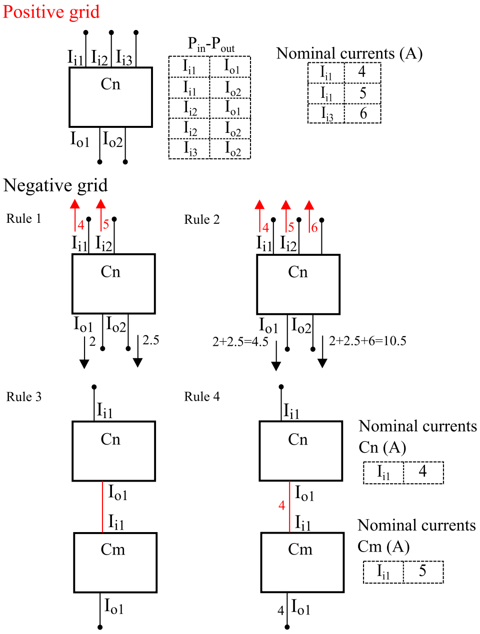

Fig. 10. Representation of nodal injections current rules for the case of consumers.

$$R(T) = R(T_0) * [1 + \alpha(T - T_0)] \tag{8}$$

Before applying the algorithm Meshed-Network Back and Forward Sweep it is necessary to detect and eliminate the branches which define loops in both positive and negative grid. A straight forward strategy to do it is by analyzing the incidence matrix: a node having associated more than one value of -1 is receiving lines which provoke cycles or loops in the system. Branches are eliminated following Algorithm 3.

Once the system is radial, a conventional BFS algorithm can be used for solving the problem, afterward, a compensation algorithm must be applied in order to estimate the currents in the cut branches. The compensation algorithm uses the Thevenin equivalent resistance in the cut branches. A very detailed explanation of the electric principle used for making this Thevenin calculation can be found in [26]. Basically it can be stated that connecting fictitious unitary current sources between the nodes of the cut branches, the voltage obtained between these nodes are the Thevenin equivalent resistance of the circuit from the point of view of a given pair of nodes.

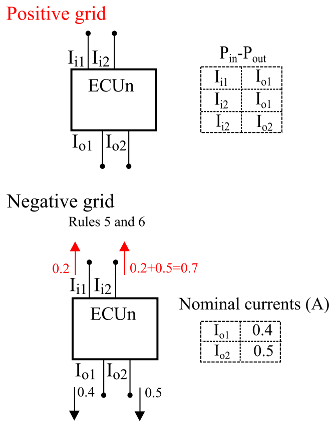

Fig. 11. Representation of nodal injections current rules for the case of ECUs.

Algorithm 3: Detection of loops.

```
Require: Γ
Ensure: $l_c, l_{nc}$
for nodes=1:1:lengthcolumns(Γ) do
    for currentpath=1:1:lengthrows(Γ) do
        Detect loops
        Save to $l_c$ the lines to be removed
        Save to $l_{nc}$ the lines to be kept
    end for
end for
```

Algorithm 4: Meshed Network Back and Forward Sweep (MN-BFS) Solver.

```
Require: $\boldsymbol{\Gamma}, R_B, \boldsymbol{I_n}, l_c, l_{nc}, V_{slack}$
Ensure: $\boldsymbol{V}, I_B$
Init. all $I_B$ to zero and all V to 1
Set $V(1)$ to $V_{slack}$
Calculate Thevenin resistance of cut branches $(R_{th})$
    using fictitious unitary current sources [26]
Calculate the total branch resistance of cut branches
    $R_B{}^{Total}$
for i=1:1:max number of iterations do
    Calculate all currents of non-cut branches $\boldsymbol{I_B}(l_{nc})$
    Calculate network voltages, except the slack V(2:N)
    Calculate the voltage drop in the cut-branches
        using the previous voltages and the Ohm's law
    if Calculated voltage drops are consistent then
        break
    else
        Calculate the new branch currents in the
            cut-branches using the new voltage profile
    end if
end for
```

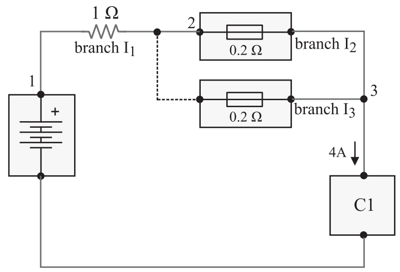

Fig. 12. Sample network to describe the power flow algorithm.

Having calculated the Thevenin resistance of the cut branches the compensation algorithm can be embedded in the radial power flow algorithm as observed in Algorithm 4. The algorithm starts with the initialization of all branch currents to zero and all voltages to one, except the slack voltage (battery) that is set to its predefined value. After that, all Thevenin resistances of the cut-branches are calculated using the unitary current sequential injection method. It must be pointed out that the Thevenin resistances are calculated just once and they don't have to be updated through the iterative process. Subsequently, we launch the iterative process, starting with the calculation of the branch currents in the non-cut branches $\boldsymbol{I_B}(l_{nc})$. This calculation is direct from the nodal currents $\boldsymbol{I_n}$, already assigned according to the six rules previously stated, using the matrix $\boldsymbol{\Gamma}$. By means of the branch currents and the resistances of the non-cut branches we can update the value of the voltages of all nodes (except the slack one). At this stage, the voltage drop in the cut branches can be calculated using two different methods. In one side, since we have all voltages in the network, we can use them to obtain the voltage drop directly in the cut branches. The other approach is the use of the branch currents and the resistance of the cut branches to calculate the voltage drop. Both calculations must match when the algorithm convergence is achieved. If not, the second approach is used to update the branch currents in the cut branches and a new iteration is launched. It has been demonstrated that this method is quite simple and yet, quite robust and effective to solve this kind of systems.

To illustrate the power flow solver described in Algorithm 4, let us consider the sample network in Fig. 12. A given resistance value is only considered for the wires where it is clearly stated. For the fuses, a resistance value is assigned.The circuit is composed by a battery feeding a consumer C1 through a couple of fuses. The nominal battery voltage (slack voltage) considered is 14 V and the consumer nodal injection current is 4A. There are three main branches identified: l_1 connecting the battery to the fuses, l_2 corresponding to one of the fuses and l_3 to the second parallel fuse. The incidence matrix $\boldsymbol{\Gamma}$ together with the nodal current injection vector I_n and the branch resistances R_B are considered inputs for the Algorithm 4, obtained in previous steps. The branch selected to be cut is branch l_3.

$$\boldsymbol{\Gamma} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 1 & -1 \end{bmatrix}, \quad \boldsymbol{I_n}^T = \begin{bmatrix} 0 \\ 0 \\ 4 \end{bmatrix} A,$$

$$\boldsymbol{R_B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.2 & 0 \\ 0 & 0 & 0.2 \end{bmatrix} \Omega$$

$$l_c = [l_3] \tag{9}$$

$$l_{nc} = [l_1, l_2] \tag{10}$$

After applying steps 1 and 2, the Thevenin resistance of the cut branch l_3 is calculated following step 3, using the Equation 7 in the form:

$$\begin{aligned} \boldsymbol{V}^T(2:n_N) &= -(\boldsymbol{\Gamma}(l_{nc}, 2:n_N))^{-1} \cdot \boldsymbol{R_B}(l_{nc}, l_{nc}) \\ &\quad \cdot \boldsymbol{\Gamma}^T(2:n_N, l_{nc})^{-1} \cdot \boldsymbol{\Gamma}^T(2:n_N, l_c) \cdot \boldsymbol{I_B}^T(l_{nc}) \end{aligned} \tag{11}$$

where n_N is the number of nodes, equal to 3 for the sample network in Fig. 12.

$$\begin{aligned} \boldsymbol{V}^T(2:3) = &-\begin{bmatrix} -1 & 0 \\ 1 & -1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 0.2 \end{bmatrix} \cdot \begin{bmatrix} -1 & 1 \\ 0 & -1 \end{bmatrix}^{-1} \\ &\cdot \begin{bmatrix} 1 \\ -1 \end{bmatrix} \cdot 1 = \begin{bmatrix} 0 \\ -0.2 \end{bmatrix} V \end{aligned}$$

The Thevenin resistance of the cut branch is calculated according to:

$$R_B{}^{TH}(:, i) = \boldsymbol{\Gamma}(l_c, 2:n_N) \cdot \boldsymbol{V}^T(2:n_N) \tag{12}$$

$$R_B{}^{TH}(l_3) = \begin{bmatrix} 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -0.2 \end{bmatrix} = 0.2\ \Omega$$

In step 4, the total branch resistance of l_3 is calculated:

$$R_B{}^{Total}(l_c) = R_B{}^{TH} + R_B(l_c, l_c) \tag{13}$$

$$R_B{}^{Total}(l_3) = 0.2\ \Omega + 0.2\ \Omega = 0.4\ \Omega$$

At this point, following step 5, the iterations start. In the first iteration, steps 6 and 7 of Algorithm 4 are as follows, considering $I_B(l_c) = 0$ from step 1:

$$\begin{aligned} \boldsymbol{I_B}^T(l_{nc}) &= \boldsymbol{\Gamma}^T(2:n_N, l_{nc})^{-1} \\ &\quad \cdot (-\boldsymbol{\Gamma}^T(2:n_N, l_c) \cdot \boldsymbol{I_B}^T(l_c) - \boldsymbol{I_n}^T(2:n_N)) \end{aligned} \tag{14}$$

$$\boldsymbol{I_B}^T(l_1:l_2) = \begin{bmatrix} -1 & 1 \\ 0 & -1 \end{bmatrix}^{-1} \cdot - \begin{bmatrix} 0 \\ 4 \end{bmatrix} = \begin{bmatrix} 4 \\ 4 \end{bmatrix} A$$

$$\begin{aligned} \boldsymbol{V}^T(2:n_N) &= (\Gamma(l_{nc}, 2:n_N))^{-1} \\ &\quad \cdot \big((-\boldsymbol{\Gamma}(:,1) \cdot V(1) + \boldsymbol{R_B}(l_{nc}, l_{nc}) \cdot \boldsymbol{I_B}^T(l_{nc})\big) \end{aligned} \tag{15}$$

$$\begin{aligned} \boldsymbol{V}^T(2:n_N) &= \begin{bmatrix} -1 & 0 \\ 1 & -1 \end{bmatrix}^{-1} \\ &\quad \cdot \left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot 14 + \begin{bmatrix} 1 & 0 \\ 0 & 0.2 \end{bmatrix} \cdot \begin{bmatrix} 4 \\ 4 \end{bmatrix} \right) \end{aligned}$$

$$\boldsymbol{V}^T(2:n_N) = \begin{bmatrix} 10 \\ 9.2 \end{bmatrix} V$$

The stop criteria makes use of the KVL in the cut branches. The voltage drops are calculated using two methods as indicated in step 8 and explained before:

$$\|\boldsymbol{\Gamma}(l_c, :) \cdot \boldsymbol{V} - \boldsymbol{R}(l_c, l_c) \cdot \boldsymbol{I_B}(l_c)\| \leq \epsilon \tag{16}$$

For the current example, the algorithm is considered convergent when calculating a voltage drop error value equal or below 0.01 V. This condition is evaluated as stated in step 9.

$$\left\| 0.2 \cdot 0 - \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 14 \\ 10 \\ 9.2 \end{bmatrix} \right\| \leq 0.01\ V$$

In this first iteration the criteria in Equation V-B is false. Then, the current in the cut branch is updated, following step 12.

$$\Delta \boldsymbol{I_B}^T(l_c) = (R_B{}^{Total})^{-1} \cdot \boldsymbol{\Gamma}(l_c, :) \cdot \boldsymbol{V_0}^T$$

$$\Delta \boldsymbol{I_B}^T(l_3) = (0.4)^{-1} \cdot \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 14 \\ 10 \\ 9.2 \end{bmatrix}$$

$$\Delta \boldsymbol{I_B}^T(l_3) = 2\ A$$

$$\boldsymbol{I_B}^T(l_3) = 2\ A \tag{17}$$

A second iteration starts.

$$\boldsymbol{I_B}^T(l_1:l_2) = \begin{bmatrix} -1 & 1 \\ 0 & -1 \end{bmatrix}^{-1} \cdot - \begin{bmatrix} 1 \\ -1 \end{bmatrix} \cdot 2 - \begin{bmatrix} 0 \\ 4 \end{bmatrix} = \begin{bmatrix} 4 \\ 2 \end{bmatrix} A$$

$$\begin{aligned} \boldsymbol{V}^{\boldsymbol{T}}(2:n_N) &= \begin{bmatrix} -1 & 0 \\ 1 & -1 \end{bmatrix}^{-1} \\ &\quad \cdot \left(- \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot 14 + \begin{bmatrix} 1 & 0 \\ 0 & 0.2 \end{bmatrix} \cdot \begin{bmatrix} 4 \\ 2 \end{bmatrix} \right) \end{aligned}$$

$$\boldsymbol{V}^{\boldsymbol{T}}(2:n_N) = \begin{bmatrix} 10 \\ 9.6 \end{bmatrix} V$$

$$\left\| 0.2 \cdot 2 - \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 14 \\ 10 \\ 9.6 \end{bmatrix} \right\| \leq 0.01\ V$$

TABLE V
LIST OF FAMILIES WITH THEIR ELECTABLE MODULES

Family	Modules
family 01	mod01 fam01
	mod02 fam01
	mod03 fam01
family 02	mod01 fam02
	mod02 fam02
	mod03 fam02

TABLE VI
EXAMPLE OF TABLE 'FAM' FOR SAMPLE NETWORK 1

family 01	family 02
mod01 fam01	mod03 fam02

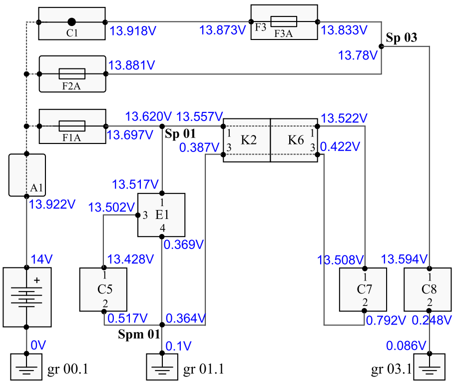

Fig. 13. Calculated node voltages for Sample network 1.

For this iteration the criteria in Equation V-B is true. Then, it is considered that the algorithm has successfully converged. The obtained values are:

$$\boldsymbol{V_n}^T = \begin{bmatrix}14\\10\\9.6\end{bmatrix} V, \quad \boldsymbol{I_B}^T = \begin{bmatrix}4\\2\\2\end{bmatrix} A \tag{18}$$

VI. CASES OF STUDY

The previously described methodology has been applied to different scenarios of a sample vehicle network after introducing a specific modularity information. In these examples, we have considered the case of two families, where each of these two families has three electable modules each, as shown in Table V.

The selection of modularity is inserted in the algorithm in the form of a table denominated 'Fam' (see Fig. 7). Table VI shows an example of modularity selection ('Fam'), where for each of the two families studied, there is a single module specified. To configure a full vehicle electrical network, there should be a module selection for more than 50 families.

Sample network 1 in Fig. 13 corresponds to the selection depicted in Table VI. This electrical network contains a 14 V battery connected to the vehicle ground as the feeder. The node A1 represents a connection to a metal plate where two fuses (F1A and F2A) and a single connection (C1) distribute the current. The fuse identified with node F3 is not connected to the common plate and receives the current through C1. 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* and couplings have been named with the prefix *K* followed by a number. Electronic control units are named ECU followed by a numeration. The reason the numbers are not exactly consecutive is to represent the fact that given the modules selected, certain components have been filtered out. The type of component (whether a consumer or source) is defined using Algorithm 1.

Component ECU1 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.

Figs. 13 and 14 show the calculated node voltages and branch currents of Sample network 1, respectively. Table VII gives a list of the components on both sample networks.

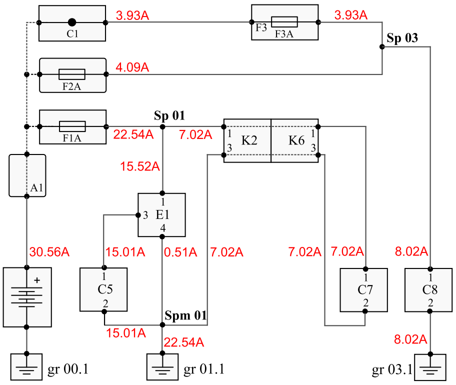

Fig. 14. Calculated branch currents for Sample network 1.

TABLE VII
COMPONENTS LIST

Code	Description
E1	ECU/Source
K2	Coupling
C3	Consumer
C4	Consumer
C5	Consumer
K6	Coupling
C7	Consumer
C8	Consumer
C9	Consumer
C10	Consumer

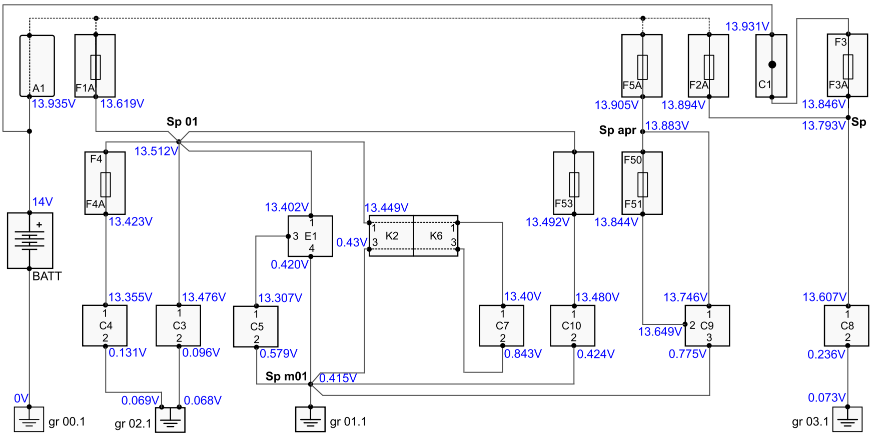

Fig. 15. Calculated node voltages for Sample network 2.

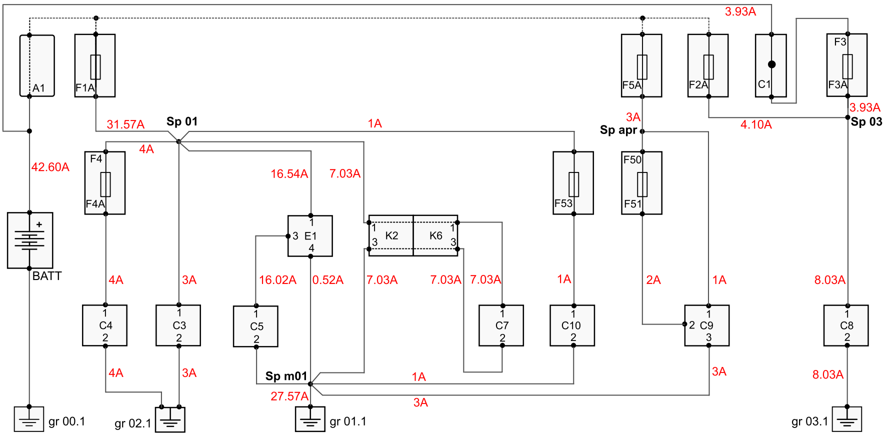

Fig. 16. Calculated branch currents for Sample network 2.

Voltage drops are observed in the lines following the calculated line resistances given their physical characteristics.

Nominal node voltages decrease following the power flow as expected. In addition, calculated branch currents are consistent all along the circuit.

Sample network 2 corresponds to a different modularity selection, as observed in Table VIII. In this case, the network is formed by a higher number of consumers, thus increasing also the amount of fuses and splices present in the network. Voltage drops are observed along the wires and fuses. The amount of voltage drop in the fuses is dependent on their type. As to sample network 1, the obtained power flow all along the network remains coherent, as observed in Figs. 15 and 16.

TABLE VIII
EXAMPLE OF TABLE 'FAM' FOR SAMPLE NETWORK 2

family 01	family 02
mod03 fam01	mod03 fam02

Usually different parts of the EDS are fed by the battery or a different set of ECUs that split the whole network in different subsystems that can be simulated and studied independently.

VII. CONCLUSION

The high complexity found in the wiring system of modern vehicles translates to several aspects such as EDS development, assembling, managing of spare parts and also documenting. To reach the level of vehicle EDS simulation is therefore mandatory to understand the way in which the network information is presented and be able to extract it and transform it.

The main contributions of this work are:

- A detailed methodology to take and adapt the vehicle EDS factory data into suitable and standard matrices that serve as inputs for a power flow solver
- The description and implementation of the Meshed Network Backward and Forward sweep algorithm, which for systems such as vehicle EDS where the network is not purely radial, performs much better compared to Newton-based methods. This method includes a minor modification on top of the traditional BFS, that allows it to be used in weakly meshed networks such as the vehicle EDS.
- The introduction of a low computational-costly method, since the required matrix inversions are calculated only once and the matrices are highly sparse, representing a low consumption of computer memory and computation time. This method is ideal for radial systems and its high speed is appropriate for future new developments where probabilistic power flows are needed and the speed becomes a key factor.
- The usability of a method able to detect faults in the vehicle EDS such as excessive voltage drops or overcurrents, that is applicable to multiple EDS configurations far beyond of what is feasible with real prototypes. The applicability of the methodology has been demonstrated by selecting different configurations and verifying the consistency of the calculated electrical variables.

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Appendix B

Conference publication

B.1 Visual Analytics-Based Computational Tool for Electrical Distribution Systems of Vehicles

X. Dominguez, P. Arboleya, P. Mantilla-Perez, I. El-Sayed, N. Gimenez and M. A. D. Millan, "Visual Analytics-Based Computational Tool for Electrical Distribution Systems of Vehicles," 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), 2019, pp. 1-5, `https://doi.org/10.1109/VPPC46532.2019.8952440`.

Visual Analytics-Based Computational Tool for Electrical Distribution Systems of Vehicles

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***Abstract*—The present work provides a solid understanding on the challenges and opportunities of visual analytics (VA) use for the development of electrical distribution systems (EDS) of vehicles. First, the need for a VA-based software platform is justified to address the associated information overload and problem complexity. Later, a detailed background on the preceding use of VA in electrical systems as well in the automotive industry is provided. Based on the previous context and agile software implementation, specific guidelines for the development of a novel and functional VA-based computational tool are then provided to appropriately visualize, analyze and simulate in-car EDS.**

***Index Terms*—Automotive industry, agile methodologies, computational tool, electrical distribution systems of vehicles, visual analytics.**

I. INTRODUCTION

THE complexity in electrical distribution systems (EDS) of vehicles has significantly increased in the last years due to the use of new electronic devices and sensors, advanced safety functionalities, higher user needs, superior efficiency demands and the continuous electrification of traditional mechanical functions including the insertion of electrically-powered traction systems. Moreover, to ensure reliability, wires in automobiles are usually oversized to avoid temperature increase so that insulation integrity is maintained, and also to warrant an acceptable mechanical resistance to withstand the manufacturing process [1]. For these reasons, more and bigger power supplies, Electronic Control Units (ECUs) and wires are required. This raise in system intricacy and weight provokes more time spending and energy in the manufacturing process as well as efficiency reduction in daily fuel or battery consumption [2]. On the other hand, the amount of information that planning engineers must handle is huge as today's vehicles may contain hundreds of power consumers, up to ten thousand possible wiring combinations and more than a thousand wires having a total extension close to 3 km and a weight above 50 kg [3], [4]. Consequently, these networks (See Fig. 1) demand an enormous amount of protections, harnesses, ECUs, splices and joints to properly transmit signals or power supply to the different components.

Despite the aforementioned requirements, these electrical networks are not only intended to be flexible and robust, but also they are expected to be aligned to fulfill efficiency standards [5], [6], design challenges [7] and emerging environmental policies on greenhouse gases reduction [8]. To satisfy these augmented demands, the use of software platforms at the design stage to suitably scheme, visualize and analyze the great amount of electrical information is crucial. In this respect, specialized visualization and simulation tools exist for the majority of other systems in modern vehicles like chassis, air conditioning, engine, power train or electrical drive. The use of simulation tools at the design stage enhances productivity and reduces prototyping costs in these systems. However, this is not the case of EDS in automobiles, where in most cases real prototyping exists at early stages. This is a consequence of the massive amount of wiring harnesses groups, paths and configurations as well as large complexity on integrating disperse and vast data from automotive manufacturers and their electrical components suppliers. Besides, the pursue of Original Equipment Manufacturers (OEMs) to add augmented comfort and customized options to consumers has provoked a significant increase in assembly logistics due to the great amount of possible harnesses architectures [9].

To overcome this information overload, facilitate human-information interaction and thus achieving a rapid and intuitive understanding of the system's structure and state, the use of visual analytics (VA) in these computational platforms is compelling. In fact, VA has been successfully employed to gain knowledge, amplify cognition and get insights from large and complex datasets in electrical systems as further will be discussed. However, all the related contributions 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. Despite this increasing interest on VA in the last years in the academic environment, VA is not consistently adopted when developing industrial applications as observed almost a decade ago [10]. Unfortunately, as the literature reports, this situation still persists to these days in some engineering fields as in the case at hand. In this context, the contribution of this work is threefold. First, section II provides a grounding understanding on the challenges and benefits of

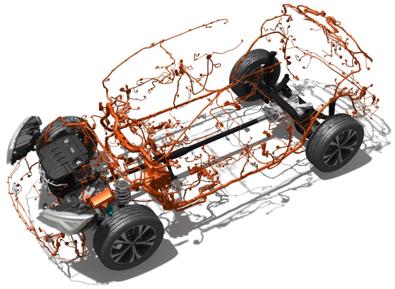

Figure 1: Electrical network harnesses of a vehicle [4]

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VA for the particular concern of the automotive industry. Then, section III gives insights on previous research related to VA in electrical systems and particularizes for the case of EDS of modern vehicles. Third, supported on the previous background and dynamic software design premises, section IV proposes specific guidelines for an efficient development of a VA-based computational tool for the proper visualisation, simulation and analysis of EDS of vehicles in the context of the automotive branch. The need for agile methodologies [11], [12] and user-centered design (UCD) [13] approaches like Design Thinking [14] is highlighted to enhance rapid software testing and user satisfaction. Finally, some conclusions are inferred in the last section.

II. VISUAL ANALYTICS IN THE AUTOMOTIVE INDUSTRY

The early definitions denoted the purpose of VA as "facilitating analytical reasoning by interactive visual interfaces" [15] and highlighted the relevance of interaction [16]. As the foregoing delimitation was vague, a more explicit demarcation was proposed settling VA as the merge of "automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets" [17]. Nevertheless, in the last years VA has been conceived as a highly multidisciplinary field that merges different research areas such as visualisation, data analysis, data mining, human-computer interaction, data processing, geo-spatial analytics, statistics and others [18]. In the automotive engineering branch, a few attempts to use VA in varying depth exist. So far they have been mostly engaged in the domain of computed-aided-design [19], artificial vision [20], vehicle collision [21], [22], engine multibody dynamics [23], virtual reality [24], aerodynamics [25], sensor data [26] and electric charging analysis [27]. Additionally to the previous references, it is worth to highlight the contributions performed in [10] regarding the systematic deployment of visualisation systems for vehicle communication networks in a large automotive company. From the previous work, some tools were derived to study communication processes correlations in sequence diagrams [28], connect multimedia components from large datasets [29] and detect errors in masses of trace data [30] among others.

Some software tools, such as EBCable® [31] and LDorado® [32], are commonly employed in the automotive industry to design the EDS of vehicles; while other tools like SaberRD® [33] and Siemens Amesim® [34] are used to validate those designs. However, none of the above complements the evaluation of electrical data by means of a VA methodic inclusion. Moreover, they neither permit a realistic power flow simulation of the network based on available factory information. This exclusion of the specific features of harnesses, wires, fuses, ECUs and loads is a significant limitation. Finally, it is worth to highlight that a large-scale industry like the automotive presents particular characteristics given its organizational intricacy, higher specialization and distributed administration. In this regard, the perspectives and recommendations exhibited in [35] can be of special relevance for software development in this ambit. On the previous reference the author also denoted that "large companies provide a lot of interesting challenges and complex real-world datasets for information visualization research". This exhortation and the lack of specialized tools motivate the development of a state-of-the-art VA-based computational platform useful for the design and analysis of EDS of vehicles.

III. VISUAL ANALYTICS IN ELECTRICAL NETWORKS

The first significant contributions of VA in electrical engineering came about the early 2000's. They were oriented to power systems and focused on showing data in aesthetic representations that included features such as color countouring [36], data aggregation, animations and 3d visualizations [37]. The usability of these representations were also evaluated [38]. Later on, the spotlight was on taking advantage of those representations in simple contingency [39] and power market scenarios [40]. Then, some years passed without relevant contributions taking place. A decade ago, the literature commenced again to enrich with efforts concerned on including electrical meaningfulness [41] to develop "weighted" graphs to highlight the physics of power systems and not only structural or geographic information [42], [43]. For instance, as in the case of EDS of vehicles, the geographic or coordinate position of buses is not compulsory for visualizing and understanding the network. Hereof, the use of force directed graphs [44] to avoid overlapping of lines or the adoption of multidimensional scaling with "electrical distances" [45] to infer electrical connectivity, represent valid alternatives.

It is also worth mentioning the attempt in [46] to propose metrics to assess the quality of network layouts for these purposes. As single-line diagrams are still broadly used by field and design engineers, some efforts have been made to develop algorithms to arbitrarily layout those diagrams. A ruled-based approach suitable for radial and small-size meshed distribution networks was suggested [47]. The performance of this last proposal was improved in [48] by means of a branch and bound technique. A particle swarm optimization method to include the depiction of substations and transmission lines was also proposed [49]. To encompass strongly meshed networks, an algorithm based on physical laws and enhanced by geospatial data was then exposed [50]. Efforts to include substations' geographic and space constraints [51] as well as rules to construct diagrams for SCADA screens [52] have also been presented. Regardless of the diversity in the aforesaid research, it is important to note that all the reports focused VA only in the domain of power systems, but not on scenarios of complex low-voltage DC distribution networks like in modern vehicles.

IV. DEVELOPMENT OF VA-BASED COMPUTATIONAL TOOL FOR EDS OF VEHICLES

A. Software development: Agile methodologies and UCD

Plan-driven traditional software development, where sequential and rigid temporal stages exist for the different phases of the process, has been reported to present some drawbacks such as focusing on goals rather than teamwork, delayed working versions availability and difficulty to adapt to rapid-changing requirements [53], [54]. Based on these evidences and the aim of developing a novel but practical VA-based computational solution to be used in a daily basis by engineers in charge of EDS of vehicles, agile methodologies [11] leveraged by user-centered design (UCD) [13] perspectives have been considered. Indeed, numerous experiences have shown that interactive applications which have been designed without properly considering final users' competences, require greater training and learning efforts [55]. In this regard, the high empathy and cooperation with customers recommended in UCD should be cleverly incorporated into the iterative rapid-testing software prototyping proposed by an agile tactic like SCRUM [12]. To do so, in the last years promising experiences on integrating the best from these two software development trends have been exhibited in large companies and industries [56], [57]. Besides, agile techniques have proven to shorten the development cycle in automotive software development [58]. In the present project, the framework proposed in [59] has been chosen due to its comprehensive methodology based on a systematic literature review.

B. Software functionalities

Given above a brief discussion on agile software development as well as a state-of-the-art background on the use of VA in the context of the automotive branch and in electrical networks, this subsection particularizes, articulates and proposes guidelines for the development of VA-based computational tool for EDS of vehicles within an industrial framework. General directives will be provided to evaluate the core question: what are the required functionalities for a VA-based tool to enhance the understanding and design of the EDS of vehicles?. Some cyclical and highly correlated aspects (See Fig. 2) have to be discussed to properly address this inquiry:

1) Enhance intrinsic knowledge from experts: It is important to note that great amount of data storage is quite simple and straightforward to handle in these days. Nonetheless, the challenge consists on gaining knowledge, amplify cognition and get insights from the datasets. This only can be achieved if the software tool firstly heightens the intrinsic experts' knowledge after considering their engineering practices. Hence, the expertise from professionals is of high relevance as the development of the on-board EDS is one of the most challenging stages in the design chain of an automobile [9]. Indeed, part of the design such as voltage drop and power calculation is carried out empirically. In this respect, to understand the nature of the problem, in-field meticulous observations, conversations and workshops have to be conducted to study the common procedure in which engineers currently design and validate on-board EDS. A relevant UCD-based technique to do so is Design Thinking [14].

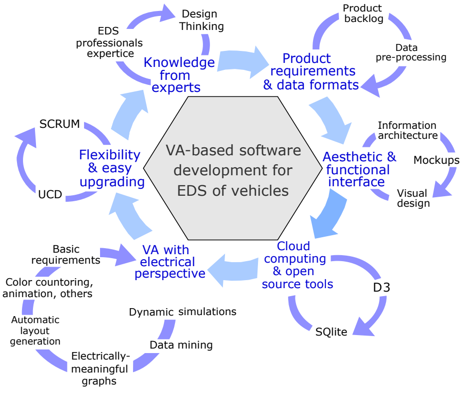

Figure 2: VA-based software functionalities

2) Address product requirements and variety of data formats: Once the experiences, difficulties and expectations from engineers have been identified, it is opportune to define the "product backlog" [12] which is a flexible list of all software requirements to achieve. From this list, the need for information pre-processing will be evident to appropriately integrate distinct data files with different formats in a single database. For instance, throughout the wiring harness development process in the automotive industry, some data formats are employed [9] such as: wiring schematics and wiring plans files (.tif), 3D wiring mechanical-routing files (.cad), electro-mechanical data container files (.kbl and .xml) and wire list/Bill Of Materiales (BOM) excel files (.xls). This variety in data types responds to the OEMs information exchange needs for assembly pursuits. However, to use these data for electrical analysis or simulation purposes, some aggregation and laborious data pre-processing are needed as factory information is disperse and not intuitive.

3) Develop and aesthetic yet functional interface: An aesthetic yet functional software appearance for an intuitive user manipulation and navigation is needed. Before coding activities, two relevant aspects of the design process have to be faced. First, define the information architecture and tasks' flow diagrams [60]. These will depend on the user objectives identified in the previous point. And second, develop and validate different application mockups including low and medium-fidelity wireframes [61]. If possible, the interface should exhibit familiar visual designs and representations from common software tools currently employed for engineers of EDS of vehicles (mentioned in section II). Similarly, the analysis of those tools suggest the use of: i) multiple-coordinated views [10] where different perspectives of single or multiple datasets are available, ii) visualization trees that permit the user an easy navigation between hierarchical levels of information, iii) proper contrast and color schemes and iii) zooming and panning options for an easy navigation.

4) Incorporate VA from an electrical perspective: At first hand, basic design and simulation requirements (See Table I) have to be handled to support typical user tasks. It is noteworthy to recall that current simulation tools of automobiles are mostly focused on energy management, electric vehicle power electronics/powertrain dynamics and battery/alternator sizing considering mainly driving profiles. For instance, they lack on analyzing in detail the on-board EDS in full network models containing all wires, fuses, ECUs, loads and other components. These technical gaps could be addressed by means of an appropriate information visualisation and data analytics grounded on VA precepts. On this subject, the inclusion of the already mentioned VA approximations for electrical networks like color contouring, animation and data aggregation represents a good starting point. Then, the use of automatic algorithms for layout generation (quoted in section III) have to be explored and particularized considering the large amount of

Table I: Basic software requirements

Design requirements
Pre-process input data files with different formats to import and modify electrical information from harnesses and components.
Integrate if required different harnesses' layouts in a single project.
Create parametric models to represent an accurate behavior of electrical components.
Have an aesthetic representation of the electrical network considering three detail levels: i) General 3D-view, ii) Simplified 2D view and iii) Detailed 2D view.
Include a practical tutorial and procure user guidance.
Simulation requirements
Permit and intuitive visualisation and rapid access to electrical information (voltage, current, power, impedance, etc) of nodes or components.
Admit steady-state and transient simulations under normal, overload or short-circuit conditions
Exhibit alerts if risky or critical conditions are reached.
Allow the creation of different load profiles and configurations.
Generate automatic simulation reports.

components' type and number, the wire harnesses' grouping complexity as well as the intricate and weakly-meshed DC network characteristics of in-car EDS. After this, the addition and usability validation of more electrically-meaningful graphs [41], [45] would represent a significant contribution. Later, the incorporation of data mining tactics could permit to rapidly determine risky and unsuitable electrical system configurations under different scenarios. Finally, to boost the software capabilities, the employment of dynamic power flow simulations to study steady-state and transient conditions will be of great significance towards advanced virtual experimentation. All these software attributes could significantly improve the design process of in-car EDS by means of a prompt validation of appropriate network schemes and avoidance of risky configurations presenting wrongly sized protections, unwanted voltage drops or high current paths that may lead to excessive temperatures.

5) Use cloud computing and open-source libraries and database managers: A cloud computing web-based application is recommended instead of a static traditional software platform. This guideline seeks to minimize costs, increase accessibility, provide elasticity to customer's demands and promote resource sharing and agile development [62]. Moreover, this could also permit the use of fast, open-source and specific data-base managers and libraries such as SQlite [63] and D3 (Data-Driven Documents) [64] correspondingly. In particular, Javascript-based library D3 is being highly employed in all kind of information visualisation projects as it permits with ease to add interaction and animation to complex datasets. Recently, D3 has even been used to increase the awareness on power distribution infrastructure [65].

6) Allow flexibility and easy upgrading: The application should be flexible enough to permit rapid upgrading to varying users' demands and a prompt iterative prototyping based on objectives. The users must periodically receive working versions so that rapid feedback on problems, improvements and bugs is given back. This way, UCD and SCRUM will be conjugated along the process as [59] suggests.

V. CONCLUSIONS

The development of the on-board electrical distribution system (EDS) is a very challenging stage in the design chain of an automobile. This is a result of the complex, vast and disperse electrical information from manufacturers as well as the great amount of wiring paths, components and configurations present in modern vehicles. In this regard, this work has evidenced the need of visual analytics (VA) to integrate all the EDS data in a single platform capable to perform simulations and facilitate human-information interaction. Despite the fact that a systematic literature review has exhibited a significant employment of VA in electrical systems, all the contributions were in the power systems field. Similarly, a detailed survey on the VA use in the automotive industry revealed the lack of software platforms permitting the analysis and simulation of detailed in-car electrical network models including the specific factory features of wires, fuses, loads, ECUs and other components. Nevertheless, the aforementioned research was of high relevance to infer the challenges and benefits of VA in a broader domain. Those general premises were adapted to propose specific guidelines for the development of a novel yet practical VA-based computational tool custom-designed to the particular needs of the EDS of vehicles. Agile software development and user-centered design approaches were also highlighted as they have proven to foster fast software prototyping and user satisfaction.

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