Ontology-based analysis of the semiconductor supply chain: the use-case of the Battery Management System

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Thesis to obtain the Master of Science Degree in

Industrial Engineering and Management

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May 2023

I declare that this document is an original work of my own authorship and
that it fulfills all the requirements of the Code of Conduct and Good Practices
of the Universidade de Lisboa

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my supervisor Professor Ana Póvoa for her dedication, wise comments, unlimited support and unconditional guidance. Her main qualities based on pragmatism, wisdom, organisation and kindness are an inspiration to me. It was very rewarding to work under her supervision.

In addition, I would like to mention Hans Ehm for the unique opportunity provided, by offering me an internship at Infineon Technologies, where this dissertation was written as well. It was an honor to be able to discuss my Master Thesis with Hans, who always made wise and pertinent advices and suggestions. It was a pleasure for me to be part of such an innovative and inspiring company.

I would also like to extend my thanks to Abdelgafar Ismail for all the support and feedback. A special thanks to Mahmoud Ismail for sharing his expertise in the field of the Battery Management Systems.

In addition, I would like to thank my friends, colleagues and people who accompanied me during this five years. It was a pleasure to pursue this path with each one of you and without you, it would not be as enriching and fun.

To my godmother, for always believing in me and never doubting my abilities. For the care in contact and for all the affection she gives me daily, especially when I visit her. For this I am eternally grateful.

Finally, but the most importantly, I would like to thank my family, especially to my parents, Paulo and Manuela, for passing on to me and my sister the taste for wisdom and especially for science. For the exceptional education, opportunities and affection they gave me that make me who I am today. To my father I thank for the inspiration he transmits to me by being brilliant and perfectionist in everything he does, starting with excellence at school and university. The love of literature and poetry I thank in particular my mother, for the recited poems, which gave me a higher awareness of the sensitive aspects in life, making it more beautiful. To my sister Beatriz, thank you for the moments and memories we have shared and will continue to share.

Abstract

Human activity has led to an increase in the average surface temperature of the planet since the industrial revolution. The European Union is an example of an organisation that aims to reverse this trend, namely by creating environmental legislation and promoting the transition from polluting energy sources to greener ones. This work presents a study that indicates that the use of semiconductors can help the development of solutions that focus on reducing carbon dioxide emissions. Semiconductors are electronic devices used in a wide range of equipment. The fact that they are an integral part of more environmentally friendly applications will be a research topic, exploring a duality between their significant carbon footprint and the savings when applied in more efficient products. Given the importance and dependence of these devices, present in various processes, the stability of their supply chains is also studied. The permanent scrutiny and monitoring of the chains contributes to their sustainability. Such monitoring can be achieved with semantic web technologies, which allow an analysis of this specific sector, the semiconductor one, in this way, discovering possible correlations with polluting substances, being possible to infer, in real time, the contributions to the reduction of the carbon footprint. The digitalization of processes or supply chains, like digital twins, allows a more analytical examination to their environmental performance. One of the contributions of this thesis is the digitisation of an application consisting of semiconductors, which is later added to a Digital Reference, which digitally represents the semiconductor supply chain. For this work the Battery Management System was selected, due to its relevance in the transition to cleaner means of transport.

Keywords

Semiconductors; Battery Management System; Sustainable Supply Chains; Industry 4.0; Semantic Web Technologies; Ontologies

Resumo

A atividade humana tem conduzido a um aumento da temperatura média da superfície do planeta desde a revolução industrial. A União Europeia é exemplo de uma organização que ambiciona inverter esta tendência, nomeadamente criando legislação ambiental e promovendo a transição de fontes de energia poluentes para fontes mais verdes. Este trabalho apresenta um estudo que indica que o uso de semicondutores pode ajudar do desenvolvimento de soluções que se concentram na redução das emissões de Dióxido de Carbono. Os semicondutores são dispositivos electrónicos utilizados numa vasta gama de equipamentos. O facto de serem parte integrante de aplicações mais amigas do ambiente será um tema de investigação, explorando uma dualidade entre a sua significativa pegada carbónica e a poupança quando aplicados em produtos mais eficientes. Dada a importância e dependência destes dispositivos, presentes em vários processos, a estabilidade das suas cadeias de abastecimento é também estudada. O escrutínio e monitorização permanente das cadeias contribui para a sua sustentabilidade. Esta monitorização pode ser conseguida com tecnologias de semantic web, que permitem uma análise deste sector em específico, o dos semicondutores, descobrindo assim possíveis correlações com substâncias poluentes, sendo possível inferir, em tempo real, os contributos para a redução da sua pegada de carbono. A digitalização de processos ou cadeias de abastecimento, como as digital twins, permite um diagnóstico mais analítico ao seu desempenho ambiental. Um dos contributos desta tese é a digitalização de uma aplicação constituída por semicondutores, que é adicionada a uma Digital Reference, representando digitalmente a cadeia de abastecimento dos semicon-ductores. Para este trabalho foi selecionado o Sistema de Gestão de Baterias, devido à sua relevância na transição para meios de transporte mais limpos.

Palavras Chave

Semicondutores; Sistema de Gestão de Baterias; Cadeias de Abastecimento Sustentáveis; Indústria 4.0; Tecnologias Semantic Web; Ontologias

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Acronyms

BMS	Battery Management System
UNFCCC	United Nations Framework Convention on the Climate Change
GHG	Greenhouse Gas
UN	United Nations
IPCC	Intergovernmental Panel on Climate Change
COP21	21^{st} Conference of the Parties
IC	Integrated Circuit
EV	Electric Vehicle
AI	Artificial Intelligence
ICT	Informationand Communication Technology
PFC	Perfluorinated Compound
WSC	World Semiconductor Council
SCOR	Supply-Chain operations reference model
WWW	World Wide Web
W3C	World Wide Web Consortium
CO2	Carbon Dioxide
URI	Unique Resource Identifier
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
OWL	Web Ontology Language
SPARQL	SPARQL Protocol and RDF Query Language
RIF	Rule Interchange Format

TBL	Triple Bottom Line
DR	Digital Reference
EU	European Union
PGMEA	Propylene glycol methyl ether acetate
IoT	Internet Of Things
PHEV	Plug-in Hybrid Electric Vehicles
HEV	Hybrid Electric Vehicles
IMPRES	Infineon Integrated Management Program for Environment, Energy, Safety and Health
SKOS	Simple Knowledge Organization System
LIB	Lithium Ion Battery
SOC	State of Charge
SOH	State of Health
SOP	State of Power
SOA	Safe Operating Area
SOS	Safe Operating Safety
BEV	Battery Electric Vehicle
CH4	Methane
N2O	Nitrous Oxide
SF6	Sulphur Hexafluorife
BEVs	Battery electric cars
GSCM	Green Supply Chain Management
IRI	Internationalized Resource Identifier
ECSEL	Electronic Components & Systems for European Leadership
DAML	DARPA Agent Markup Language
SC	Supply-Chain
XML	Extensible Markup Language

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Introduction

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This chapter will address the structure of this work, as well as its context and objectives. First, the problem will be presented, followed by the objectives, methodology and structure of this dissertation.

1.1 Problem Contextualization

The worldwide economic progress of the previous two centuries was achieved at the expense of environmental deterioration, over usage of natural resources and fossil energy sources. The scientific community has evidence that the warming of our planet is the result of human activities which have affected the balances of the climate system, particularly evident in the last two centuries, a state that has worsened in recent decades [6]. The increasing population and inadequate industrialization policies have contributed to this situation. As a consequence, natural resources are being depleted and levels of environmental pollution increasing. Such changes have impact not only in human beings but also on natural systems. Climate change is now perceptible, with greater frequency and amplitude of extreme events such as droughts, floods, the average rise in air temperature and the melting of the polar ice caps, leading to rising sea levels. Such events bring unprecedented risks for vulnerable human populations and lead to irreversible biodiversity loss [7].

Climate change means, under the United Nations Framework Convention on the Climate Change (UNFCCC) , "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The emission of Greenhouse Gas (GHG) through human activities, contributes to the warming of the planet, due to the greenhouse effect [8]. The greenhouse effect is an interaction between solar energy and GHG. Due to their molecular structure, these gases may trap heat in the environment and transfer it to the ground surface. This continuous cycle of heat-trapping contributes to an overall rise in air temperatures on Earth [9].

In 1989, was created by the United Nations (UN), the Intergovernmental Panel on Climate Change (IPCC). This Panel gives a full scientific perspective on climate change, including the political and economic effects on societies, pointing out the dangers and the solutions to mitigate or solve the problems. Three years later, in 1992, a framework convention on climate change [10] was established by the UN, concluding that both natural and anthropogenic GHG are "gaseous constituents of the atmosphere that absorb and re-emit infrared radiation" that cause the greenhouse effect.

The four most relevant GHG are listed in annex A of the Kyoto Protocol [11] as Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O) and Sulphur Hexafluorife (SF6). The energy sector, industrial processes, solvents and other products, agriculture, land-use change and forestry waste are the six major responsible sectors for the emission of these gases. According to the UNFCCC Handbook, CO2 is responsible for 50% of the overall warming effect arising from human activities, followed by CH4 with an 18% contribution and finally N2O, responsible for 6%. [12]

To tackle climate change and its negative impacts, world leaders at the UN Climate Change Conference (COP21) in Paris reached a historical agreement. Implementation of the Paris Agreement requires economic and social transformation, based on the best available science. The Agreement includes commitments from all countries to reduce their emissions and work together to adapt to the impacts of climate change, and calls on countries to strengthen their commitments over time. It was signed by 195 nations in December 2015 during the 21^{st} Conference of the Parties (COP21). Its main aim is to hold "the increase in the global average temperature to well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels" [7]. With this goal in mind, more and more countries, regions, cities and companies are setting carbon neutrality targets. Zero-carbon solutions are now competitive in many of the economic sectors that account for 25 % of emissions. By 2030, zero-carbon solutions could be competitive in sectors representing more than 70 % of global emissions. Nowadays, it is more frequent to find consumers which are interested in the origin of the products, carefully assessing their composition, manufacturing site and, also, with its carbon footprint. Therefore, companies were as well forced to adapt their practices, processes and raw materials to comply with the aims of the Paris Agreement.

Electrification of the means of production, transport and operation of human-driven processes appears to be the most capable way of leading to the abandonment of polluting technologies and making use of renewable and clean solutions [13] [14]. In the electrification of our society and transition into the new industrial revolution, the Industry 4.0, semiconductors will gradually become more prominent in our electronic devices.

Semiconductors have become an indispensable part of everyday life and play a key role in shaping a better present and future where microelectronics connects the real and the digital world. Semiconductors are complex electronic devices with extraordinary capabilities that, used in multiple applications, enable efficient energy management, smart mobility as well as secure and seamless communications in an increasingly connected world. While the production processes of these devices emit a considerable amount of greenhouse gases, the benefit of their use in improving the efficiency and control of equipment means that during their lifetime less energy is consumed and huge amounts of CO2 are saved. The balance of their contribution to improving the energy efficiency of processes and systems and reducing the amount of greenhouse gases produced will be the motto of this work.

The European Union (EU) represents less than 10% of the global production of these chips. The COVID-19 pandemic enhanced the importance of such small chips in our daily live, and as well the importance of having flexible, resilient, and more efficient supply chains, resulting in less disruption. The global shortage and tensions between China and the United States open a space for European digital sovereignty. The European Chips Act is a legislation aimed at enhancing the security of semiconductor supply in the European Union. The three pillars of this regulation are: (1) strengthen EU´s production capacity and support businesses; (2) assure security of supply; (3) monitor and respond in case of crises, having better mechanisms and coordination. This will proportionate an in-depth and holistic view of the global semiconductor supply chain. Another measure presented by the EU is that the sale of CO2 emitting vehicles will be prohibited from 2035 on. The fact that these vehicles will be replaced by battery-electric vehicles, makes the semiconductor demand spike. In order to guarantee a safe usage of Lithium Ion Battery (LIB), they need to have an incorporate Battery Management System (BMS), which is basically an assembly of semiconductors. Therefore, given the importance of this device, it was chosen as object of research for this work. Firstly, by analyzing its potential CO2 savings, and then, by contributing to the project in which is integrated, the Productive4.0. This project was funded by the EU&Electronic Components & Systems for European Leadership (ECSEL) and coordinated by Infineon, addressing all the digital industry issues. The Digital Reference (DR) is a digital twin representing all the levels of the semiconductor Supply-Chain (SC). It can be used for simulation, auto-scheduling, automated hardware, smart software, integrated control, and data analysis.

This work was developed in collaboration with the semiconductor company Infineon Technologies Ag, in particular as a contribution to the project Productive4.0, financed by EU. The final goal will be to extend the Digital Reference with a new semiconductor end-application, the BMS.

1.2 Dissertation Objectives

This master's thesis aims to analyse the impact of incorporating semiconductors in devices, equipment, and systems, integrated in a collective effort to, directly or indirectly, reduce the negative impact of activities and processes of our modern societies in the environment. It will help demonstrate the role and importance of semiconductors in the shift from today's polluting technologies to greener ones.

The use of semiconductors for improving equipment and processes lowers their long-term environmental ecological impact of the manufacturing process for semiconductors even though it is highly polluting and energy intensive. Chips allow building complex digital or computational devices capable of monitoring and control systems, making them more efficient, less energy consuming and less polluting, with very significant cumulative impacts in the long term. To demonstrate this virtue, this work will study the impact of the Battery management system, BMS, in terms of reducing the carbon footprint, particularly in electric vehicles. The main function of BMS is the supervision and management of lithium-ion batteries, promoting safer usage and longer life span. Its contribution to CO2 savings will be here discussed in more detail.

This research is aligned with the objectives of Industry 4.0 by using Semantic Web Technologies for the study and optimisation of supply chains, making them greener. As a tool, Semantic Web Technologies allow standardisation of vocabulary and cross-domain data. An ontology is a formal and structural way of representing the concepts and relations of a shared conceptualization. They can act as an inter-language that enables knowledge extraction through queries. In this way, it is possible to model smart factories, production lines and supply chains. A schematic simplification can be developed, making the connection between machines, people, and products.

This work proposes the expansion of the digital reference by the development of an ontology of a semiconductor end-application, taking as an example the BMS. In this ontology, besides all the constituents of the main application, the potential CO2 savings of that device will also be included. In this way, the DR will be able to answer in regards to the contributions of a set of semiconductors used in BMS to CO2 savings and the role of each semiconductor.

Here, the BMS is studied as part of the batteries' system that integrates the Electric Vehicle (EV). Their importance in this system will be analyzed in detail and a representative schema will be presented. This scheme is fundamental for the creation of an ontology, later implemented in the Protégé software. Ontologies are a component of the World Wide Web Consortium (W3C) standards stack for the Semantic Web and one of the fundamental elements of semantic technology. They ensure shared knowledge of the content, knowledge binding and make explicit domain assumptions. Once validated, it will integrate a digital twin of the semiconductor supply chain, the DR, which reflects the semiconductor supply chain and the corresponding supply chains [15]. Thus, the new ontology will be added in order to link knowledge and build a standard way of communication between different actors and machines. In this way, a new knowledge layer will be established, contributing to the holistic view of the whole supply chain.

1.3 Dissertation Methodology

Researching about the sustainability of semiconductors in the supply chain is not a straightforward and unique task. To abbreviate these difficulties and to guarantee the fulfilment of the main aims of this study, a set of practices, an advanced bibliographic search, analysis and processing methods, representative formalisms, flowcharts, software packages, programming language and computational tools, were used in the methodology followed and represented in Figure 1.1. The methodology involved six main stages detailed below:

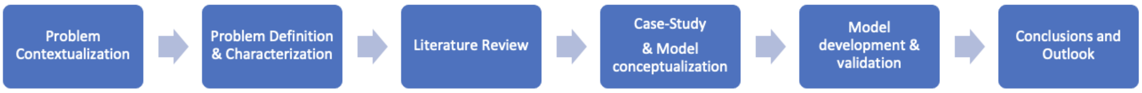

Figure 1.1: Methodology steps

- **Stage 1: Problem Contextualization**
  First, the context of the problem under study and the motivations of this work were performed. International reports were used to frame the problem to solve. Market studies, white papers, databases, as well as reports and data sheets of electronic devices, supplied by Infineon, were used to understand the semiconductor industry sector. The causes that are at the origin of climate change, with the most recent scientific knowledge, will be discussed. Considering semiconductors both as a contributor to the problem and as an important piece of the solution, by contributing to the manufacture and use of devices, equipment, and process management in a more ecological way.

- **Stage 2: Problem Definition & Characterisation**
  The second stage was focused on defining the problem in more detail. Firstly, a general view about the semiconductor industry was developed. Secondly, Infineon's internal supply chain structure was studied. Thirdly, the semiconductor manufacturing industry was identified as a highly polluting industry. In this context, the main purpose of the electrification and digitalisation of our society were understood, as well as their implications in supply chains. The way semiconductor industry is dealing with this transition was analyzed. The digital reference system, as a digital twin of the semiconductor industry, was explored due to its high importance in the sector, specially in the transition towards more digitalized systems. A semiconductor end-application, the BMS was chosen to proceed the research.

- **Stage 3: Literature Review**
  Hundreds of scientific articles, master's theses, doctoral dissertations, technical reports, and many other sources of information were read and summarised. The focus was mainly on the topics: sustainability in supply chains, the semantic web, and the semiconductor industry, thus giving some theoretical background to the thesis.

- **Stage 4: Case Study & Model Conceptualization**
  In order to formulate the digital model of the BMS, several technical reports from Infineon were consulted and studied in depth. First, due to the ever-growing battery market, the exponential growth of BMS usage in the near future is predicted to be certain. Next, the architecture of the BMS system was analyzed and described. Finally, the environmental impact of BMS is estimated, namely in accounting for the CO2 savings achieved when included in battery energy storage systems.

- **Stage 5: Model development & Validation**
  In this stage, the ontology is developed by defining its structure and later transfer into the Protégé, the ontology software program. This free, open-source software was used as ontology editor and as framework for building our intelligent systems. Two other software were used, WebVOWL as

WOL visualisation tool and the GraphDB to write queries and to validate the proposed ontology. Ontology computation is the interpretation of a group of ideas within a specific domain that defines the interrelationship between those ideas. Here, it was used as a new tool to determine the impact of the semiconductors in the sustainable economy with ecological concerns, where the BMS was chosen as the case of study to test the proposed solution. The paper [16], made by Standford University, was used as a guideline to implement the ontology. From the BMS architecture documentation, a scheme was built for easier visualization of the multiple functional blocks, labelled with their associate semiconductor devices. The BMS was analyzed in two ways: first, to understand their contribution towards a more efficiency electric storage system based on batteries, and second, to determine the relevance of the semiconductors in the BMS. These two tasks were done by inquiries of technical expertise and by consulting (internal and public) technical documents published by Infineon. To validate the proposed modelled scheme, the help and advice of an Infineon expert was procured. Queries were as well used for model validation.

- **Stage 6: Conclusions & Outlook**
  The main conclusions of the work are drawn. An outlook of future work is presented.

1.4 Dissertation Structure

The organisation of this work is as follows:

- **Chapter 1**: Introduction - in this chapter, the dissertation problem is contextualized, and the objectives, methodology and structure are presented.
- **Chapter 2**: The Semiconductor Industry - a general overview of the semiconductor industry is presented. The reality at Infineon Technologies Ag is described in more detail. The problem of pollution created by industry semiconductor is here characterized.
- **Chapter 3**: Literature Review - it is presented the state of the art regarding sustainable practises in the supply chain, the semantic web and the relationship between ontologies and the semiconductor industry.
- **Chapter 4**: Case Study: Battery Management System - in this chapter, the end-application context and its system architecture are described in detail. The role of the BMS in the transition to more intelligent and ecological means of transport is highlighted.
- **Chapter 5**: The BMS Ontology - This chapter describes the framework used and the steps taken to build the ontology. After its design, the ontology will be submitted to a validation test using the

SPARQL program. This process is described, as well as the steps required to integrate it into the digital reference, DR.

- **Chapter 6**: Conclusions and Future Work - The conclusions, limitations and outlook of this research are presented.

1.5 Chapter Summary

This work is aligned with the objectives of the Paris Agreement, which it is crucial to stop the global warming on our planet. Despite the high carbon footprint of the semiconductor manufacturing processes, they are crucial elements for the transition to greener devices and for digital transformation. Their use in equipment, control of processes and manage systems will significantly improve their performance, particularly in reducing the CO2 emitted over time. The BMS was chosen as the case study. It integrates a set of semiconductors, contributes to carbon reduction in the production, and it is fundamental to the running of high-voltage lithium-ion batteries.

Semantic Web technologies introduced as an important tool for digitization and interconnection between, humans, machines and products. Its use for understanding and studying the impact of BMS on reducing the carbon footprint was explained. An ontology will be developed to be part of the DR system. DR will be a tool in the semiconductors' manufacturing, contributing to a higher sucrinity and digitalisation of its processes.

This chapter presented the problem under study, its context and the main objectives to be achieved. The methodology used in this work is described and the dissertation's structure is presented.

2

The Semiconductor Industry

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The second chapter focuses on providing the background information on semiconductors, a key component of this work. A broad overview of the sector will be provided first, followed by information about the company Infineon Technologies Ag. The problem's description will be specified as well.

2.1 The semiconductor industry overview

Semiconductors are materials which have a conductivity between conductors and insulators. They can be pure elements, such as silicon or germanium, or compounds such as gallium arsenide or cadmium selenide. Silicon is the mostly chosen material for its manufacturing. In a process called doping, small amounts of impurities are added to pure semiconductors causing large changes in the conductivity of the material. The junction of two distinct doped semiconductors give to the semiconductor proprieties to control the electric current. Their properties enable it to be the foundation for computers and other electronic devices, thus, having an important role in our lives.

Since the development of the first Integrated Circuit (IC), semiconductors have been used in a number of electronic devices. Its peak was achieved in 1920, along with the development of the transistor. Transistors, resistors, and condensors are just a few of the many functional components found in an IC. These devices are integrated on the silicon wafer and later divided into chips. The semiconductor industry is characterized by high demand volatility, high capital intensity, long cycle times and high energy usage. According to a Harvard study in 2020, it "accounts for most of the carbon output" from electronic devices [17]. The exponential increase in semiconductor production during recent decades results in increasing energetic needs. The energy sources and efficiency must change to an environmentally friendly approach.

The technology that the semiconductor industry produces is essential to society. The result is an increase in demand for semiconductors as a result of the worldwide digitalization of all activities. Difficulties in the supply of raw materials and lack of preparation of logistics chains have led to failures in the availability of electronic components, which are notorious in the automobile and computer industries. It is remarkable how crucial tiny chips are to the smooth running of the world economy. According to McKinsey's article predictions [18], due to megatrends which include remote working, Artificial Intelligence (AI) Growth and EV, the need for chips will increase over the coming 10 years about 20 %. The growth is predicted to come from three industries: automotive, computations and data storage and wireless. Due to applications such as autonomous driving and e-mobility, the automotive industry is the industry with higher growth potential.

In the outlook of the semiconductor industry, performed by Deloitte this year [19], it was again emphasized the importance of a chip in multiple end markets. Two years of shortages in the semiconductor and consumer industries costed the global economy US$500 billion, of which US$210 billion was regarding the automobile sector in 2021. The sharp increase in the number of chips incorporated in motor vehicles is one of the causes for this problem. In 2021, it became evident that there was an imbalance between supply and demand for chips, which resulted in shortages that affected several businesses globally. According to the Deloitte analysis [19–21], better preparation and higher competence can only partially alleviate the issue and cannot totally remove the unreliability.

Semiconductors are key devices to support the transformation of technologies towards a cleaner and more efficient use of energy, promoting a more sustainable world. They act as the core enabling technology of contemporary electronics, Informationand Communication Technology (ICT). Transportation, industry, health care, heating and cooling, and other significant sections of the economy may all benefit from electronic devices and ICT systems. According to the Global e-Sustainability Initiative, [22], information and communication technologies will enable the reduction of 20% of the global GHG emissions by 2030. In addition, this sector was one of the first industries to establish global voluntary reduction targets for Perfluorinated Compound (PFC). In 1999, the World Semiconductor Council (WSC) agreed to reduce PFC emissions by at least 10% by the end of 2010 [23]. Over the years, this industry has always exceeded the initial goals, achieving in 2016 a reduction value of 16.1% when compared to 2010. Some of the initiatives taken were the following:

1. Reporting and Reducing Emissions of PFC: voluntarily reported on emissions of PFC, a group of global warming gases that are essential to the manufacturing of advanced semiconductors,

2. Reduction in energy used in manufacturing: for example, over the period 2001-15, the U.S. semiconductor industry has achieved a reduction of 34% in the total energy consumed in its operations. Many companies have shifted to renewable sources of energy or cleaner fuels to power their operations.

3. Improving the energy efficiency of semiconductor devices – through continuous research and development efforts, the semiconductor industry constantly improves the efficiency of semiconductor devices, while also improving product performance. Every technical innovation helps achieve ever-increasing levels of performance at reduced levels of power. As a result, modern semiconductors are vastly more efficient than earlier generations, while at the same time generating millions of times more computing power per watt.

Transparency and a holistic view of the chip manufacturing supply chain are imperative requirements to achieve a higher supply chain resilience. In order to address this issue, the EU finances projects such as the Horizon 2020, which is a collaborative research and innovation program. The Productive 4.0 project is part of this program, which aims to improve semiconductor manufacturing and supply chain management by supporting research and development projects. The DR, which is an integrating part of this project, will serve as a data format interface for intelligent and effective communication between the parties involved in the semiconductor industry and related supply chains, as well as in other industrial areas. The Semantic Web will be the digital structure to design the DR. Instead of merely linking documents, ”Semantic Web allows the connection of data itself and the integration of data from various sources, so that the data is presented in a unified view and is reusable across different applications” [24]. In addition, the DR contributes to the B2B market by facilitating data flow and information sharing between businesses, playing the role of a supply chain digital twin [24].

2.2 Case-Study: Infineon Technologies AG

Infineon is a German semiconductor manufacturer created in 1999, formerly the semiconductor section of Siemens. It has a total of 50280 employees and it is a leading player in automotive, power management, energy-efficient technologies and the Internet Of Things (IoT). Infineon occupies the first market position in the automotive and power industry, sectors that have the higher revenues, with 44% and 29% of the revenue share, respectively [25]. Its major product categories are power generation from renewable energy sources, energy transmission and distribution, energy storage and energy usage. Semiconductors contribute directly to areas like electromobility as they represent a core device in eBikes, eScooters, hybrid or fully electric vehicles and as well high-speed trains. Energy efficiency is essential because rising energy demands, the depletion of fossil fuel reserves, and climate change encourage more responsible energy production, transmission, storage, and use.

2.2.1 Infineon´s Market Segments

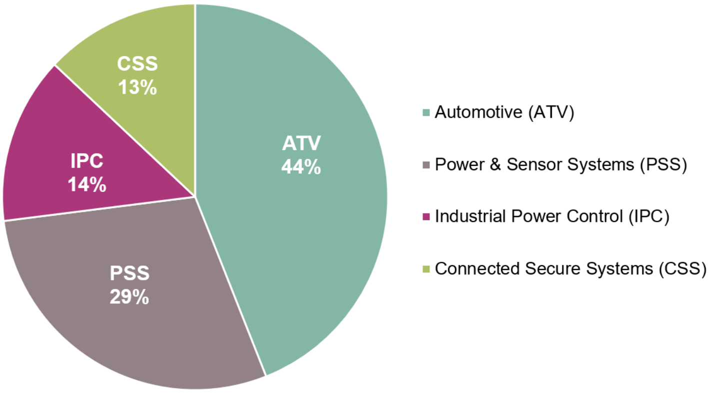

Figure 2.1: Infineon market segmens and its revenue share for the fiscal year of 2021

Infineon´s main segments are, as it can be observed in Figure 2.1:

- Automotive: Infineon is a global leader in this segment, contributing to automated driving and giving prominence to connectivity digitalization and security. It gives support in the transition to

Hybrid Electric Vehicles (HEV) and EV. In 2021 fiscal year, the automotive sector was responsible for 44% of the revenue.

- Industrial Power Applications: this segment contributes to the smart generation, transmission storage and use of electrical energy. Applications include industrial power supply, energy storage systems, high-voltage direct current transmission, wind turbines, and photovoltaic installations, among many others. In the fiscal year of 2021, its revenue share was of 14%.
- Power & Sensor Systems: contributes to the reduction of size and weight of chargers, power tools and lighting systems, increasing energy efficiency at the same time. This segment was the second most relevant for the revenue in 2021, having a share of 29%.
- Connected Secure Systems: assures a secure connection within the connectivity network. This sector was the one with least representation in the total revenue of the fiscal year of 2021, having a share of 13%.

2.2.2 Infineon's Internal Supply Chain

Infineon's internal supply chain is organized as in Figure 2.2. Its main management tool is the Supply-Chain operations reference model (SCOR). All Infineon SC sub-processes are merged in one core process designed by the SCOR model. This allows standardization of the SC´s relevant processes and a reliable and fast benchmarking. The end-to-end SC is also described in accordance to the referred framework. The SCOR model has been created to explain all of the business actions involved in meeting customer demand, it is so far the most complete framework. The model is organized into six primary management processes: Plan, Source, Make, Deliver, Return and Enable. In Figure 2.3 the five main SC blocks are represented. Sourcing logistics is the connection with the supplier; the Production Logistics, which is included in the Make process, is related to the internal supply chain; for instance, the Distribution Logistics is in respect to the connection with the costumer; finally, the interface with third parties is done through Warehouse Logistics and Transport Logistics.

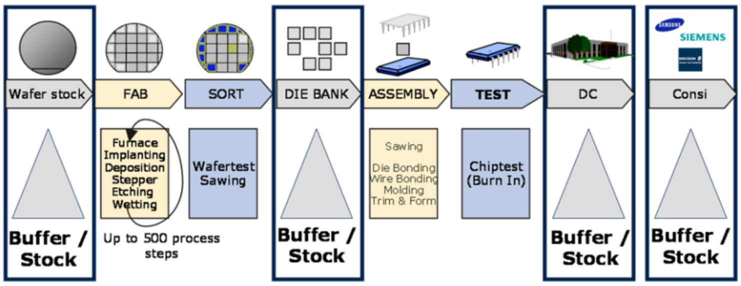

Figure 2.2: Infineon SC processes

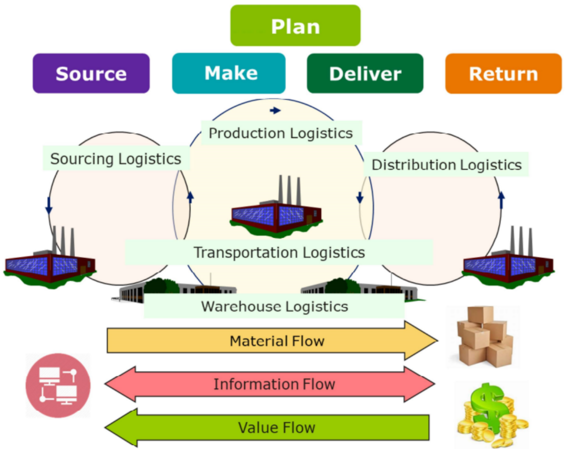

Figure 2.3: Major Supply Chain Processes according to SCOR [1]

Before delivery of the chip to the end consumer, it goes through eight steps along the SC (Figure 2.2). The wafer stock, the fab, sort, die bank, assembly, test, distribution center and consignment. These SC steps can be subdivided into two main groups, the frontend and the backend. The frontend is composed by fab and sort. ”Fabs”, also named ”foundries”, are the semiconductors fabrication plant. The input of the frontend process is an empty silicon disk; the output, a configured ensemble of transistors. Due to the fragility of this device, its configuration is done under clean room conditions. Considering the 0.35 nm chip size, the smallest particles can ruin the entire wafer manufacturing process. The peculiar environmental conditions for semiconductor manufacturing require advanced climate technology that consumes a lot of energy, with the ability to renew and clean the air 400 times per hour. On the other hand, die bank, assembly, test, distribution center and consignments are part of the backend processes. Once the wafer is processed, it is forwarded to another step of the manufacturing process. The chips are checked, repaired when needed, and then packed. Due to the extreme sensitivity of these products, special techniques are used, in order to keep them as safe as possible. Examples of it are laser saws, innovative materials, complex gluing. Because the handling conditions of the manufactured parts are less complex and the working environment is less demanding, the terminal phase, backend stage, consumes less energy than the initial one.

2.2.3 Infineon’s Green Supply Chain Management

Infineon is ranked among the most sustainable companies worldwide, according to Dow Jones Sustainability™ World Index [26]. This company aims to reduce the carbon footprint of its products not only during the production process, but also during their use (lifetime). To integrate targets and processes related to ecological sustainability and as well occupational safety and health protection, Infineon set a global management system, named by Infineon Integrated Management Program for Environment, Energy, Safety and Health (IMPRES). It was subject to the ISO14001 and ISO45001 standards and later as well to the ISO 50001 standard for energy management (in the European manufacturing sites). The Management Board is then provided with the outcomes of these procedures, as well as the accomplishment of goals, among other things, at the Annual Management Review.

One of the biggest global issues of our time is the decreasing availability of natural resources. Utilizing resources as efficiently as possible brings advantages for the environment and for the economy, which it is a crucial part of Infineon's global sustainability plan. According to World Semiconductor Concil, Infineon's uses the production resources more efficiently than the global average of the semiconductor industry [26]. There is evidence that per square centimeter manufactured wafer, Infineon consumes less 44% electricity, less 17% water and finally, it produces less 67% waste. Infineon invests more than 30 million euros towards a sustainable business, which includes capital investments and operating expenses, and saves around 19,5 million euros in energy, tax refund related to environment and benefits from waste recycling, as stated in Figure 2.4

Figure 2.4: Infineon environmental expenses vs savings

Infineon's environmental actions can be split into six major groups: Carbon Neutrality, Water Management, Energy, Greenhouse Gas Emissions, Waste Management and Product-related Environmental Sustainability [25]:

- **Carbon Neutrality**

  Two pillars that support of Infineon climate policy are the ongoing reduction of its own emissions, the improvement of resource management politics and best product design, by research of cutting-edge new chips and solutions to safeguard of the environment and the climate. It is part of Infineon mission to make life greener.

  Infineon is a committed contributor to reduce CO2 gases worldwide, and it is aligned with the targets defined in the Paris Climate Agreement. In addition, it was one of the first semiconductor companies to voluntarily commit to the Ten Principles of the UN Global Compact, having as target the carbon-neutrality in 2030, namely for Scope 1 and Scope 2, which are direct energy and indirect energy and heat-related emissions. For that, it plans to cut 70% of carbon emissions between 2019 and 2025.

Infineon comitts to:

  - Lower energy use while avoiding direct emissions;
  - Buying green power. Otherwise, buying carbon credits for the emissions that cannot be avoided;
  - Use certificates that combine CO2 reduction and development support to make up the minimum amount of compensation.

- **Water Management**

  Large quantities of ultra-pure water are needed for semiconductor manufacturing in order to prevent any contamination of the electronic devices. The water withdrawal in 2021 was 30,522,876 cubic meters, being used in Production and Sanitary Systems. The water used for cooling processes can be, after purification, transformed into ultrapure water for manufacturing means. In 2021 Sustainability Report Infineon achieved the following interesting results:

  - Used 17% less water to produce one square centimeter wafer;
  - 60% of the water returned to nature is as pure or purer than before;
  - The reuse of 2,419,080 cubic meters of ultrapure water and 2,419,080 cubic meters of production waste water;

- **Energy**

  In the global effort to save energy, lower greenhouse gas emissions, and address climate change, efficient energy management is a crucial matter. Electricity is the main source of Infineon's energy, used throughout the whole semiconductor manufacturing process. Oil and gas, are merely a minor contributor. Most of the energy is used in front-end processes, due to its sophisticated physical processes with high energy requirements.

  The results achieved in 2021 were:

  - Global energy consumption was 2437 Gwh;
  - Green energy makes up 37% of the power used;
  - One square centimeter wafer was produced using 44% less of energy;
  - Energy use per unit of revenue was 0.22 Kwh/euro.

- **Greenhouse Gas Emissions**

  Early on, Infineon began formulating plans to reduce energy use and the amount of material needed to manufacture its products, thereby reducing CO2 emissions. Another way to reduce greenhouse gases is by controlling PFC emissions. These gases are emitted on the wafer structuring and as well as on the cleaning equipment phase. Unfortunately, there is currently no substitute for these harmful emissions. The CO2 emitted can be divided in three different scopes, as shown in Figure 2.5.

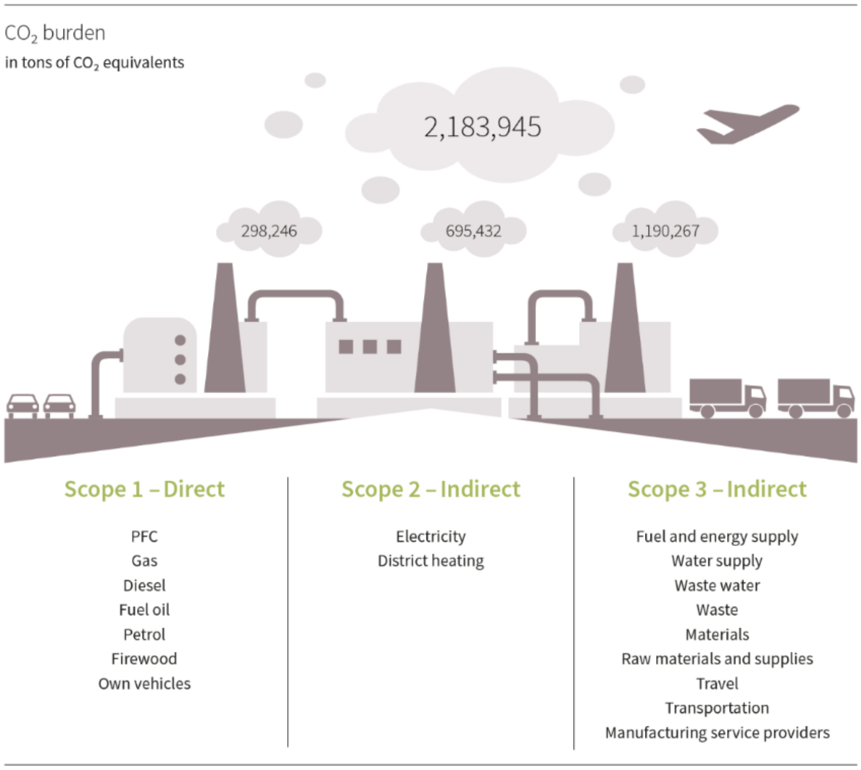

Figure 2.5: CO2 burden in different scopes

  - Scope 1 - Direct emissions

    PFC, Gas, Diesel, Fuel oil, Petrol, Firewood, Own vehicles emissions are some of the components responsible for GHG emissions. Wafer-etching procedures used in the semiconductor industry, cleaning manufacturing equipment and structuring wafer processes emit gases with greenhouse effects. These gases, which make up 81.6% of scope 1 emissions, cannot be replaced by any other class of compounds.

  - Scope 2 - Indirect emissions

    Electricity and climatic heating use, are both responsible for the most GHG emissions in

  Infineon. Due to the architecture of Infineon's sites and other factors, the potential for green power production is constrained.

  - Scope 3 - Indirect emissions
    Fuel and energy supply, water supply, waste water, waste, materials, raw materials and supplies, travel, transportation and manufacturing service providers are processes with indirect carbon emissions.

- **Waste Management**
  A great part of the waste generated comes from manufacturing and building activities. Despite its greatest attempts to use resources carefully, Infineon still generates a lot of waste. Nevertheless, it has implemented good practices in the management of its waste. The results achieved in 2021 were:

  - To make one square centimeter wafer, 67% less waste was produced;
  - Recycling of non-hazardous and hazardous waste stood at 66% and 55,2%, respectively;
  - Distillation was applied to recover and reuse 176.38 tons of Propylene glycol methyl ether acetate (PGMEA), an important solvent in the semiconductor industry.

- **Product-related Environmental Sustainability**

  Despite the high energy consumption of the semiconductor industry, its end-products have the ability to make the equipment and solutions in which they are integrated more environmentally friendly. From internal sources of information, Infineon estimates that its products contribute to more than 72 million tons of CO2 equivalents savings per year. Essentially, semiconductors make it possible for finished products to use less energy throughout the course of their lifespan, which is essential for reducing their environmental impact. The ration is around 1 part of CO2 burden for 33 parts of CO2 savings, in CO2 equivalents, as represented in Figure 2.6

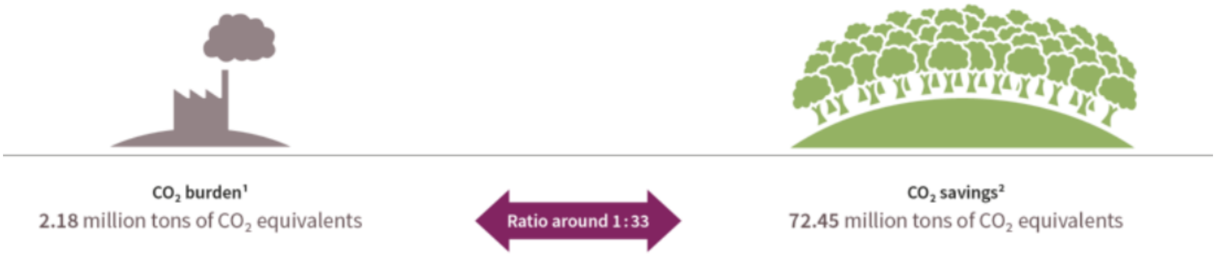

Figure 2.6: Infineon´s Carbon Footprint

2.3 European digital industry: Productive 4.0

The European research initiative called Productive 4.0 aims at advancing the digitalization and integration of the European electronics and ICT industries. It is funded by the EU and ECSEL and coordinated by Infineon Technologies Ag. The project is focused on creating and implementing innovative technologies and procedures for the next era of connected and smart manufacturing, referred as Industry 4.0. Its main goal is to create a reliable and flexible framework that enables the efficient collaboration and integration of different stakeholders, including suppliers, manufacturers, service providers, and customers, within the value chain. The project aims to enhance the productivity, quality, and sustainability of manufacturing processes by leveraging digital technologies, such as the IoT, cyber-physical systems, and data analytics.

By adopting Industry 4.0 principles and technologies, Productive 4.0 seeks to enable the realization of smart factories and interconnected production systems. This involves the seamless exchange of data, information, and knowledge across the entire supply chain, fostering real-time decision-making, increased automation, and improved resource utilization. The digitalization of the processes, supported by an increased number and functional capabilities of semiconductor devices, accelerates the pace of the world, i.e. on the economy, technologies, communication processes and people's lives. Chips are the backbone of IoT, making these devices smarter, more user-friendly, improve energy-efficient and allowing the human-being to have a more comfortable lifestyle.

A higher connectivity between players in the supply chains implies more flexible and transparent networks, where the information sharing is a priority. In this framework, the use of supply chains' digital twins in is an example [27, 28]. A digital twin is a produced digital replica of an actual factory, machine, worker or supply chain, that can be independently extended, automatically updated, and instantly accessible around the world [29]. The DR is a digital replica of the semiconductor industry, supported by this project. It aims to establish a shared understanding and consistency across the various aspects of the project, including processes, technologies, and standards. It encompasses a wide range of information, such as best practices, guidelines, technical specifications, and interoperability requirements, which are relevant to the advancement of Industry 4.0 concepts and solutions. This DR is a digital representation of all the chip supply chain, involving all the players. The prospect of data accessibility, interpretability, and interoperability is increased through the usage of Semantic Web and linked data [30]. The use of semantic web technologies enables the creation of data stores on the Web, build vocabularies, and write rules for handling data. Linked data are empowered by technologies such as Resource Description Framework (RDF), SPARQL Protocol and RDF Query Language (SPARQL), Web Ontology Language (OWL), and Simple Knowledge Organization System (SKOS), which are standardized languages where the information is linked by a ”semantics” assigned [30].

This allows not only a better organization and schematic perception of the supply chain (from the the acquired knowledge), but also an extraction of new knowledge by using reasoning tools and rule-based inference engine [31]. It makes possible to consult multiple pieces of information relating to the supply chain in a more agile manner.

In this project, the web ontologies support the modelling of rich and complex knowledge about things, groups of things, and relations between things. It is an effective tool to help to find sustainable decisions. Sustainability, which is also a goal to be achieved in this project, is perceived as a different and more comprehensive way to obtain supply chains with a lower impact on environment and society [32]. Environmentally friendly products have drawn increased attention since consumers may favour them over others. Therefore, markets, rules and self-consciousness have led to companies extensive initiatives that support environmentally-friendly operations. However, practices are not universal, and the sustainability issue is not properly understood neither with same concern by all businesses and executives. In order to share relevant and unambiguous information during the lifecycle of a product, the industry requires new technologies interoperable among systems and that use semantic information with intelligent skills [33]. According to [34], the usage of ontologies is one of the most promising methods for handling interoperability concerns between engineering applications and other significant information systems used in product lifecycle management.

This thesis will be a contribution to the project Productive4.0, with the inclusion of a new semiconductor end-application in the DR. An ontology will be created and another semiconductor end-application digitalized, in this case including its CO2 savings parameters in the model. A step towards digitalization and transition to Industry 4.0 will be made.

2.4 Problem Description

From EU sources, the sector with the most emissions are the electricity producers, followed (closely) by the domestic transport sector, responsible for a quarter of CO2 emissions [35]. The same occurs in the USA, where about a third (29%) of greenhouse gas emissions come from transportation and a quarter (25%) of emissions come from things like heating homes, running appliances, lighting buildings, and powering our computers and data storage facilities [36]. On June 8, 2022, the European Parliament voted to ban all new gasoline and diesel cars by 2035. The car market is changing rapidly, with increasing sales of EV, Plug-in Hybrid Electric Vehicles (PHEV) and HEV, vehicles that will comply with new regulations. These new vehicles need intelligent technologies such as the BMS, a device necessary for the supervision and safe usage of lithium-ion batteries, thus, their demand expected to increase exponentially.

Infineon has a strong concern and desire for its supply chain to be ’green’. In fact, it is not by chance that one of Infineon´s slogan is ”Part of your life. Part of tomorrow”, which enhances that a sustainable future is one of the company´s major concerns. They provide a strong energy efficiency improvement in a wide variety of processes and system mechanisms, used in a broad range of applications and equipment. Examples of end-applications are the smart home, smart meters, smart plugs and smart lightning, power electronic devices, BMS, etc., which all share a comprehensive perspective on the system, analysis, and subsequent management to reduce energy use.

The BMS was chosen as case-study where all Infineon semiconductors within this device are considered, as well as the ways in which the BMS contributes for carbon emissions savings. This is integrated in the discussion on the role of semiconductors in the transition to more efficient and ecological equipment. An environmental analysis will be done to this device in order to take conclusions regarding its footprint. Then, after analysing its main parts, a diagram will be built reflecting its functional blocks with information on carbon savings values. This diagram will work as a base for the BMS ontology, being a contribution for digitalization and an expansion of the Digital Reference system, increasing the transparency in the semiconductor supply chain. Ontologies play a role in sustainability in supply chains because they provide a structured framework for organizing and integrating sustainability-related information. They enable comprehensive assessments of environmental and social impacts, support risk identification and mitigation, and promote transparency and traceability throughout the supply chain. By utilizing ontologies, stakeholders can make informed decisions, optimize sustainability outcomes, and drive the transition to more environmentally responsible practices in supply chain operations.

Two problems are addressed in this work, taking into accounting the global warming situation. First, it aims to contribute to the increase in the efficiency of supply chains, making them consequently more green due to better resource management and higher resilience. In this case, this efficiency will be achieved through digitalization of the supply chains with semantic web technologies. A background on existent environmental measures and on further ideas will be as well exposed. Secondly, it answers the question on how can semiconductors contribute to greener end-applications despite their considerably high environmental footprint. For both problems, Infineon's BMS will be taken into consideration. Both an ontology and an environmental analysis will be developed.

2.5 Chapter Summary

An overview of the semiconductor industry and the company Infineon Technologies Ag was presented. It was stated that this industry is characterized by high demand volatility and high energy use. With the growth of the electronic devices' market, more chips will be made, resulting in a higher energy demand. Transparency and a holistic view of the chip supply chain are important to avoid bottleneck events and make the process more efficient. A possible answer to this problems is the digital twin of the semiconductor industry, DR, which is being developed in the european project Productive 4.0. Using

Semantic Web technologies as its digital framework to implement new solutions, new functionalities will be included to measure the impact of semiconductors in terms of energy efficiency and carbon footprint.

In this chapter, several problems of the semiconductor industry were identified, namely in regards to its state of sustainability. There are not enough studies on the contribution of semiconductors to the transformation of polluting technologies into green ones. In the semiconductor supply chain there are still difficulties on interpreting, reading and sharing data intelligently. This work suggests some approaches to address such problems:

1. Semiconductors as part of the transition to greener technologies. An environmental analysis to the BMS will be done, in order to test this hypothesis.
2. Semantic web technologies as enablers of the transition to industry 4.0 where networks will no longer be rigid and opaque, but flexible and transparent. In this transition is included the digitalization of supply chains and modelling smart factories, assuring a smooth information sharing. This will allow a more simplified approach towards complex networks, enabling analysis and possible solutions to make it more efficient and sustainable. An ontology of the BMS including its CO2 savings will be developed, contributing towards this digitalization.

3

Literature Review

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3.5 Chapter summary 34

This state of the art will address topics such as sustainable practices in supply chains and the transition to industry 4.0. The fundamentals of the semantic web and ontologies are presented, which are technological solutions that can promote sustainability solutions in the semiconductor industry. This will be explored along this thesis.

3.1 Sustainable practises in the supply chain

The research, planification, implementation and validation of more efficient and profitable procedures in the supply chain is a permanent need for companies. Today, society demands that such processes are also ecologically sustainable. Products must have a fair price-quality ratio and, in addition, a reduced and reasonable environmental footprint. Sustainable production and consumption of goods is identified as one of the essential requirements for a sustainable development [37].

A sustainable supply chain is a ”complex network systems that involve diverse entities that manage products from suppliers to customers and their associated returns, accounting for social, environmental and economic impacts” [38], which represent the Triple Bottom Line (TBL) of sustainability [39]. Despite the fact that the TBL of sustainability is established, there is still a clear lack of unified frameworks to evaluate the companies´ sustainable performance. Examples of the few existent environmental frameworks are the ISO 14001, which is designed to help businesses in integrating environmental responsibility into their internal operations while remaining profitable; the Total Quality Environmental Management, which integrates the Total Quality Management guidelines and environmental principles strategies aiming to reduce waste and pollution, improving the overall environmental performance [40]; the Design for Environment, for research and implementation of strategies to decrease the environmental impact of products [41] and the Life Cycle Analysis, which ”is a method of quantifying the environmental impacts associated with a given product.” [42].

Green Supply Chain Management (GSCM) is a framework that integrates environmental aspects, concentrating on all the steps of the supply chain to have a minimal impact on the environment [43]. Some of their SC stages are the extraction of raw material, manufacturing [44], distribution and reverse logistics [45] [46]. In addition, this framework can also be applied to corporate social responsibilities.

- **Extraction of raw material**:
    - Sustainable sourcing: Businesses are increasingly buying materials and goods from suppliers who follow sustainable business principles. This includes obtaining goods from vendors who limit waste, use renewable resources, and lower carbon emissions [47].

- **Manufacturing**:
  - Sustainable Design: Sustainable design seeks to reduce environmental consequences while enhancing business environmental performance [48]. In order to guarantee the success of this environmental friendly design, all the supply chain partners both internal and external must be in full cooperation throughout the whole supply chain [49];
  - Green production: depending on the type of industry, multiple techniques can be applied in order to have cleaner means of production. This is expected to lead to more efficient energy consumption and a reduction in the amount of industrial waste, its recycling and treatment, i.e. better energy and waste management system [50];
  - Lean Philosophy: Lean production is a social-technical management philosophy that encompasses multiple disciplines that focus on increasing the manufacturing productivity by emphasising on the elimination of waste, and increasing the value-added activities [51].
  - Maintenance: it avoids disruptions in the SC, by applying preventive and maintenance strategies [52].
- **Logistics**: Sustainable logistics refers to the practices and processes aimed at improving the sustainability of supply-chain activities, ranging from the supply of raw materials to the storage, manufacture and distribution of products [53]:
  - Sustainable distribution. [54].
  - Reverse and Green Logistics: Companies are implementing environmentally-friendly transportation methods to reduce carbon emissions. This includes using hybrid or electric vehicles, optimizing shipping routes, and consolidating shipments strategies [55] .
  - Circular economy: Companies are adopting circular economy principles, which aim to reduce waste by designing products that can be easily repaired, reused, or recycled. This includes implementing closed-loop systems that minimize waste and maximize the use of resources.
  - Supply chain transparency: Companies are increasingly adopting transparency measures to ensure that their suppliers adhere to sustainable practices. This includes tracking the environmental and social impact of suppliers, and providing consumers with information on the origin and sustainability of products.
  - Collaboration: Companies are collaborating with suppliers, customers, and other stakeholders to develop sustainable supply chain solutions. This includes partnering with suppliers to improve sustainability practices, and working with customers to promote sustainable products.

- **Social Responsability**:
    - Corporate social responsibility (CSR): Many companies are adopting CSR policies that address social and environmental issues throughout their supply chain. This includes addressing issues such as child labor, fair labor practices, and environmental protection.

The discussed sustainability in supply chains lays a solid foundation for the study of the shift to Industry 4.0 and the impact on supply chains that follows. Organizations are embracing digitalization and automation technologies as they work towards sustainable operations, which are essential elements of Industry 4.0. Adoption of Industry 4.0 technology not only improves operational efficiency but also provides opportunities for supply chains to improve their economic sustainability, social responsibility, and environmental performance. Therefore, comprehension of the possible effects of technology improvements on the overall sustainability of supply chains is essential in order to transition to Industry 4.0 and understand the link between sustainable practices. An in-depth investigation that emphasizes the connections between sustainable practices, the shift to Industry 4.0, and their combined impact on creating sustainable and resilient supply chains may be presented in the following section.

3.2 The transition to industry 4.0 and the impact in supply chains

In 2011, the German government presented a plan to ensure high competitiveness in German industry. Value chains, as we know them today, will be replaced by versatile and intelligent chains, connected in a planetary network, where information will be complete and instantaneous, allowing new ways of selling products accompanied by exchange of ideas and solutions [56]. This requires the implementation of digital ecosystems where data must be available in a transparent and accessible form. To successfully implement this industrial transformation, the key points are autonomy, interoperability and sustainability. Ecosystems must be designed in a decentralized, open and flexible system.

In the literature, the highlights of this transition are ”vertical and horizontal ICT integration” and ”end-to-end engineering throughout the product life cycle” [57]. This will mean the existence of a complete link between factories along the entire supply chain, where all the players are assumed to cooperate in fair competition. A digital infrastructure, accessible by all actors, must exist for sharing information while ensuring the protection of sensitive data. Standardized protocols about knowledge, coding and communication, supported by decentralized systems, should ensure an interoperability of global system, taking advantage of an integrated ecosystem structures and the usage of small and big data collected from local or global sources. This system will allow a more efficient management of resources in a circular economy perspective [58]. Here, all stages of the product's life are considered, from the extraction of raw materials, production phase, their useful life, until their end of life, where recycling closes the circuit.

The exchange of information will take place in real time and in all sectors of the SC.

The digitalization of the processes and new digital networks are imperative to assure this transition, contributing to a holistic vision and higher control of the chain. Data backflow control is implemented across the supply chain, namely with data used in manufacturing and design, based on digital twin design of products and processes [59]. Real-time data and increased network surveillance enables higher customer satisfaction, greater efficiency and less end-product waste [60]. The agility characteristic of the SC will be supported by a more mature process of decision-making and preparation for possible disruptions [61]. Data collection and mining are fundamental to a consistent data analysis and for the decision-making. [59].

Digital solutions and tools, which connect the world and use information intelligently, are fundamental for Industry 4.0, specially in ensuring ecological preservation and battling climate change. It enables the collection of amount data in real time, which allows the extraction of relevant information about the processes and status of systems for intelligent decision-support.

The internet-connected smart systems open the doors to innovative strategies for the above addressed problems [62]. According to [63], ”The role of digitalization and the technologies associated with the internet of things (IoT) have been discussed for their potential to solve big challenges in the food-water-energy nexus, and enabling Industry 4.0, improving social wellbeing, and reducing the effects of climate change”. However, in the new technological framework, there is a risk of using more energy than before, even under the pretext that it is greener. If this is the case, the goals of using less energy may not be achieved, which is a counterproductive situation [64]. Semantic web technologies are a power digital tool that can help to implement strategies for the transition to Industry 4.0 in an intelligent way. Their importance will be further analysed in the next section.

3.3 Fundamentals of the semantic web

The Web Standards were created by the W3C, composed by people and international organizations. The main task of W3C is to formulate protocols and rules that ensure the Web’s long-term expansion. The essential components of the World Wide Web (WWW) are defined by W3C standards. According to W3C, Semantic Web is the Web´s linked data [65]. It enables computers to intelligently search, aggregate, and interpret Web material based on the meaning that this content has to humans. Semantic web technologies have multiple practical applications such as in the fields of health care, life sciences, social spaces, digital libraries and financial services. In Figure 3.1 is represented the architecture of the Semantic Web.

The main elements of the semantic web stack will be briefly explained, particularly those elements which are already standardized by the W3C:

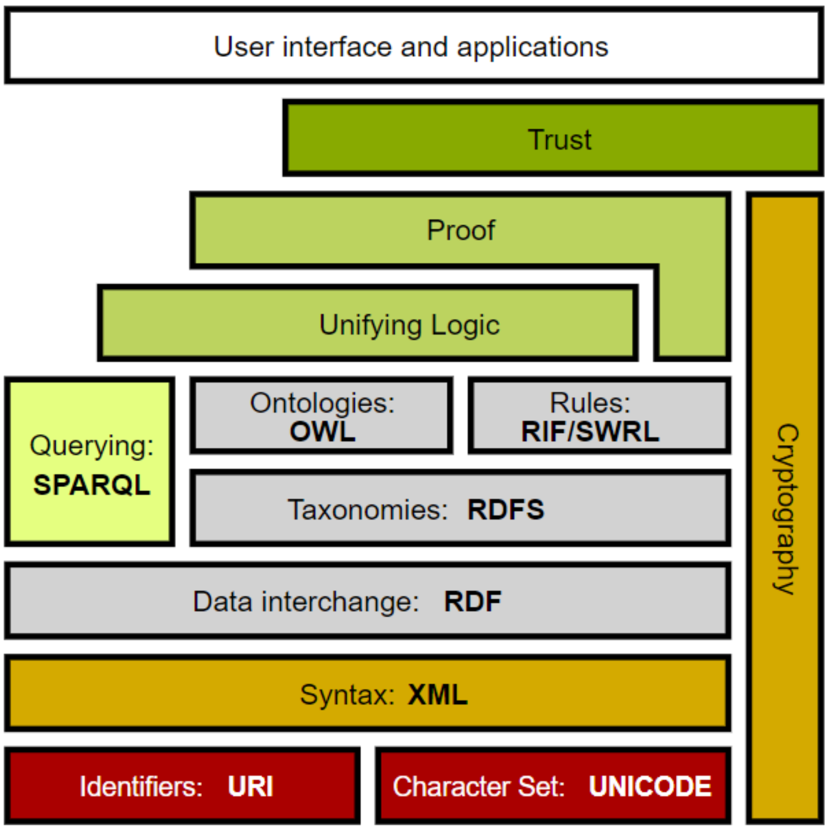

Figure 3.1: The Semantic Web Stack

1. Unique Resource Identifier (URI), is a unique identifier of the semantic web resources;

2. Unicode helps to modify and represent text in a variety of languages. The Semantic Web should be able to bridge documents written in several human languages;

3. Extensible Markup Language (XML) is a markup language from which documents with semi-structured data can be generated [66];

4. RDF is a general framework for representing interconnected data on the web, which enables standardized exchange of data based on relationships. It provides a uniform way of encoding resources and gives a consistent manner of finding and understanding them on the Web, making them intelligible to various software. It was designed by W3C, having since 1999 a recommended RDF specification, the Model and Syntax Specification (”RDF M&S”) [67]. Due to their standard format, conversions or access to the existing databases is easier. The RDF model consists of: Resources, Properties and Statements. A Resource is something that can be described by RDF and it is identified by the URI. The relationship between resources and their values is described using properties. On the other hand, a statement is composed by the resources, properties and values associated

to it. The RDF data-model is based on subject-predicate-object triples, which represent the statements. The subject is the ”thing” which we want to make a statement about, it is unambiguously identified by its URI. The information related to this subject is the predicate and its content the object.

5. Resource Description Framework Schema (RDFS) is considered a semantic extension of RDF. It is represented in the basic RDF model and provides (i) abstraction mechanisms, such (multiple) class or property subsumption and (multiple) classification of resources; (ii) domain and range class specifications to which properties can apply; (iii) documentation facilities for names defined in a schema. It provides tools for describing collections of linked resources and the connections between them. It is a simple ontology definition language that enables users to specify the terminology required to represent the resources in the domain with meta-data.
6. OWL is a language that outperforms RDFS because it is more comprehensive. It has a larger vocabulary set, allows annotations to be made and constraints to be added. These additional features, increase its expressiveness when compared to RDFS. [68]. An ontology is an explicit, formal specification of a shared conceptualization. It defines the terms used to describe and represent an area of knowledge. Explicit formulation means that each ontology’s notions must be described in detail. Formal specification indicates that the concepts are stated in a machine-understandable way. Shared conceptualization implies that there is agreement over the conceptualization. [69]
7. SPARQL is short for “SPARQL Protocol and RDF Query Language” [70]. It enables users to query information from databases or any data source that can be mapped to RDF. While RDF is useful for publishing and linking the data, it needs a specific query language. Querying is a type of technology that can give information about the Web of Data, tool usefully for the semantic web applications to extract information [71].
8. Rule Interchange Format (RIF) enables the description of relations that cannot be explicitly stated using the OWL’s description logic [72].

To navigate the web of data, it is imperative to have linked data and to be empowered to use ”large-scale data integration and reasoning on the Web” [73]. In 2006, Tim Berners-Lee, the director of the W3C, defined the four principles of the linked data [74]:

1. URI should be the standard way to identify things, identifying any type of object or concept;
2. HTTP URIs should allow the search for that URI;
3. When searching for a URI, it is preferable to use the standards (RDF*, SPARQL);
4. Mentioning links to other URIs increases the spreading of the linked data.

The theoretical background of OWL ontologies will be introduced in Chapter 5. Nevertheless, three main OWL's components can be highlighted [5]:

1. Individuals or Instances of Classes (in the Protégé software) are objects in the domain of the ontology. They are unique objects that are members of a class and can be a tangible thing [75].
2. OWL classes represent a ”concrete representation of concepts”. In OWL ontologies, it is frequent to have ”superclass-subclass” hierarchies [76]. An example of this type of taxonomy is presented in [5] where the class `Animal` is a superclass of the class `Cat`, since all instances of the class `Cat` are instances of `Animal`, all cats are animals;
3. Properties create a connection between two things, which are relationships between instances of classes. For instance, if we consider the instances `Biology` and `Mary`, being the first a subject and the second a teacher, it is possible to relate both through a property. The subject `Biology isTeachedBy Teacher`. `isTeachedBy` is the connection between the instances `Biology` and `Teacher`.

An ontology is a controlled vocabulary (i.e. list of terms that describes a certain domain of knowledge), that apart from being a list of agreed terms, also captures relationships between these terms. Vocabularies explain the ideas and connections that are used to characterise and represent a particular area of focus. Vocabularies can be complex, ie. with many terms that embodying more than one concept, or very simple, i.e. terms that embody one or two concepts. In Semantic Web, data integration can benefit from the richest and uncorrelated vocabularies [77]. For example, to eliminate ambiguities that may exist on the terms can lead as well to the discovery of relationships. Vocabularies can also be used to organize knowledge such as newspapers, libraries and governmental portals. There are different techniques to define multiple forms of vocabularies in a standard form, offered by W3C: the RDF and RDF Schema, SKOS, OWL and the RIF. Depending on the richness of the vocabulary, the complexity of its links and the necessary structure, different languages can be used. The inference mechanism used by the semantic web can improve data integration and promote the discovery of new relationships. These relationships can be created from existing data or under additional information, making a new set of linked rules.

The discussion of semantic web technologies in the preceding section sets the stage for examining how ontologies might contribute to supply chain sustainability. Semantic web technologies, such as RDF and OWL, provide a standardized and interoperable framework for the representation and integration of data, enabling a deeper understanding of the relationships and context within supply chain operations. The incorporation of ontologies, which formally represent knowledge and domain-specific concepts, allows a higher ability to capture, structure and reason about sustainability-related information. The identification of dependencies, impacts and opportunities for sustainable practises in multiple stages of the supply chain is now possible. Therefore, by connecting the concepts of semantic web technologies and the use of ontologies in supply chains, a comprehensive examination of how leveraging ontological representations can contribute to improved sustainability practices across the supply chain ecosystem will be discussed.

3.4 Semiconductor supply chain: the benefits from using ontologies towards sustainability in supply chains

Semiconductor supply chain is a highly complex system due to short product life cycles, fluctuating demand, capital-intensive investment and a series of cooperative decisions are required to make the whole chain work [78]. The manufacturing supply chain can be divided into four levels (see Figure 3.2). The first level represents the tool; the second level, includes the factory; the third level describes the internal supply chain and, finally, the fourth level, the end-to-end supply chain. Only by increasing the agility and resilience factors of this complex chain system is it possible to ensure a competitive and sustainable advantage in this industrial sector [79]. The US Department of Energy report highlights the complexity of the Deep Supply Chain Assessment of the semiconductor sector [80].

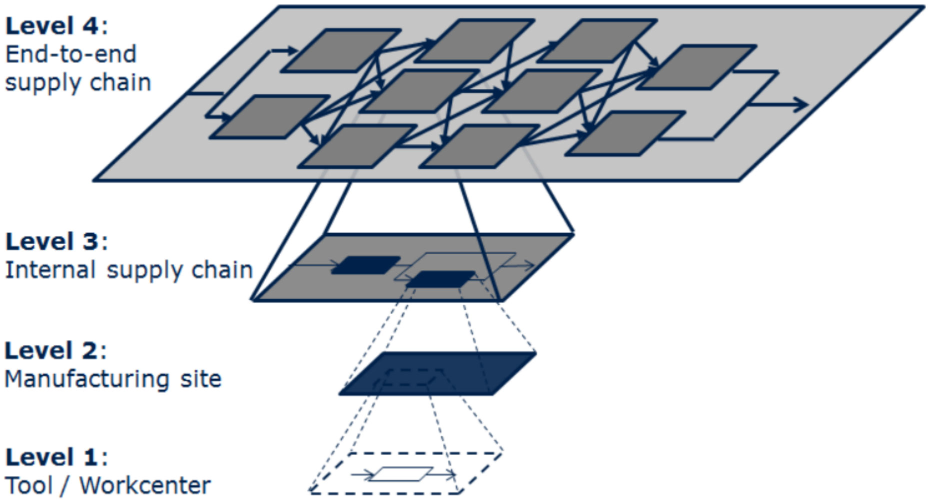

Figure 3.2: Four levels of the Supply Chain in the Semiconductor Industry

The digitization of semiconductor supply chains is a key part of the proper functioning of the whole system, also providing an up-to-date and real-time view of the status of all processes. The digitalization transition has been accelerated due to the COVID-19 pandemic and chip shortage events, which has uncovered some fragilities in these supply chains. Deloitte´s Semiconductor Transformation Study stated that 3/5 of semiconductor companies had somehow started a digital transition, most of them supported by the European Union funds [20].

Building a holistic digital twin is a good strategy to bridging the gap between the physical and digital worlds to speed up digitalization process, which is based on Semantic Web technology [81]. Data is collected and used at every stage of the product life cycle, making it a viable source for the development of a product at a later time. A framework should be in place to ensure that all relevant information is cyclically extracted, updated and made available. Due to lack of frameworks that guarantees a successful management of the SC, except for the mentioned above SCOR model, an Overall Supply Chain Effectiveness was proposed in this work [78]. Its aim is to provide improvement solutions and detection of root causes for possible failures. In a framework with metrics and a hierarchical decision structure, an ontology was designed to plan and control decisions in a more explicit way. Based on this ontology, a simulation model capable of performing a root cause analysis was built. This ontology allows ”an understandable and generic structure to the system for information sharing, collaboration and simulation” [82]. Ontologies are essential for achieving data interoperability and integration within the semantic web and linked data paradigm.

The semantic web and linked data provide methodologies and algorithms that make data more accessible, interpretable and interoperable, while encouraging the sharing of data and information across domains. However, semantic web technologies have not yet been sufficiently tested in the areas of sustainability and product life cycle assessments, notably in the semiconductor sector [83]. Semantic Web technologies, as a transition tool for Industry 4.0, allow the extraction of web information and processing of web data, which contributes to an easier decision-making process. One of the goals of ontologies is the identification and modelling of implicit information. Secondly, it acts as a *lingua franca* among experts from multiple subjects, due to its innate ability of language understandability and interpretability [84, 85]. In [82] a model for transferring knowledge from existing collections to simulation models is presented.With Parsing software it is possible to implement ontologies and perform simulations. Decision support systems for uncertain supply chains, like the semiconductors one, make use of simulation models supported by complete and exact process relationships [86]. Ontologies not only enable the formalisation of knowledge and information, but also allow the sharing and development of a common understanding between humans and machines. Furthermore, they provide easy extension and effective reuse of knowledge. The ontology is developed by stating the classes and its relations by a specific attribute. The combination of ontologies and simulation models is, as mentioned, beneficial for this type of industry. A simulation is the virtual creation of a system behaviour that may be used in test experiments. Simulations make it possible to study system behaviour in hypothetical situations, without affecting the actual system state, but also make predictions about its future behaviour. Their combined ability is very useful for the semiconductor supply chains, and it is a great competitive advantage [87].

3.5 Chapter summary

Literature review was made with an emphasis on sustainable supply chain practices, semantic web technologies, and ontologies in the semiconductor sector. It can be concluded that despite multiple actions towards sustainability in supply chains, there is still a lack of standard frameworks. The digitalisation process will play an important role as it enables data collection, analysis and processing. Greater efficiency in process monitoring and surveillance will be possible through fast and complete networked communications infrastructures, but also better management of resources and of the product life cycle. A greater level of customer satisfaction is a direct result of this increased reaction capability. .

Semantic Web Technologies are the support for digitalization. With its multiple components, which constitute the Semantic Web Stack, one is able to standardize vocabulary and linked knowledge. The semiconductor industry can take particular advantage of this technology once it is composed of a highly complex supply chain. In order to be competitive and sustainable, it is important to have a holistic view of the system.

The shortage of chips in recent years, due to the COVID pandemic, and the consequent breakdown of supply chains has posed serious problems for the global economy. Improving semiconductor supply chains is key, but to do so, it is necessary to explore resilience and have a greater degree of agility. New technological solutions are necessary for its proper functioning. Aligned with principles of the Industry 4.0, the known rigid value chains will be replaced by versatile and more connected allowing also the creation of more environmentally friendly supply chains. Autonomy, interoperability and sustainability are crucial pillars towards this transition.

4

Case Study: Battery Management System

Contents

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4.2 BMS in the transition to greener means of transportation 41
4.3 Environmental analysis 43
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The BMS and its applications will be the main topics of this chapter. First, a background on its importance, application, and purpose will be provided. The system architecture will then be thoroughly examined. The relevance of this equipment will subsequently be emphasized, namely its influence on the transition to more environmentally friendly modes of transportation. An environmental assessment regarding the way this device minimizes CO2 emissions is presented as the chapter's conclusion.

4.1 Contextualization and system architecture

The present tendency towards the electrification of processes increases the role of the Lithium-Ion Batteries. The technology which manages these battery packs is the BMS. This chapter makes a summary description about the BMS, namely about its purposes, architecture and the CO2 savings that it can provide.

4.1.1 Lithium-Ion Batteries - energy storage market leader

The current energy storage systems, according to the United States department of energy, are [88]:

- Lithium Ion Battery, LIB, which have a high energy efficiency per unit mass, show good performance under high temperatures and have low self-discharge. A higher power-to-rate ratio and a high energy efficiency, make this battery the most popular in EV and PHEV vehicles;
- Nickel-Metal Hydride Batteries are mostly used in computers and medical equipment. Although they offer a reasonable energy capacity, they have two drawbacks: easily self-discharge and are pricey. They are frequently used in HEV;
- Lead-acid batteries have low specific energy and perform poorly at cold temperatures. While they may have features such as high power, safety, reliability and affordability, these batteries have a short life cycle.
- Ultracapacitors supplement the primary source of energy from batteries, which cannot consistently deliver brief bursts of power. The ultracapacitors energy is stored in a polarized liquid between the electrode and the electrolyte. It can give additional power during acceleration, as well as in steep roads, helping to recover the braking energy. It can serve as well as a secondary energy-storage device for EV.

Among the multiple types of energy storage systems, the LIBs are the most promising technology. They have a high market potential due to their lightweight and high energy density, being popular as portable and rechargeable batteries. Compared to other battery technologies, it offers a higher energy density and life cycle. The LIBs have multiple applications such as in areas like aerospace and biomedicine, however, the EV and HEV are the sectors where it is most used. Moreover, they have additional useful features such as their small self-discharge and charge value, voltage efficiency, energy efficiency, higher life cycle, fast charge capacity and a wide range of operating temperatures, which makes these batteries market leaders [89].

Despite the excellent features of LIBs, such batteries are unstable and therefore dangerous to use when not correctly managed. The operating temperature and ideal State of Charge (SOC) are examples of crucial factors for a safe functioning of this device. The solution to face such peculiar and rigorous working conditions is through the use of BMS.

The Battery Management System, BMS, is an essential component for the practical utilization of batteries, which are based on semiconductors devices (power electronic, digital electronics and sensors). A battery is made up of battery cells, which when combined, form battery modules, which in turn form the battery pack. These connected battery modules provide a nominal electric power, i.e. electric current with at constant voltage, during a period of time. The quantity of energy contained in a system or area of space per unit volume is known as the energy density [**?**]. These cells can be prismatic, pouch or cylindrical shaped and are assembled in parallel and in series, to achieve their required capacity and voltage, correspondingly [2].

Infineon´s BMS is an end-application that is included in one of its main market sectors, with particular relevance in the automotive industry. Its primary function is to control and supervise lithium-ion batteries so that they are reliable and operate safely and efficiently. It consists of hardware based on a microcontroller, voltage regulators, current sensors and a communication interface.

In Figure 4.1 is represented a diagram of a high voltage automotive BMS as presented in Infineon's technical report [2]. Its functional blocks consist on :

- Cell Supervision and Balancing;
- Isolated Communication;
- Pack Monitoring;
- Battery Control Unit;
- Current Sensing.

Each block performs a specific function, having for it a dedicated integrated circuit. Infineon manufactures a complete set of ICs for the BMS, like shown in the Figure 4.1. For example, the hall effect sensor, TLE4972, has as function the measurement of the battery current, the TLE9012DQU is a multichannel battery monitoring and balancing IC designed for Lithium-Ion battery packs, the TLE9015DQU is a transceiver IC designed for connecting several TLE9012DQU (by UART asynchronous serial communication protocol), the TLE9350SJ is used to implement the high speed CAN transceiver [90] and

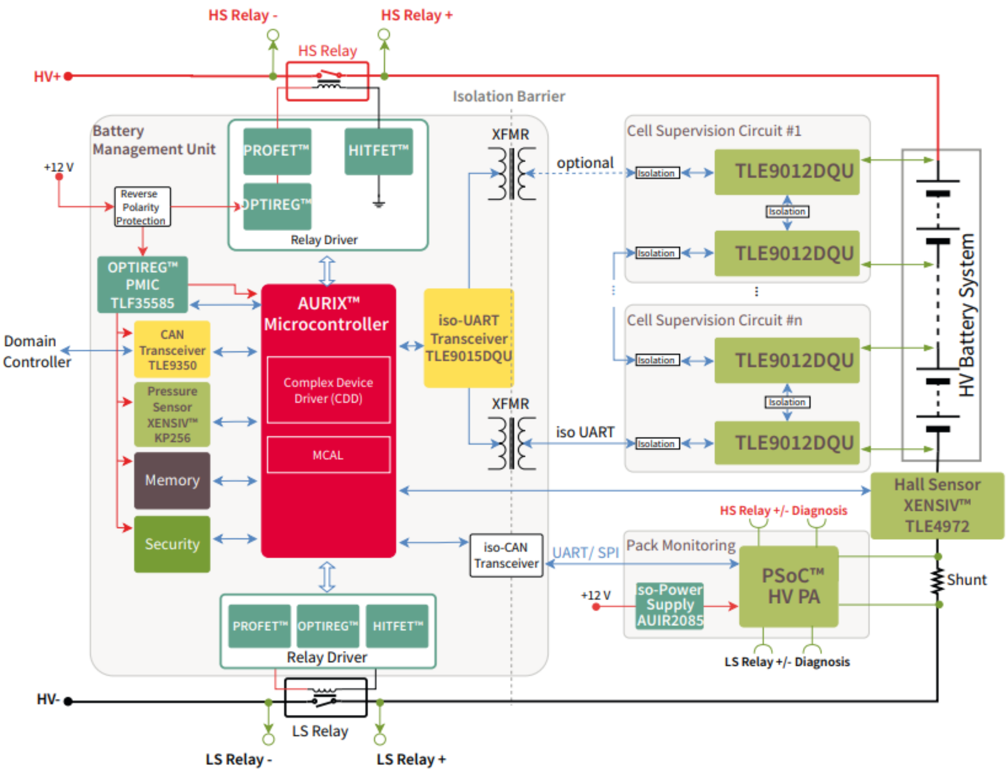


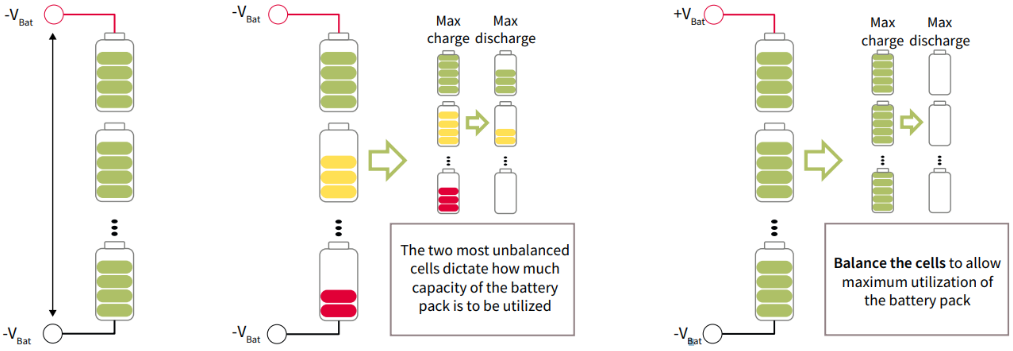
Figure 4.1: High voltage automotive Battery Management System [2]

AURIX (Automotive Realtime Integrated Next Generation Architecture) microcontroller is a multicore architecture of up to three independent 32-bit TriCore CPUs, targeted for the automotive industry. The isolation barrier is made by isolation transformers.

4.1.2 System Architecture

The state of a LIB will be described by a set of variables [91], namely: SOC, State of Health (SOH), State of Power (SOP) and Safe Operating Area (SOA). The SOC indicates the capacity level of the battery in comparison to its design power. When the State of Charge is 100%, it means that it is fully charged; on the contrary, a value of 0% means it has no available capacity level [92]. Furthermore, the SOH transmits the battery current performance in comparison to the initial state. It detects the point and condition in its lifespan [93]. Moreover, the SOP has a significant impact on a vehicle's ability to accelerate, reach its maximum speed and brake. In short words, it is the battery's capacity to take or provide power at a certain moment. Finally, SOA, which constitutes one of BMS main responsibilities: keep the battery healthy and assure operating safety.

The cell supervision and monitoring functional block of the BMS is responsible for measuring cell temperature and voltages and transmission of this data to the microcontroller. This information is important to ensure that the cells are operating under the recommended SOA conditions, i.e. the temperature and the voltage are within a range of safety values. If some of the cells are unbalanced, this will interfere and limit the battery's capacity. The semiconductor that performs these tasks is the TLE012DQU, a 12-channel cell monitoring and balancing. It is able to balance the cells, re-establishing the battery's normal capacity. When the cells are overcharged, the risk of explosion increase significantly; on the other hand, the chemical properties of the battery can be deteriorated with successive undercharging processes. To avoid both situations, a charge equalization controller must ensure a safe handling of this powerful, yet dangerous device. Figure 4.2 shows two schemes, one for the case of unbalanced cells charge of the cells (middle part) and another for the case of balanced charge of the cells (right part), where only the latter case guarantees greater durability and safety of the battery.



The two most unbalanced cells dictate how much capacity of the battery pack is to be utilized

Balance the cells to allow maximum utilization of the battery pack

Figure 4.2: A representation of the cell balancing [2]

Measuring the battery's electric current is very important for monitoring and controlling the battery's state condition, as well as calculating the stored energy. The SOC instability when exposed to external elements like temperature, age, and operating conditions demands for a Coulomb counting current sensor in order to achieve an accurate measurement. The TLE4972 sensor measures the battery current and detects overcurrent events. For safety reasons, when an abnormal event occurs, the battery should be immediately disconnected from the load.

The pack monitoring block, must detect insulation faults and arcing, overcurrent events, thermal range and battery disconnect states. The PSoC HVPA sensor continuously measures the insulation impedance, as the high voltage battery is isolated from the rest of the car. Furthermore, in case of a overcurrent event (e.g. due to a short circuit), the pack monitoring block should react very quickly (about a few milliseconds) to disconnect the battery.

The AURIX microcontroller is the brain of the battery control unit. It receives all information directly from sensors (such as voltage, current, temperature or pressure) or from other peripheral devices via UART serial data lines. To prevent damage, the control unit is electrically isolated from cell supervisory circuits and package monitoring blocks. The semiconductor responsible for the isolated communication, in order to avoid this damage, is the TLE015DQU. The KP256 (a miniaturized Digital Barometric Air

Pressure Sensor) and the OPTIREG TLF35585 (with a voltage regulator, a precise voltage reference, a watchdog and others electric devices) are both part of the control unit. When the software is run, the battery control unit guides through all the monitoring units, stores all the supervised values and then calculates the SOC,SOH,SOP and Safe Operating Safety (SOS).

Due to the aging of electronic devices, the accuracy and performance of the BMS may be lower. However, Infineon aims to offer robust, accurate and durable devices that contribute to:

- Monitoring of cells and batteries, as the total capacity of the system is limited by the weakest cell;
- Compute the level of charging/discharging energy, the state of health, the instant power and safety conditions;
- Improved battery performance, for example by balancing the cells.

4.2 BMS in the transition to greener means of transportation

The European Federation for Transport and Environment, has performed a life-cycle analysis of the CO2 emissions of an Electric Vehicle (EV) [94]. Three types of vehicles were taken into account, the Battery Electric Vehicle (BEV), the Hybrid Electric Vehicles (HEV) and the Plug-in Hybrid Electric Vehicles (PHEV). A BEV is a vehicle whose source of propulsion comes only from the chemical energy stored in a battery pack. On the other hand, the HEV source of propulsion is both electric and internal combustion. Finally, the PHEV is a hybrid vehicle, which means it has an electric motor and can be charged both by connecting a plug cable to a power source and as well through an internal combustion power generator.

In 2021 one out of ten cars sold in the EU was a BEV. In this study it was stated that there is no doubt that HEV are cleaner than HEV and PHEV, i.e. have lower CO2 emissions. For instance, only 38% of PHEV's kilometers are driven in electric mode, producing then twice more pollution than BEVs. When compared to conventional motor vehicles, this model just slightly reduces CO2 emissions during actual trips. Despite the significant carbon impact in BEVs manufacturing, the average EU BEV is above three times cleaner than the equivalent petrol car bought in 2022, which means less 69% of CO2 emissions [94]. In the best case scenario, with Sweden as production and charging site, a BEV would be almost six times cleaner, with 83% less CO2 emissions than the equivalent petrol car.

The current BEV has so far a good prognosis, but they still have a lot of room for improvement regarding their CO2 footprint. New research on electric batteries, manufactured materials and charging processes will be effective contributions to make the BEV more popular. It is expected that by 2030, 62% of vehicles in the EU will be of the BEV type, a fact that will have a strong impact on reducing carbon emissions. In addition, battery supply chains are as well getting cleaner, a best-in-class supply chain in the source of Lithium, Nickel or graphite and make the BEV life-cycle emissions reduce in 13%. According to a study from IVL Sweden [95], the carbonic impact of producing a battery can go from 61 to 106 kgCO2e/kWh. It is important to note that the carbon footprint of an electric car depends on its geographical location, as it depends on the sources of electricity and on the environmental regulations of each country. A car will have a smaller carbon footprint if it is charged in Sweden, the nation with the cleanest electrical network, as opposed to Poland, which has a high carbon-heavy electrical infrastructure. Despite this fact, even if a car is charged in Poland over its lifetime, is still 40% cleaner than the correspondent petrol vehicle. A medium-sized EU-average EV sold in 2022 has lifetime emissions a value of 75gCO2e/km, which is considerably low compared to a petrol car, emitting 241gCO2e/km. It is proven that if the best conditions were provided in terms of lowest production, supply chain impact and the cleanest electrical grid, the BEV would have a lifecycle emissions value of only 21gCO2e/km.

According to EU forecasts, the battery market will be strategic. These are essential devices for the storage of intermittent renewable energy, for the digital economy and for the transition to mobility with fewer carbon emissions. LIBs are key devices for the transition towards greener sources of transport. On EU roads, it is expected by 2030, that at least 30 million electric vehicles will be emissions-neutral.

Although we expect from electric vehicles a great benefit in the reduction of GHG emissions, their batteries have a negative impact on the environment. Accompanied by increased manufacturing of BEV, figure 4.3 shows, that the demand for electric batteries is increasing at a constant rate. From 2018, the demand will be even greater, in the form of exponential growth. It is expected to be eighteen times higher in 2030 and sixty times bigger in 2050 [3]. The Circular Energy Storage, a London-based consultancy company, has stated that in 2030, more than 400000 tons of batteries will reach its end-of-life in EU [94]. Based on the scrutiny of their life cycle, EU is implementing new measures to reduce the impact of this situation. As first measure, it is imposing a label on battery that displays their carbon footprint [96]. Another objective of EU is to increase battery recycling and to impose a minimum percentage of recycled raw materials in new batteries.

Circular economy policies are the best sustainable solution for an end-of-life battery. Valuable metals and other materials are reused to make new devices. EU also addresses the problem of raw material extraction for batteries, such as Cobalt, Lithium, Nickel and Manganese. These are highly polluting activities, have significant impacts on our environment and on the health of populations. The smaller the need for extraction, the greater the guarantee that the impact of extraction is less significant, also contributing to the circular economy. For example, *Hydrovolt* is a large European company working on battery recycling. It has the capacity to recycle 12,000 tons of batteries annually, which corresponds to around 25,000 batteries. However, the number of companies in Europe and their recycling capacity are still insufficient.

The LIB is a fragile and expensive device, so the BMS is extremely important to ensure its safer and

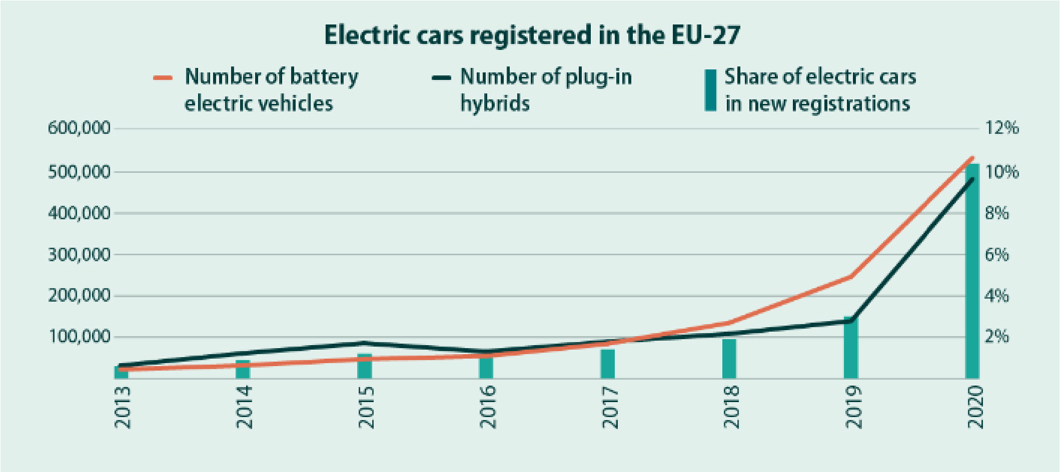


Figure 4.3: Electric car demand in the EU [3]

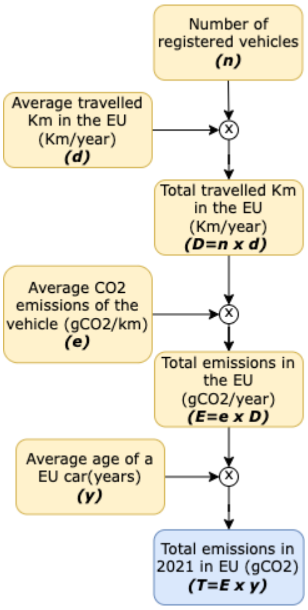
healthier use. The intelligent semiconductor capabilities of the BMS allow an optimal cell control, which ensures a longer battery lifetime. Despite the fact that they also contribute to global warming because of their peculiar manufacturing procedures, their emphasis on greener electronics is considerably more important. In this work, three ways of potential CO2 savings, provided by the BMS, are considered:

- Transition to Electric Means of Transportation: without the BMS, using LIBs would not be possible. As previously mentioned, this type of energy storage system is the most efficient and promising one. Therefore it is due to this semiconductors assembly that we are able to use it.
- Battery´s Longer Lifespan: with the usage of the BMS the battery cells are better managed which can reduce the necessity for replacement batteries and the associated manufacturing CO2 emissions.
- Optimized charging and usage: using the BMS, the cells are charged in an optimized way. Keeping pace with the optimal temperature, optimal voltage etc, assuring a longer lifespan. It ensures that the battery is working at the most efficient level, resulting in a reduction of energy losses.

After presenting the BMS potential CO2 savings, an environmental analysis having as basis this three hypothesis will be conducted. This analysis is divided in two studies, the first one, observing the carbonic impact in the switch to greener transportation, and the second one, examining the impact of the BMS, its optimized charging and utilization in the lifespan of the battery.

4.3 Environmental analysis

Today we are witnessing a revolution in the means of transport. New transport vehicles will be powered by electric motors instead of traditional fossil fuel engines. These are, therefore, more ecological, and contribute to the reduction of greenhouse gas emissions. These are powered by electric batteries, mostly Lithium. However, without the BMS it would not be possible to use it effectively or with the required security. In this way, the improvement of the BMS in CO2 savings results from the combined sum of the (indirect) contribution of the batteries with the (direct) contribution of the improvement in efficiency achieved by the BMS. From the information available today, it is possible to determine the contribution of the BMS to CO2 savings, particularly due to its use in electric cars. From the known predictions about the growth of electric car use in the near future, it is also possible to estimate the future CO2 savings. To evaluate these savings, a model will be proposed and the meaning of its parameters, constants and relationships will be explained. With this model, the total carbon emissions of electric cars circulating in the European Union in 2021 are calculated. From these values, the savings achieved by BMS are estimated. Figure 4.4 shows the proposed model (in the form of a flowchart) to calculate the CO2 savings by BMS.



x - algebraic product

Figure 4.4: Environmental analysis flowchart

The model´s parameters are:

- Number of registered electric cars in the EU in 2021 [97];
- Average distance travelled per year (Km/year) [98];
- Average CO2 emissions of a petrol/electrical car (gCO2/km) [99];
- Average age of the cars in the European Union (years) [100].

Two studies are presented to conclude on the BMS carbonic savings. The first study demonstrates the positive effects of having electric vehicles in circulation; the second study focuses on the carbonic savings inherent of the longer life expectancy of batteries.

- **Study 1: Transition to electric means of transportation** - Carbon emissions from the circulating Battery electric cars (BEVs) instead of petrol cars

  For this study was considered a vehicle, either an electric or petrol, with an age corresponding to the average in the EU of 11.5 years and with a consumption of the petrol and electric vehicles of respectively 127 gCO2/Km and 37.67 gCO2/km. This means that the average European electric vehicle emits 69% less than the equivalent petrol car [94]. In the year 2021, the number of BEVs, n, circulating in the EU was $1,729,000$ [97] and they made an average travel distance, d, about of $11,300$ km/year. The estimated number of kilometres travelled by cars, D, in the EU is, according to Eq. 4.1, 1.95×10^{10} km/year.

  For petrol car: Taking into account the average carbon emissions of a petrol car, e, which is about 127 gCO2/Km, the total emissions produced by petrol cars in 2021 was, according to Eq. 4.2, 2.47×10^{12} gCO2/year (E). Since the average lifespan of petrol cars, y, in the EU is 11.5 years, the amount of CO2 produced, T, by these cars during their lifetime of use is, according to Eq. 4.3, 2.84×10^{13} tons of CO2.

  For E-car: Now, in order to conclude regarding the CO2 saved with electric cars, the same analysis will be made considering the E-car emissions. Taking into account the average carbon emissions of an E-car, e, which is around 36.7 gCO2/Km, the total emissions from E-cars is, according to Eq. 4.1, 0.7×10^{12} gCO2/year. The amount of CO2 produced, T, by these cars during their lifetime of use is, according to Eq. 4.3, 0.8×10^{13} tons of CO2.

$$D = n \times d \tag{4.1}$$

$$E = e \times D \tag{4.2}$$

$$T = E \times y \tag{4.3}$$

Table 4.1: Environmental analysis data - Study 1

Model Parameters	Petrol	E-Car
Number of registered vehicles in 2021, n	1729000	1729000
Average travelled Km in the EU (Km/year), d	11300	11300
Total Km travelled in the EU (Km/year), D	1.95×10^{10}	1.95×10^{10}
Average emitted CO2 by the vehicle (gCO2/Km), e	127	36.7
Total quantity of emitted CO2 in the EU per year (gCO2/year), E	2.47×10^{12}	0.7×10^{12}
Average age of an EU car (years), y	11.5	11.5
Total quantity of emitted CO2 through the vehicle's lifetime (gCO2), T	2.84×10^{13}	0.8×10^{13}

  The saved CO2 due to the circulating electric cars instead of the petrol ones is done by subtracting the T values above calculated,i.e., $T_{petrol} - T_{E-Car}$. The savings reach up to 28% less of the emissions, with 2.04×10^7 tons of CO2 saved.

- **Study 2**: **Battery Longer Lifespan**

When the Lithium-Ion cells are working, there is, as previously mentioned, a safe operating area in terms of voltage and temperature which guarantees efficiency and safe usage. However, there is a chance that the BMS is able to broaden the operating area (i.e. for the yellow region shown in Fig.4.6), which maximizes the charge capacity of the cells. This has some relevance in the SOC of the battery in its end-of-life, which is usually when it reaches 80% of its initial capacity. Having this possibility, the battery can work until its capacity reaches 60 % of its initial one and thus extend its life expectancy [101]. The capacity of a battery degrades with the number of charge-discharge cycles, as shown in Fig.4.5. The battery reaches 80% of its capacity after 600 cycles. However, with an adequate strategy of control, it can work until 60% of its capacity, which means another additional 125 cycles, meaning an extra 20% of working cycles. Considering that a battery has a carbon footprint of 77 gCO2e/kWh [94] in its manufacturing, and considering that a medium car needs a 60 kWh battery [94], it means that its footprint is 4620 gCO2e. Similar to the first part of this analysis, two scenarios will be described.

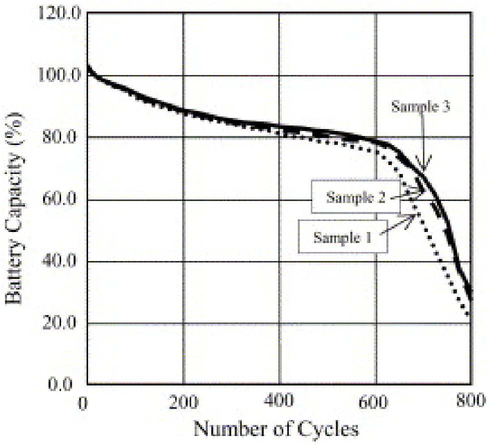


Figure 4.5: Battery capacity characteristics [4]

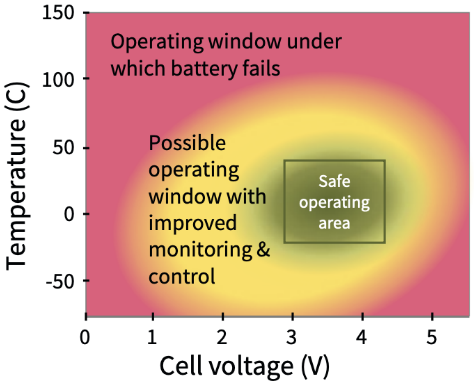


Figure 4.6: Operating window of a Li-Ion cell [2]

Considering the manufacturing emissions of a battery for a medium car of 4620 kg CO2e and an average life expectancy of 15 years [102]:

- **Scenario 1**: Normal usage of the battery until it reaches 80% of its initial capacity, corresponding to 600 cycles. If the battery´s carbon footprint, 4620 kg CO2e, is divided by its number of cycles, 600 cycles, the footprint of the battery per cycle can be deducted, $7.7kg$ CO2e/cycle. When dividing the battery´s carbon footprint, 4620 kg CO2e, by its average life expectancy, 15 years, it is calculated the battery emissions per year, 308 kg CO2e/year.

- **Scenario 2**: Usage of the battery´s SOC until 60%, i.e. 20% extra Deep of Discharging, which allows the battery to have extra 125 cycles, having in total 725 cycles. As the battery can outlive an extra 125 cycles, this means 20% of additional lifespan, corresponding to 18 years instead of 15. Following the same reasoning described above, dividing the battery´s carbon footprint, 4620 kg CO2e, by the number of cycles, 725 cycles, the battery is responsible for $6.4kg$ CO2e/cycle, emitting 9% less compared to the first scenario. Yearly, dividing the battery´s carbon footprint, 4620 kg CO2e, by the average life expectancy, 18 years, the battery emits around 6% less emissions per year than in the first scenario, corresponding to 257 kgCO2e/year.

Table 4.2: Environmental analysis data - Study 2

	Scenario 1	Scenario 2
Battery Footprint (gCO2e)	4620	4620
Battery number of cycles in end-of-life	600	725
Footprint/cycles	$7,7$	$6,4$
Battery average lifespan (years)	15	18
Footprint/year (gCO2e/year)	308	257

After these studies, it can be concluded that the impact of BMS, an assembly of semiconductors, is extremely positive, not only in the means of CO2 savings, but also as an ally in the shift towards more environmental means of transportation. In the first study, the carbonic savings proportioned by the registered electric cars in 2021 was of 2.04×10^7 tons of CO2 through the vehicle lifetime. In the second study, when optimizing the battery's performance, extending its lifespan, it can be concluded that yearly, each battery emits less 6% of CO2.

4.4 Chapter summary

The BMS is a device that controls and regulates the charging and discharging of a battery, its key functionalities are among:

- Supervise the pack and cells parameters;
- Deduct the battery and cells states (SOC, SOH, SOP, SOS);
- Improve the battery performance by balancing the cells, inform to cool/heat the battery pack;
- Safeguards the battery from operating under hazardous and unsafe conditions.

This device allows a better management of the cells during their lifespan, allowing a longer life cycle and the possibility of a second life. An environmental analysis, including two studies, was made to this device. The first study was regarding the transition to electric means of transportation, reflecting the impact of BEV instead of petrol cars. The second study was to demonstrate the BMS's direct impact to a LIB's increased lifespan and subsequent carbon emissions reductions.

Additionally, aligned with the Industry 4.0 goals, a digital twin of this device will be developed. As the Semantic Web Technologies allow the creation of ontologies, this will be explored, enabling a detailed analysis of the BMS´s functional blocks. All its constituent parts will be defined with a standardized vocabulary, understood by both humans and machines. Such detailed characterization will contribute to standardized information and facilitate the process of analysis of its supply chain. For instance, by carefully examining the battery's life-cycle data, we may contribute to the study of how we might make the battery supply chain cleaner. The following chapter will go into more detail about this procedure.

5

The BMS Ontology

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The semiconductors' contribution towards supply chains higher sustainability was presented in previous chapters. Among all the applications that use semiconductors, the BMS assumes an important role in the present and future, since they are essential in modern electrical systems that replace those dependent on fossil energies. In this chapter a BMS ontology will be developed, taking into account the semiconductors employed in its construction. The BMS architecture will be translated into an ontology, which will allow a better visualization and holistic perception of the system. The inclusion of the BMS ontology in the Digital Reference will allow the semiconductor business sector to learn, to assess its results and to conclude about its benefits, namely about its contribution in the process decarbonization task.

5.1 Building an ontology

Ontology is a formal representation of knowledge that defines concepts, relationships, and properties within a specific domain. It provides a structured framework for organizing information and enables machines to understand and reason about data [103].

The design of this ontology is carried out in two parts. First a global structure is defined. Next, it is translated by an ontology software into an appropriate code. For this task the Protégé software is used, a program developed by Mark Musen in 1987 [104] and since then improved by Stanford University. Two documents were used as guidelines for this process, namely the *Ontology Development 101: A Guide to Creating Your First Ontology* from Standford University [16] and *A Practical Guide To Building OWL Ontologies Using Protégé 4* [5]. A naming convention for the terms will be used to transfer the ontology to Protégé. In the ontology design phase the following rules were considered:

1. There is no single way to conceive of an ontology. The correctness of an ontology depends on its final application;
2. Designing an ontology is an iterative process, and it is refined with each revision;
3. The ontology should be a representation of the reality of the world and its concepts need to reflect it.

The steps followed to build the ontology will be highlighted here and then developed in their own sections:

- Definition of the domain and scope;

- Determining the competency questions;
- Checking for previous existing ontologies;
- Listing important terms for the ontology;
- Defining the class hierarchy;
- Creating individuals;
- Defining the object properties;
- Final ontology;
- Ontology model.

5.1.1 Defining the domain and scope

For the first step of the ontology design, we must start by defining the domain and scope of it:

1. **What is the ontology sphere of coverage?**

   In this work, the ontology has as main topic the representation of a BMS in a LIB. Its system architecture and main functions will be as well covered.

2. **What is the purpose of the ontology?**

   This ontology has multiple objectives, among them are the creation of a digital twin of a semiconductor end-application, the BMS. Later on, its inclusion into the Digital Reference, contributing to a higher holistic perception of the product. The CO2 savings possibilities of this end-application will be as well included in the ontology.

3. **For what should the ontology provide answers to?**

   It must answer the questions: In which ways can the BMS contribute to CO2 savings? Which components are part of the BMS? Which semiconductors make part of the BMS?

4. **Who will use and maintain the ontology?**

   This ontology will be integrated within the Digital Reference, which is a digital system that contains all the existing relationships in the semiconductor industry. Therefore, it will be used and updated by the multiple players in this industry.

5.1.2 Determining the competency questions

Answering a set of additional questions can help design a clearer, more concise and readable ontology. Such interrogations, give the possibility to test whether the ontology is sufficiently comprehensive and contains the necessary relations that answer the initial questions. These are:

1. What are the functional blocks of a BMS?
2. Which semiconductors are included in the BMS?
3. How can the BMS contribute to CO2 savings?

Considering these questions, the ontology will include information about the battery´s architecture, location and its potential contribution for CO2 savings.

5.1.3 Check for previous ontologies

Before starting the process of building new ontologies it is common to check the existence of those already in use. By doing this, it is possible to improve previously developed ontologies by convenient updates. In this way, we extend the knowledge already acquired, in an iterative process. In this line of work, some libraries that include reusable ontologies present in the literature were consulted, such as the ontology libraries Ontolingua and the DARPA Agent Markup Language (DAML). In both libraries, the search for existing ontologies was done by searching the keywords ”Battery Management System”, ”Battery” and ”BMS”. After some searches, it was decided to create a new ontology, since there were none that directly related to BMS.

5.1.4 Ontology terms

After defining the domain, scope and competency questions, the next step is to list terms and words that will be covered by the ontology. Each domain ontology typically models domain-specific definitions of terms. Table 5.1 contains a list of terms, which are associated with specific categories of the current problem. They were collected from Infineon’s BMS technical reports and data sheets, as presented in Chapter 4. After analyzing the technical components of a high voltage BMS, provided by Infineon’s technical reports, its composition was deconstructed into its five main functional blocks and its correspondent semiconductors. The battery monitored by the BMS was also referred as an important term, the Lithium-Ion battery. It was considered that the battery was included in a vehicle, in these circumstances from the type electric. Lastly, this ontology will include the CO2 savings allowed by the usage of the BMS, namely in three aspects, discussed already in Chapter 4, the Battery Longer Lifespan, Optimized Charging and the Electric Means of Transportation.

Therefore, this list is composed by the terms:

- `E-car and Lithium Ion Battery` which belong to the category **Vehicle**;
- `Cells, Battery Management System and Pack` corresponding to **Battery Component**;
- `Electric Means of Transportation, Battery Longer Lifespan and Optimized Charging` which are related to the **CO2 savings** section;
- `Battery Control Unit, Cell Supervision, Current Sensing, Isolated Communication and Pack Monitoring` are all part of the **Functional Blocks**;
- The chips `AURIX`, `KP256`, `OPTIREG`, `PSoC HVPA`, `TLE015DQU`, `TLE012DQU`, `TLE4972` belong to the **Semiconductor group**;
- `Infineon` is the **Semiconductor company**;

Table 5.1: List of important terms and its respective category

Category	Terms
Vehicle	E-Car Lithium-Ion Battery
Battery Component	Cells Battery Management System Pack
CO2 Savings	Battery Longer Lifespan Optimized Charging Electric Means of Transportation
Functional Block	Current Sensing Battery Control Unit Pack Monitoring Isolated Communication Cell Supervision
Semiconductor	TLE4972 KP256 OPTIREG AURIX PSoC HVPA TLE015DQU TLE012DQU
Semiconductor Company	Infineon

5.1.5 Class hierarchy

The next procedure is to create a class hierarchy. As mentioned in Chapter 3 (OWL ontology components), the classes (and respective subclasses), individuals and properties will be defined in order to create a taxonomy. There are three ways in which the ontology can be organized, the *top-down*, *bottom-up* and *combination* [105]. A *top-down* approach begins by defining the domain's most general ideas, followed by the concepts' specialization. In *bottom-up´s* method, the most detailed classes, or the leaves of the hierarchy, are defined on first place, being later grouped into more generic notions. Finally, the *combination*, is as implicit by the name a mixture of both techniques. For the BMS ontology, the approach chosen was the top-down approach, looking first to the big picture, the E-car, then the battery components, following its functional blocks and finally reaching the semiconductors devices, making it more specific in each iteration.

The definition of the classes will start by analyzing the list of important terms created, Table 5.1, and pick the ones which have an independent existence. This means that classes are not terms that describe objects, but terms that have an independent existence. Every object in a subclass is a "kind of" the superclass. *"If a class A is a superclass of B, then every instance of B is also an instance of A"* [5]. From the list created the classes were firstly selected. The picked terms for classes were `Vehicle`, `Lithium Ion Battery`, `Battery Component`, `CO2 Savings`, `Functional Block`, `Semiconductor`, `Infineon`. The subclasses, are all the "kind of" the previously determined classes: `Optimized Charging`, `Electric Means of Transportation` and `Battery Longer Life Span` as kinds of CO2 Savings; `Cells`, `Battery Management` and `Pack` as different Battery Components; the `E-Car` as a type of Vehicle and, finally, the different Functional Blocks like `Battery Control Unit`, `Cell Supervision`, `Current Sensing`, `Isolated Communication` and `Pack Monitoring`.

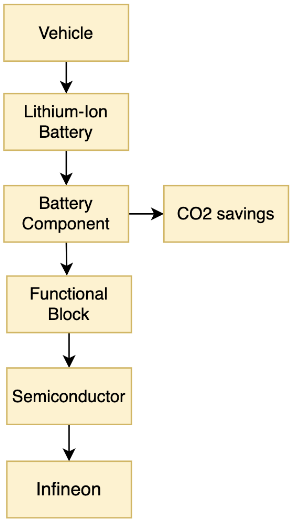


Figure 5.1: Classes scheme

A scheme representing the selected classes and their connections is presented in Figure 5.1. Each class has an inherent meaning associated and represents a certain group of instances. The definitions applied in this ontology's classes are presented below:

1. **Vehicle** - A vehicle is a machine with wheels and an engine, used for transporting people or goods.
2. **Lithium-Ion Battery** - The Lithium-Ion Battery represents the set of cells together, which is the

battery pack, plus the battery management system.

3. **Battery Component** - Battery component refers to a specific part or element that is integral to the functioning of the battery.
4. **CO2 Savings** - CO2 Savings refers to several solutions that might reduce carbon emissions throughout the course of a Lithium-Ion battery's lifespan.
5. **Functional Blocks** - A Functional Block is a component of the battery management system.
6. **Semiconductor** - Semiconductor is an electronic device which electrical conductivity value is between an insulator and a conductor. Here, Semiconductor also includes electronic devices as power electronic (e.g. bipolar junction transistor, field-effect transistor and diodes), microcontrollers, integrated circuits, or chips, electronic sensors and many other semiconductor devices.
7. **Infineon** - Company responsible for the manufacturing of semiconductors.

5.1.6 Creating individuals

After defining the classes and subclasses, it is important to select the terms from the list which are unique objects, i.e the individuals or instances. Analyzing the list on Table 5.1 it is clear that the words `AURIX, KP256, OPTIREG, PSoC HVPA, TLE012DQU, TLE015DQU, TLE4972`, belonging to the Semiconductors category, are "one of a kind" object, therefore, constituting the individuals group.

5.1.7 Defining the object properties

Object properties are terms that define relationships between two objects, having an associated range and domain for each one. For the sake of comprehension, Figure 5.2 and Table 5.2 were included below. Both contain examples of the multiple BMS object properties and, for each one, its correspondent domain and range.

In Figure 5.2 the domains are represented by blue squared rectangles and the range by yellow circles. An example on how to analyze the object properties and its features for the three upper schemes, in Figure 5.2, will be shown:

- **domain**:`E_Car`; **object property**:`is_vehicle`; **range**:`Vehicle`;
- **domain**:`Cells`, `Pack Housing`, `BMS`; **object property**:`is_battery_component`; **range**:`Battery Component`;
- **domain**:`Battery_Longer_Lifespan`, `Electric_Means_Transportation`, `Optimized_Charging`; **object property**:enables_CO2_savings; **range**:`CO2_savings`

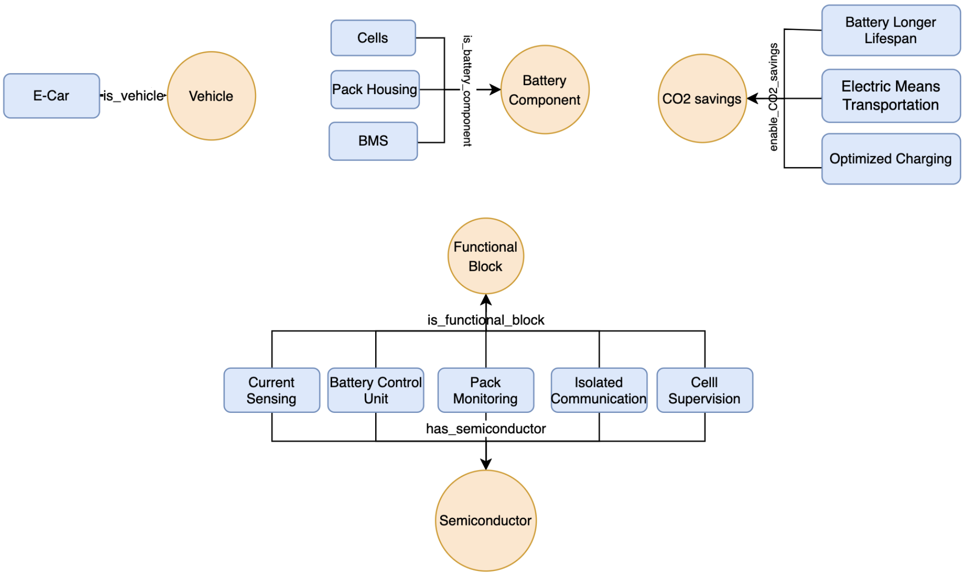


Figure 5.2: Examples of object properties, its domain and range

Table 5.2: Ontology object properties, its range and domain

Object Property	Domain	Range
`contributes_for_CO2_savings`	`Battery_Management_System`	`CO2_Savings`

`has_semiconductor`	`Pack_Monitoring`
	`Cell_Supervision`
	`Isolated_Communication`
	`Battery_Control_Unit`
	`Current_Sensing`
		`Semiconductor`

`has_battery`	`E_Car`	`Lithium_Ion_Battery`
`has_component`	`Lithium_Ion_Battery`	`Battery_Component`
`has_functional_block`	`Battery_Management_System`	`Functional_Block`

`is_battery_component`	`Battery_Management_System`
	`Cells`
	`Pack`
		`Battery_Component`

`is_functional_block`	`Pack_Monitoring`
	`Cell_Supervision`
	`Isolated_Communication`
	`Battery_Control_Unit`
	`Current_Sensing`
		`Functional_Block`

`is_vehicle`	`E_Car`	`Vehicle`
`is_produced_by_Infineon`	`Semiconductor`	`Infineon`

`enables_CO2_savings`	`Electric_Means_Transportation`
	`Battery_Longer_Lifespan`
	`Optimized_Charging`
		`CO2_Savings`

On the other hand, in Table 5.2, the first object property `contributes_for_CO2_savings` has as domain the class `BMS` and as range the class `CO2_Savings`; the second object property, `has_semiconductor`, has as domain the classes `Pack_Monitoring`, `Cell_Supervision`, `Isolated_Communication`, `Battery_Control_Unit` and `Current_Sensing` and as range the class `Semiconductor`, etc.

The elements of the table obey a selected naming convention. In the research literature, there is no consensus on terminology and naming conventions, particularly for BMS. Thus, the Infineon´s ontology naming convention [106], was here applied to all the classes, subclasses, individuals and respective object properties. The selected style was that the classes and individuals should be capitalized and separated by an underscore; and the object properties should contain verbs and be decapitalized.

5.1.8 Final Ontology

During the process, several schemes were developed in order to have a more organized approach. Figure 5.3 depicts the first draft of the ontology structure, in a top-down approach and including the selected classes, subclasses and individuals. The classes and subclasses were represented with the colour yellow and grey, respectively. The semiconductors, which belong to the individuals, are represented by a blue text box. In this diagram, one is able to observe a simplified representation of the BMS, the components that contribute to its carbon footprint and the possible carbonic savings. The software used to develop this diagram was the `draw.io` web program.

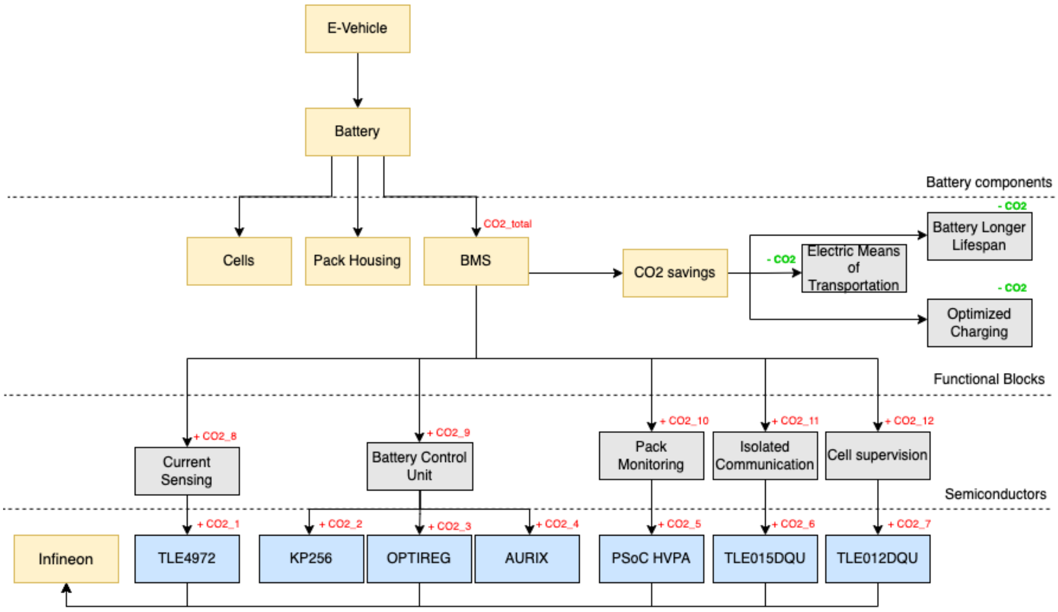


Figure 5.3: Battery Management System ontology building

A second scheme is represented in Figure 5.4, includes not only the classes and individuals, but also the object properties between them. The classes are represented by yellow circles, the subclasses by light blue round rectangles, and the individuals in a blue diamond shape. The object properties are written above the arrows connecting its domain and range.

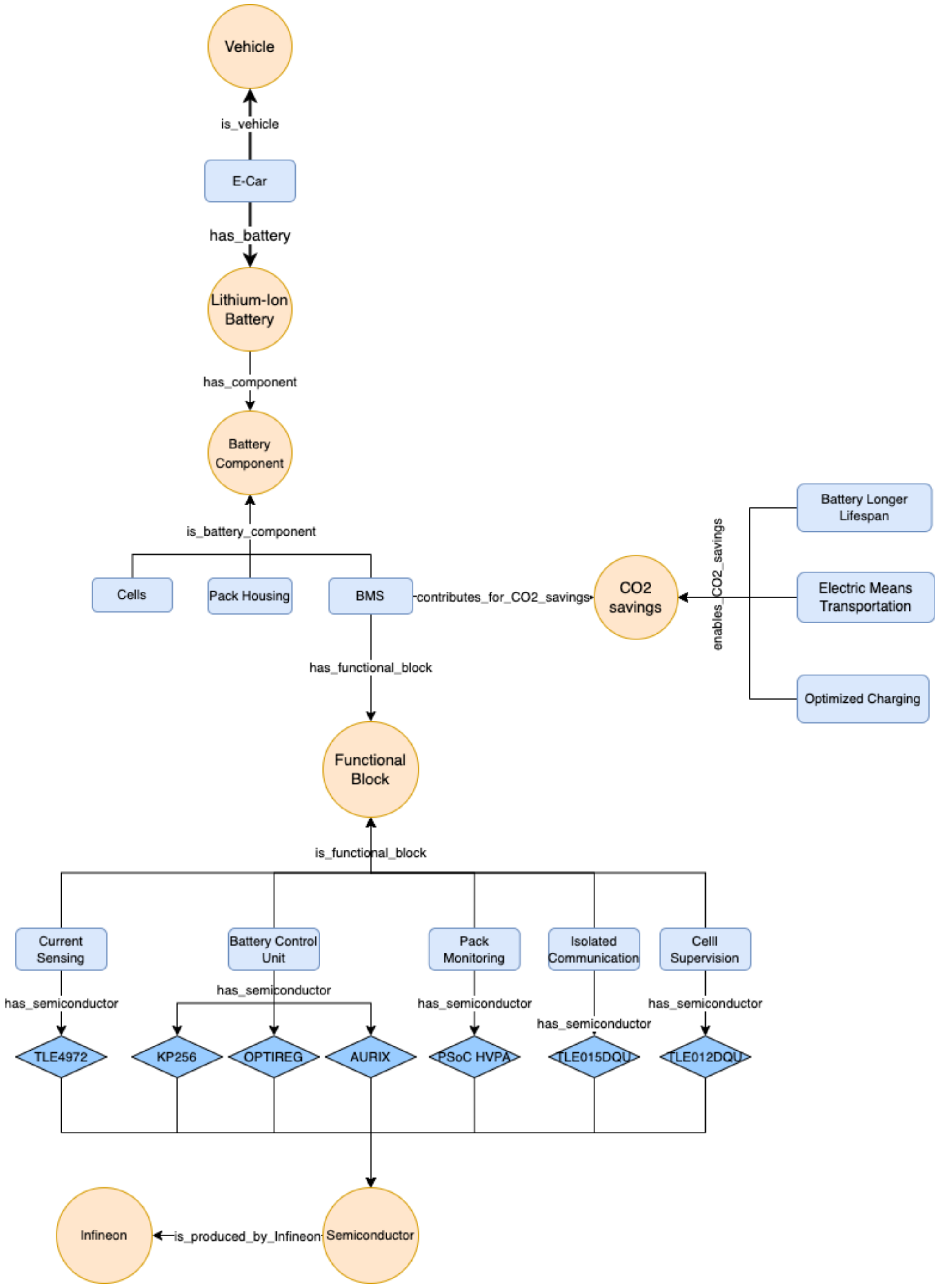


Figure 5.4: Battery Management System ontology building - top-down approach

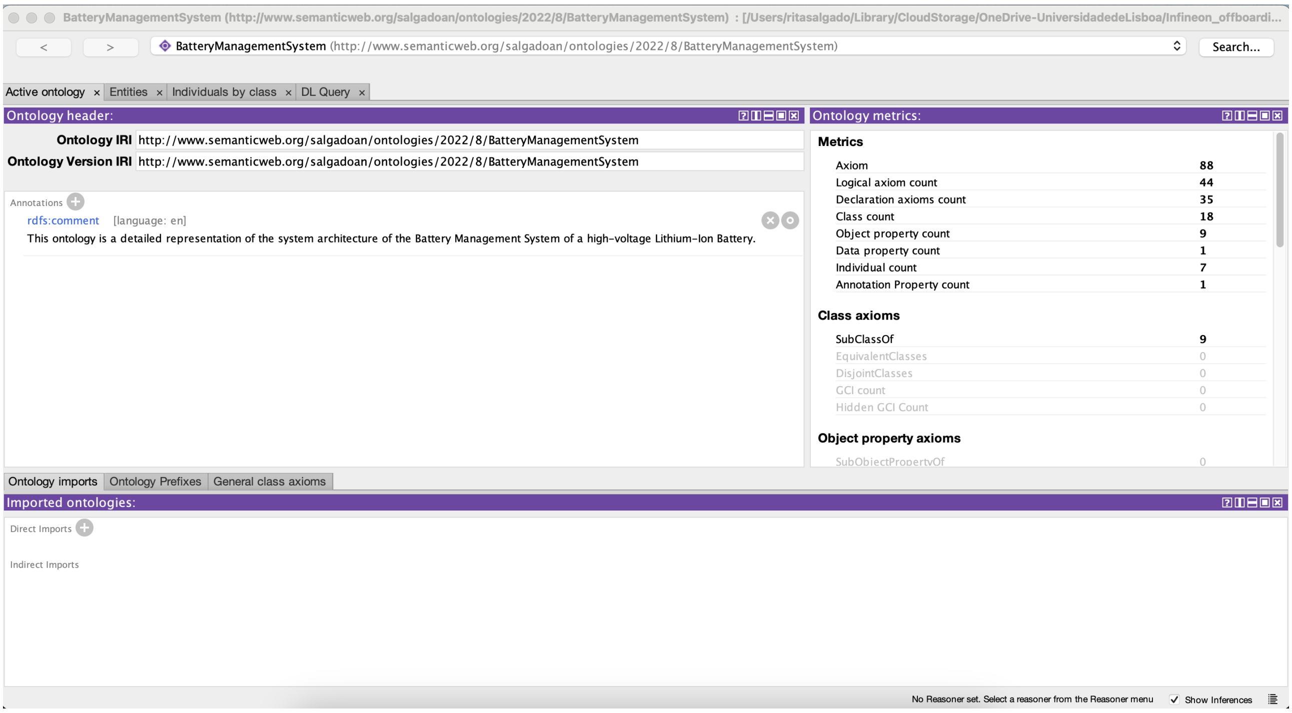
5.2 Ontology Model

Having completed the task of design the ontology structure, the next step is to transpose it into ontology code, using ontology implementation software, in order to create a model. The steps were the following:

1. **Creating a new ontology**;
2. **Inserting classes**;
3. **Inserting subclasses**;
4. **Inserting individuals**;
5. **Object properties**.

The most popular and widely used ontology editor in the world, Protegé, was chosen to materialize the BMS ontology. Next, the main steps (and sub-steps) of the creation of the BMS ontology will be presented.

1. **Creating a new ontology**
   (a) Start Protégé;
   (b) Press ”**Create New OWL Ontology**” in the Protégé dialog box;
   (c) After the ”**Active ontology**” tab is opened, substitute the Internationalized Resource Identifier (IRI), which is a more generalized version of the URI, by `"http://www.semanticweb.org/salgadoan/ontologies/2022/8/BatteryManagementSystem`;
   (d) In order to specify the purpose of this ontology, a comment was added in the same tab, by pressing the add icon (+) in the ”**Annotations**” view. In the editing window, which appears after, the option ”comment” and the language ”english” were selected. Afterwards, the comment typed was `"This ontology is a detailed representation of the system architecture of the Battery Management System of a high-voltage Lithium-Ion Battery."`



Ontology IRI http://www.semanticweb.org/salgadoan/ontologies/2022/8/BatteryManagementSystem

Ontology Version IRI http://www.semanticweb.org/salgadoan/ontologies/2022/8/BatteryManagementSystem

rdfs:comment [language: en]

This ontology is a detailed representation of the system architecture of the Battery Management System of a high-voltage Lithium-Ion Battery.

Metrics

Axiom	88
Logical axiom count	44
Declaration axioms count	35
Class count	18
Object property count	9
Data property count	1
Individual count	7
Annotation Property count	1

Class axioms

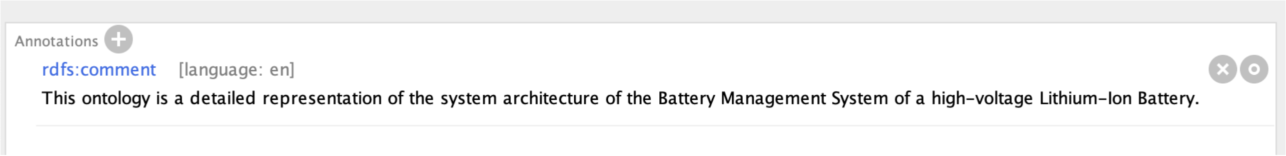
SubClassOf	9
EquivalentClasses	0
DisjointClasses	0
GCI count	0
Hidden GCI Count	0

Object property axioms

SubObjectPropertyOf	0

No Reasoner set. Select a reasoner from the Reasoner menu

Figure 5.5: Active Ontology Tab



rdfs:comment [language: en]

This ontology is a detailed representation of the system architecture of the Battery Management System of a high-voltage Lithium-Ion Battery.

Figure 5.6: Ontology annotation window

2. **Inserting Classes**

The input of the classes was based in the previous guidelines and defined hierarchy, namely on the scheme of the Figure 5.4. All the classes will be subclasses of the class `Thing`, which is the class that contains everything. The steps followed in Protégé were the following:

(a) Open the "**Entities**" tab and next the **Classes** window;

(b) Press "**Add subclass**" button as shown in Figure 5.7 and write the desired classes one by one. The terms selected as classes were `Vehicle`, `Lithium_Ion Battery`, `Cells`, `Pack`, `Battery_Management_System`, `CO2_Savings`, `Functional_Block`, `Semiconductor`, `Infineon` as shown in Figure 5.8;

(c) For each class was added an annotation in order to allow a smooth future update of this ontology. This annotation is the classe´s exact semantic definition. In this way, whoever manages this ontology in the future has a complete comprehension of what was intended with each class, as showed in Figure 5.9. The definitions applied for each class were written in the subsection **Class hierarchy**.

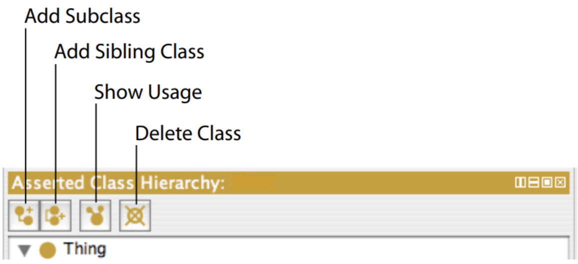


Figure 5.7: Class hierarchy buttons [5]

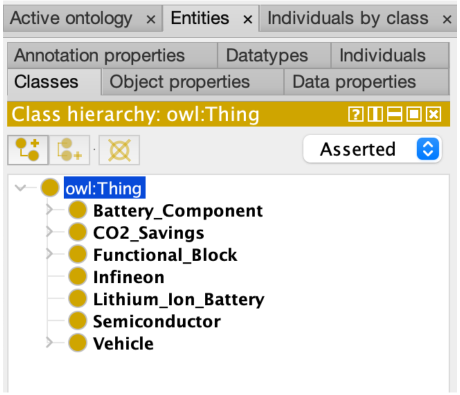
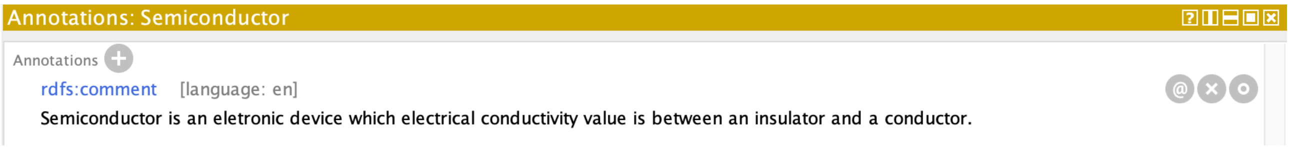


Figure 5.8: Classes window



Semiconductor is an eletronic device which electrical conductivity value is between an insulator and a conductor.

Figure 5.9: The annotation for the class Semiconductor

3. **Inserting Subclasses**

Furthermore, the subclasses were as well added in a similar way. The process followed for one of the subclasses will be exemplified:

(a) In the "**Classes**" window press the class `CO2_Savings`;

(b) Click "**Add subclass**" button as shown in Figure 5.7 and wrote the desired subclasses one by one. The subclasses of `CO2_Savings` were `Electric_Means_Transportation, Battery_Longer-_Lifespan, Optimized_Charging`;

(c) The process was repeated for the classes `Functional_Block and Vehicle` as shown in Figure 5.10.

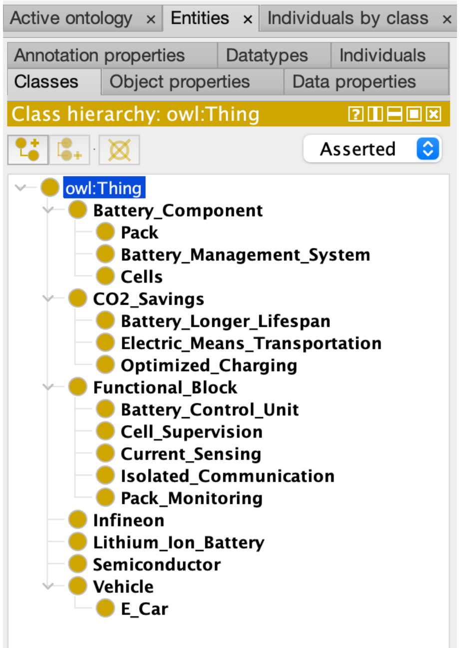


Figure 5.10: Subclasses

4. **Inserting Individuals**

In order to add individuals to the BMS ontology, the following steps are required:

(a) In the **Entities** tab, open the **Individuals** window;

(b) Click "**Add Individual**" button as shown in Figure 5.11 and then wrote the desired elements one by one. In this case, the individuals added, represented in Figure 5.12, were `AURIX`, `KP256`, `OPTIREG`, `PSoC HVPA`, `TLE012DQU`, `TLE015DQU`, `TLE4972`;

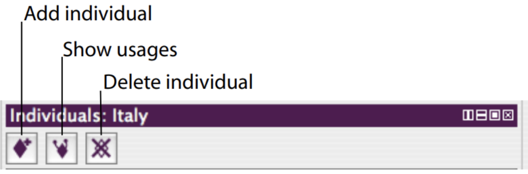


Figure 5.11: Individuals panel buttons

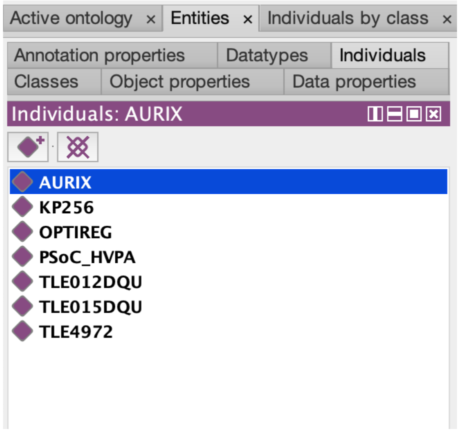


Figure 5.12: Individuals in Protégé

5. **Object Properties**

Finally, the object properties, which define the link between instances, were added to the BMS ontology by performing the following steps:

(a) In the **Entities** tab, open the **Object Properties** window like shown in Figure 5.13;

(b) Click "**Add Object Property**" button as shown in Figure 5.14;

(c) Adding a domain and range to each property was done in the "**Property description view**", in the bottom right corner of the Figure 5.13. Then, by pressing the icon (+) next to "**Domain**" and "**Range**" was added the desired information. For instance, the property `is_part_of_battery` has as domains the classes `Cells, Pack, Battery_Management_System` and range the class `Lithium_Ion_Battery`;

(d) The process was repeated for all the object properties represented in Table 5.2.

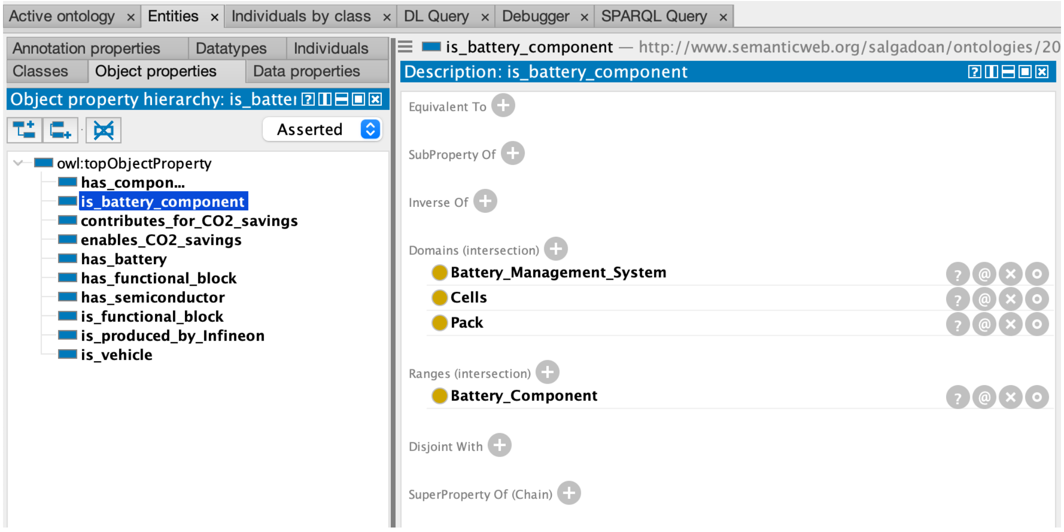


Figure 5.13: Object Properties Window

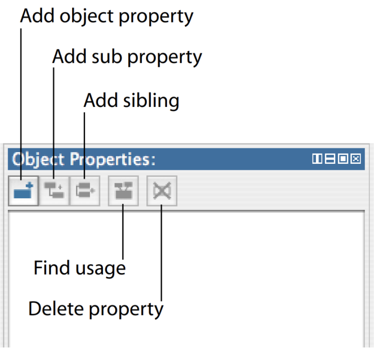


Figure 5.14: Object Properties panel buttons

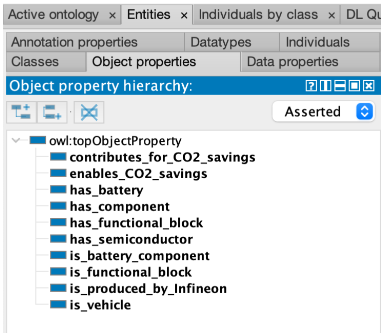


Figure 5.15: Object properties in Protégé

5.3 Software ontology validation

After defining all the classes, subclasses and object properties, the ontology model needs to be validated in order to check its coherence, before the transfer into the Protégé. It was done in two ways: first, by testing the model through queries and verifying the results. Secondly, the expert validation, as all this process was supervised by Dr. Eng. Mahmoud Ismail, the Global Application Director of the Automotive Energy Management Systems department at Infineon. All the structure and all parts of the ontology were analysed, concluding the validation of the BMS ontology.

One way to verify the model is through the use of queries. In this case by turning the competency questions, formulated in the beginning, into queries. If the answers are as expected, it means the ontology is correctly connected and formulated. In this work, these queries were written with the support of GraphDB software. After a brief theoretical background to the SPARQL, the formulation of the queries will be presented together with the corresponding answers.

5.3.1 SPARQL - Theoretical Background

As described in Chapter 3, SPARQL is the standard query language and protocol for Linked Open Data and RDF databases, namely to query a great variety of data. It can efficiently extract information hidden in non-uniform data, that can be in the graph shape manner. This graphs are a set of triples and RDF is a standardized syntax to represent data on the Web. RDFs include a resource (the subject, which has the URI), a description (predicates which are the attributes) and a framework (object that is the literal that the subject is related to). SPARQL allows the withdraw of information from the Web of Data.

The structure of a SPARQL Query can be the following [107]:

1. Defining the `PREFIX` of the used URIs, so that it is not necessary to type every time these are mentioned;

2. Define the type of query, which can be a `SELECT, CONSTRUCT, DESCRIBE or ASK`;

3. Choose the variables, i.e. what to search. SPARQL variables are prefixed with a `?` or a `$`;

4. Finally, the `WHERE` clause, which are the RDF triple patterns.

5.3.2 Queries development

On the first section of this chapter were presented the competency questions, formulated in the beginning of the process. These questions cover key aspects of the domain and were designed to evaluate the ontology's ability to provide accurate and meaningful questions. The query used was of the type `SELECT`, on all the queries formulated, these were: 1.What are the functional blocks of a BMS? 2.Which semiconductors are included in the BMS? 3.How can the BMS contribute to CO2 savings?

Below, it is possible to see the formulated queries and its results, which are a table of all the elements that satisfy the stated conditions. For example, the result of the first query is a list of the functional blocks that belong to the BMS, see Figure 5.16.

1. What are the functional blocks of a BMS?

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX : <http://www.semanticweb.org/salgadoan/ontologies/2022/8/untitled-
    ontology-17#>
SELECT ?Functional_Blocks
WHERE {
?Functional_Blocks rdfs:subClassOf :Functional_Block.
}
```

Listing 5.1: Query of the first competency question - GraphDB Environment

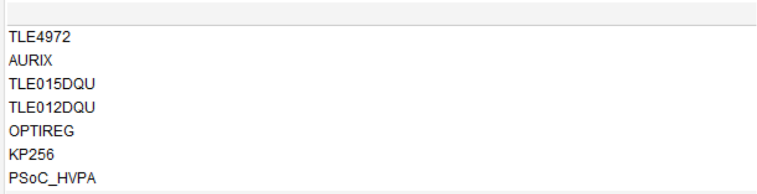
```
Cell_Supervision
Battery_Control_Unit
Pack_Monitoring
Isolated_Communication
Current_Sensing
```

Figure 5.16: Query answer for the constituent Functional Blocks - Protégé Environment

2. Which semiconductors are included in the BMS?

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX : <http://www.semanticweb.org/salgadoan/ontologies/2022/8/untitled-
    ontology-17#>
SELECT ?Semiconductors
WHERE {?Semiconductors rdf:type :Semiconductor.}
```

Listing 5.2: Query of the second competency question - GraphDB Environment



```
TLE4972
AURIX
TLE015DQU
TLE012DQU
OPTIREG
KP256
PSoC_HVPA
```

Figure 5.17: Query answer for the Semiconductores - Protégé Environment

3. How can the BMS contribute to CO2 savings?

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX : <http://www.semanticweb.org/salgadoan/ontologies/2022/8/untitled-
    ontology-17#>
SELECT ?CO2_Savings
WHERE {
?CO2_Savings rdfs:subClassOf :CO2_Savings
}
```

Listing 5.3: Query of the third competency question - GraphDB Environment

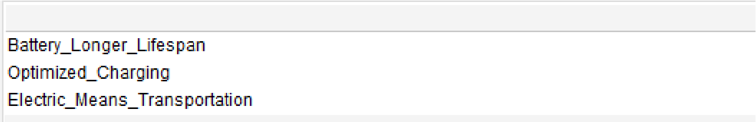

Battery_Longer_Lifespan
Optimized_Charging
Electric_Means_Transportation

Figure 5.18: Query answer for the CO2 Savings - Protégé Environment

All the queries performed returned the expected results correctly. It can be concluded that there is confidence that the BMS ontology is strongly linked and coherent. These queries are an example of an easy extraction of information from this ontology. Such tool can increase the time-efficiency when performing an environmental study, for instance, a life-cycle assessment, in order to know the architecture of the product. This studies are crucial to monitor the footprint of the produce goods, ensuring sustainability in supply chains.

5.4 Ontology merge into the Digital Reference

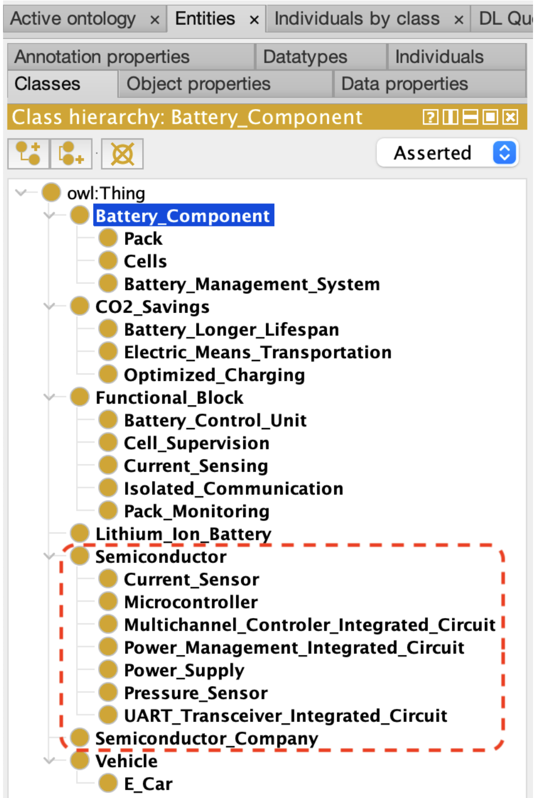
The proposed BMS ontology was formulated taking into account the specificities of Infineon's products. However, its integration into the DR, is only achievable with some adjustments. Note that a generic ontology should be considered, in order to be used by any involved player. The DR is a digital representation of semiconductor supply chains and supply chains containing semiconductors, used by most manufacturers and their retailers. It is, therefore, a digital platform for general use, involving multiple agents and including a huge variety of semiconductor devices, which are used in a wide variety of products and solutions. For that reason it must have high levels of compatibility and usability. Therefore, the adjustments made will be towards the generalization of the ontology.

In Table 5.3 is represented the old ontology (lower level of generalization), which is called ”Infineon's ontology”, and on the right sided column, the new designed ontology, the ”Digital Reference ontology”, having a higher level of generalization. For instance, all the semiconductors (classified as individuals as they represent unique instances) were substituted by a more generalized designation, its type of semiconductor. For example, the semiconductor ”TLE4972” is, in fact, a current sensor. The same reasoning was applied to the remaining semiconductors. The class ”Infineon” was as well substituted by the class ”Semiconductor Company”, as the DR can be used by many players of this industry. The new subclasses are listed under the column ”Digital Reference ontology”.

The new Protégé environment is represented in Figure 5.19 and the changes are highlighted in red. The digital twin is organized in topic clusters, represents all phases of the supply chain and offers a knowledge base that is accessible to both computers and people [108]. It is an ontology in expansion, which integrates multiple ontologies, like represented in Figure 5.20.

Table 5.3: Changes in the old ontology

Infineon´s ontology	Digital Reference ontology
`TLE4972`	`Current_Sensor`
`AURIX`	`Microcontroller`
`OPTIREG`	`Power_Supply`
`TLE012DQU`	`Multichannel_Controller_Integrated_Circuit`
`PSoC HVPA`	`Power_Management_Integrated_Circuit`
`KP256`	`Pressure_Sensor`
`TLE015DQU`	`UART_Transceiver_Integrated_Circuit`
`Infineon`	`Semiconductor_Company`



Class hierarchy: Battery_Component

- owl:Thing
  - Battery_Component
    - Pack
    - Cells
    - Battery_Management_System
  - CO2_Savings
    - Battery_Longer_Lifespan
    - Electric_Means_Transportation
    - Optimized_Charging
  - Functional_Block
    - Battery_Control_Unit
    - Cell_Supervision
    - Current_Sensing
    - Isolated_Communication
    - Pack_Monitoring
  - Lithium_Ion_Battery
  - Semiconductor
    - Current_Sensor
    - Microcontroller
    - Multichannel_Controler_Integrated_Circuit
    - Power_Management_Integrated_Circuit
    - Power_Supply
    - Pressure_Sensor
    - UART_Transceiver_Integrated_Circuit
  - Semiconductor_Company
  - Vehicle
    - E_Car

Figure 5.19: Digital Reference ontology - classes and subclasses in the Protégé

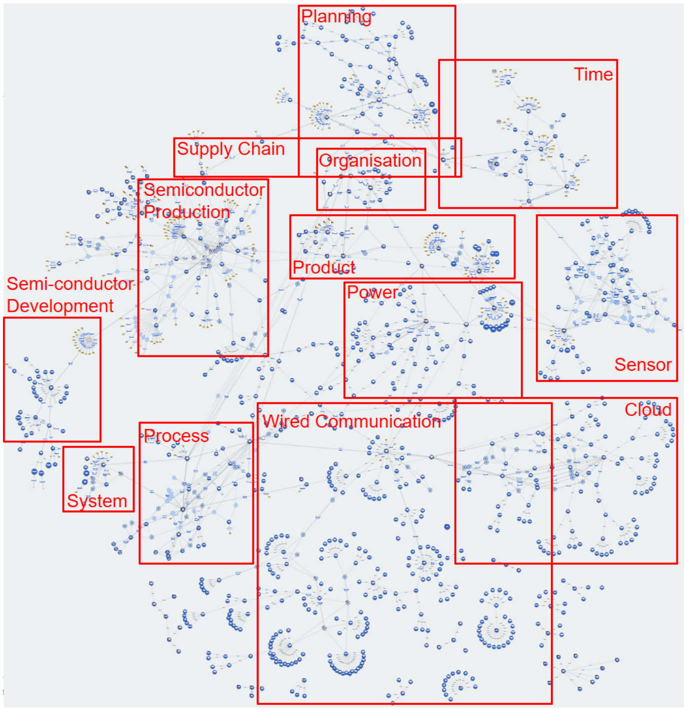


Figure 5.20: The Digital Reference

With the above changes, the BMS ontology got ready to be included into the Digital Reference (DR). All project files were handed over to the DR maintenance team for validation and inclusion in the system. With their approval, this ontology was included in the DR, a moment where it started to be used by all. A common class was selected as a merging point, in this case, the `E-Car` class.

The steps to follow in order to merge two ontologies in the Protégé were:

1. Open the Protégé window;
2. Press the option "**Refractor**" as shown in Figure 5.21;
3. Find the option "**Merge Ontologies**" and click.

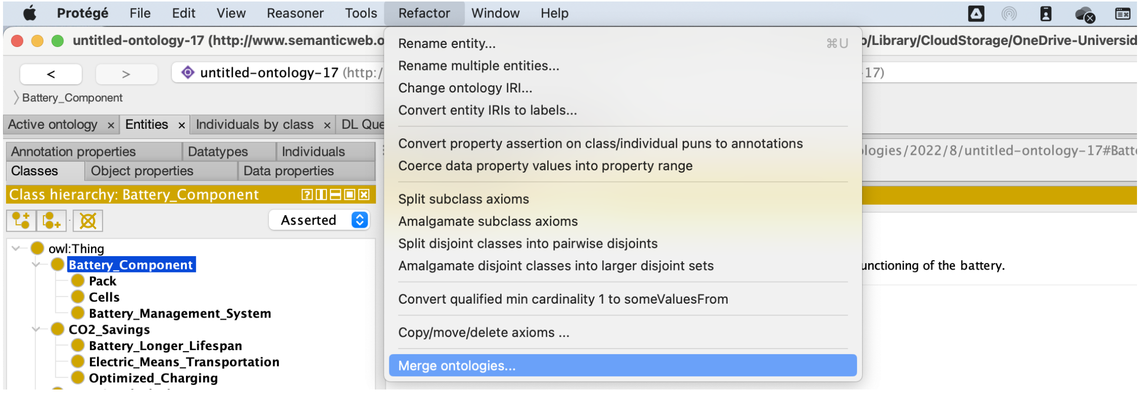


Figure 5.21: Ontology merge - Protégé Environment

The BMS ontology was built on an architecture that highlights the potential CO2 emission reduction values. Its representation was chosen to be taken as standard and its architecture to be easy to read and understand.

5.5 The impact of the digitalization of the BMS

The present work, through the development of the BMS ontology in the semiconductor digital twin, the DR, contributed as a step towards digitalization. Digital twins allow the test of physical systems with virtual simulations, representing a contribution towards process optimization, cost reduction and real-time monitoring. The digital BMS contributes towards a standardized and structured approach to knowledge representation and management and vocabulary standardization. The fact that this device is now represented in a more granular and detailed way, allows a higher control and monitorization in its manufacturing. This can lead to faster responses to possible supply disruptions and consequent cost savings. The reduction of disruptions in supply chains contributes to making them more environmentally friendly by minimizing wastage and inefficiencies. By enhancing their resilience and ensuring smooth operations, companies can optimize transportation routes, reduce energy consumption, and minimize their overall environmental impact.

The integration of this ontology in the DR improves the holistic view in the semiconductor supply chain as it integrates this device with other systems. Potential bottlenecks and ways of optimizing these networks can be more easily identified. The BMS was digitalized and its functional blocks were defined in a standardized shape that computers and humans can understand. The architecture of this product can be analyzed in detail, and processes towards its assembly can turn out to be more efficient and, therefore, more green.

5.6 Chapter Summary

In this chapter, the method used to design the BMS ontology was described in detail. Firstly, defining the domain and scope, then, creating the competency questions and finally, listing the terms that will be included in the ontology and defining the hierarchy. Along this process, it was as well necessary to analyze in detail the architecture of a BMS, so that all its components were included in its digital representation. The software used was introduced and its environment exemplified graphically. The ontology created was submitted to a generalization process, in order to be included into the semiconductor digital twin, the DR. The ontology with a higher-level of generalization was successfully completed and merged into the DR. One more semiconductor end-application was digitalized, contributing to the expansion and development of the EU-funded project Productive 4.0, more specifically for the DR system, allowing an higher efficiency as well as environmental control of the system.

6

Conclusions and future work

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Political decisions, stemming from the Paris Agreement, are being taken daily aiming to reduce the emission of greenhouse gases. The effort of reversing global warming, at a planetary level, is gigantic and intends to change the energetic paradigm towards cleaner energy sources. This work had the objective of contributing to the evaluation of the carbon footprint of the semiconductors and to propose an ontology that has as base the semiconductors constituents of a BMS. In this way, it is possible to assess the impact that semiconductors have in reducing the carbon footprint of an equipment and its manufacturing processes. This chapter presents the main conclusions of the work carried out and its future continuity.

6.1 Main Conclusions

The rise of the average temperature of our planet and its consequences require a drastic change in our lifestyle and the switch from fossil fuels to the clean energies. The EU is in favour of a ”low-carbon, more resource-efficient and sustainable economy” aligned with the Paris Agreement and the 2030 UN Sustainable Development Goals. The investment made by EU and its members is the highest in the world, being around 23 billion euros in 2021. The EU climate goals are [109]: (1) To become climate-neutral by 2050; (2) Reduce its emissions by 55% by 2030; (3) Assuring that until 2027, 30% of the EU’s expenses will be applied to climate-related projects.

To achieve the above-mentioned goals, a new industrial revolution is needed, where semiconductors will play a key role. Assessing the impact of semiconductors in reducing the carbon footprint was the focus of this research. The developed research was within the Productive 4.0 EU funded project that aims to promote the development of digital solutions for the world of real applications, exploiting the potential of digital industry where environmental goals were also pursued. Included in this project, a Digital Reference was created as ”*lingua franca*” for digitalising semiconductors’ supply chains.

Having the BMS as case study, this work is a contribution to the project in two fronts:

1. An environmental analysis which proved that semiconductors can be allies in the transition to a more electrified and green world, despite their carbonic footprint;
2. The development of an ontology including the BMS CO2 savings, proving the digitalization is a determining factor for sustainability practises and a smooth information flow.

The environmental analysis showed that the semiconductors are indispensable to BMS and essential towards the carbon footprint reduction. In this case, they simultaneously improve the energetic efficiency, the safety and the batteries cells' lifespan. The estimation of CO2 savings was computed, showing values that prove the importance of the BMS and its semiconductors. The three BMS potential CO2 savings are: (1) in a greener transportation sector (BEV, PHEV and HEV), contributing to the carbonic neutralization of this sector; (2) longer lifespan to the LIB (a healthier battery boosts a longer life-cycle and a potential second life) and (3) optimized charging of batteries, keeping temperature and voltage within desired intervals.

The ontology was developed with the free, open-source ontology editor and framework for building intelligent systems, the Protégé software. Infineon's scientific literature was also used as support. After the validation, the ontology was merged into the DR. To validate the ontology, it was used a set of competency questions, formulated in the beginning of ontology design, which were later turned into queries, that were used to validated the model developed. The DR is a useful tool to measure and collect relevant data of semiconductors devices, from the manufacturers, through markets and until end-consumers.

In summary, this work presents a study that highlights the importance of semiconductors as fundamental devices in our society. The BMS, used as case study, proves this dependence. Its design was described in detail and the ontology developed validated and integrated into the digital reference. With this solution, the semiconductor technology sector has now a useful tool available for the analysis and study of its semiconductor market with the advantage of including the parameters that contribute for CO2 savings, achieved by its chips.

6.2 Future work

This dissertation is a final product of a work that intends to know the role semiconductors can have in the energetic transition to a greener planet. Changes in technology and energy sources are currently taking place, from polluting fossil fuels to clean energies. However, uncertainties still remain in which paths to take and in the choice of best decisions, in order to consummate this transition. This work provides answers to some of these questions, namely about the benefit of semiconductors, included in the BMS, being an essential part of battery systems that support the electrification of most human activities, particularly the electric vehicles, industrial machinery and our homes. Despite much of what has been done in this work, more ideas, lines of research and achievements arise daily. Other ideas await their maturation to be presented to the scientific and technological community.

Further research:

- More quantitative analysis of semiconductor carbon emissions and savings, e.g. through the development of a life-cycle assessment.
- Development of new ontologies for devices from other sectors, involving industry, supply chains and consumers.
- Comparing the carbon footprint of BMS semiconductors between various manufacturers.
- Account the carbon footprint in the product's end of life including other scenarios such as recycling.

This will contribute to enhance the digitalization of the semiconductors supply chain and to the creation of a more sustainable system.

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