The Vehicle Platform Architecting Process: Will Model Based Systems Engineering help organizations with the architectural transition from ICE to battery power?

by

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Submitted to the System Design & Management Program
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ABSTRACT

The CO₂ emission reduction regulation set for automakers led them to develop BEVs on modified Internal Combustion Engine (ICE) platforms between the late 1990’s and early 2010’s. However, a long-term strategy to be competitive on range in the market demanded the development of BEV-dedicated platforms. Legacy OEMs (Toyota, VW, GM, and others), in theory, had deep process experience architecting vehicle platforms. The challenge from their perspective was to adapt that process to a new architecture and power source and to react to other recent technologies trending in the market. By contrast, the new market entrants (Tesla, Rivian, BYD, etc.) had almost no process experience but were unencumbered by compatibility with legacy platforms. The modules and software required to power BEVs make them more complex than ICEVs despite the fewer pieces in their powertrain. A series of interviews with Systems Engineering experts in the automotive industry were held to understand the differences in the architecting process between ICEs and BEVs. In the study, 45% of the interviewees claimed that BEVs are more challenging to architect than ICEVs, another 45% stated exactly the opposite, and the remaining 10% stated that the difficulty level is the same for both. Additionally, over 80% of the participants stated that an architectural change in a BEV is as smooth as in an ICEV. The study suggests that the architecting difficulty perception between ICEVs and BEVs is linked to the experience of the companies as well as some practices like module incompatibility tracking and key interface identification that happen during the architecting process.

Model-Based Systems Engineering (MBSE) is a methodology largely developed in the Aerospace industry, but which presents a potential solution for managing the increased complexity of BEV-dedicated platforms. During an MIT MBSE course, 5,379 professionals have been surveyed from 2017 to 2024. The data from these surveys was analyzed to identify trends in MBSE adoption over time. The study revealed that MBSE adoption has increased at a rate of 4.11% annually across several industries and has been used primarily for the transformation of processes and workflows. The MBSE implementation in the automotive industry is around 15% higher than in other sectors. However, it has not experienced growth over the past four years. The study also suggests that the main challenges to extending the MBSE adoption are the lack of guidelines and the low credibility of models. Nevertheless, survey respondents remain positive about this approach; between 60% and 70% of them think...
that their companies should implement MBSE, suggesting a future increase in its adoption and an important role of this methodology in managing new BEV-dedicated platforms’ complexity.

Thesis supervisor: Bruce G. Cameron
Title: System Architecture Group Director
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Chapter I

1 Introduction

The automotive industry is undergoing another significant transformation, probably the most important after the introduction of the Internal Combustion Engine (ICE) in the XIX century. It is now leaving the Internal Combustion Engines behind to adopt lithium-ion batteries as the primary power source.

Even though the development of electric cars started in 1881, their limited speed and insufficient range were rapidly surpassed in the twentieth century by the ICE vehicles, which are still dominant in the market (Enge et al., 2021). However, some countries and regions worldwide have recently imposed restrictions and regulations to reduce CO2 emissions. The European Union, for instance, has established a target of 0 gCO2/km starting in 2035 (European Commission, n.d.), whereas California will sell only zero-emissions vehicles by 2035 (California Air Resources Board, n.d.). In 2021, the transportation sector accounted for 29% of the greenhouse gas emissions. Of that, 58% came from light-duty vehicles (US EPA, 2015).

These regulations have created a market niche in the automotive industry. Since Tesla launched its Roadster in 2008, start-ups like Rivian (2009), Lucid Motors (2014), and Canoo (2018) have been founded with the promise of creating electric vehicles. Furthermore, many Original Equipment Manufacturers (OEMs) have joined the electrification race with significant investments in Research and Development (R&D) and new facilities. In 2022, Volkswagen invested 53.57 billion dollars towards EVs, followed by Ford and BYD, with 47.72 and 44.66 billion dollars, respectively (EV Investment by Manufacturer 2022, 2023).

The energy transition in the automobile sector has not only brought opportunities for OEMs but also challenges when transforming the vehicle powertrain. While all-electric vehicle
companies designed new platforms from a clean sheet, larger and more experienced OEMs like Nissan, General Motors, and Renault decided to modify existing lines and platforms to generate ICE-based electric versions. While this strategy allowed them to avoid large capital investment, share components with ICE vehicles, and use the same manufacturing facilities, it brought some difficulties. There was space in the rear designated for a fuel tank but not enough room for a big battery. A space designed for a radiator now had to become a trunk for storage (McElroy, 2022). The Nissan Leaf, for instance, was built on the same platform as the ICE Versa, and the Chevrolet Volt was based on the Cruze platform for complexity reduction purposes. Both cases carried additional structural mass and volume that were unused in the EV configuration.

Other OEMs have started to design flexible platforms that can share ICE and BEV vehicles. By doing this, car companies can mitigate the risk of EV demand deceleration, although the design and performance spread achievable from a single platform might be limited. Geely Holding Group follows this strategy with its Compact Modular Architecture (CMA), which carries the Volvo C40 and the Polestar 2 (Gaton, 2022).

Conversely, many carmakers have opted for BEV-dedicated platforms to optimize battery packaging and, thus, energy density and range. For example, Ford filed a “Vehicle Chassis with Interchangeable Performance Packages and Related Methods” patent in January of 2024, similar to the Global EV Ultium Platform announced by General Motors in 2020. Like the American automakers, Hyundai launched its E-GMP platform to expand its electric vehicles portfolio, and the alliance Renault–Nissan - Mitsubishi plans to build 35 EV models by 2030 using four different BEV dedicated platforms (Renault-Nissan-Mitsubishi, 2022). According to a study developed by Bloomberg, dedicated platforms reduce costs by 10% to 30% because vehicles are designed to manufacture, and components are ordered in higher volumes (Transport and Environment, 2021). Another advantage of a dedicated platform is the battery pack’s rectangular geometry, which enables modularization to achieve different ranges and a flat floor that provides more space inside the vehicle (Loukas, 2022).
While an S&P Global survey shows that the consumer willingness to acquire an EV has dropped from 86% in 2021 to 67% in 2023, it is also estimated that the market share of electric light vehicles will increase to between 39% and 50% in 2030 (Jeff Meyer et al., 2024). This projection suggests an increment in the volume of BEV components that will allow car companies to opt for dedicated platforms, increasing efficiencies.

Martin Peter defines a vehicle platform as “...the sum of all common components, systems, and functions across different vehicle models” (Martin Peter, 2022). Usually, each platform has its own architecture, which is an essential differentiator of an OEM’s strategy. In the literature, the terms architecture and platform might be used indistinctly (Schuh et al., 2016). In the case of BEV, a common concept is the Skateboard, which integrates the power source and the electric powertrain with the chassis. After being revealed by General Motors in 2002, it has been used by other companies due to its flexibility in adjusting to different vehicle sizes (Husain, 2021).

The Architecting Process of a platform must be aligned with the company's goals. It captures the needs of the stakeholders through requirements and lays the groundwork for the Engineering Development to achieve an expected performance and avoid costly unplanned iterations later in the process. The fewer components of an electric vehicle, along with its faster assembly process, could suggest that its architecting process might be simpler or at least different. The powertrain of an ICE relies on liquid fuel, and its heart is the engine, which is often located at the front end of the vehicle. On the other hand, the BEV’s powertrain relies on electricity and is centered on the battery due to its packaging constraints, weight, and cost. The battery’s modularity provides flexibility and is usually located under the vehicle. These, among other drivers, suggest that carmakers should follow a different architecting process for their new dedicated BEV platforms.

Daniilidis et al. propose a process to define a modular platform strategy in four steps based on the Structural Complexity Management concept that allows companies to deal with abstract high-level issues (Daniilidis et al., 2012). Schuh et al. present conceptual structural features (CSF) essential in modular platform development because they provide exogenous
factors and company-specific targets. The authors claim that companies are more likely to reach their targets by incorporating these CSFs (Schuh et al., 2016). Furthermore, Simpson et al. compile some methods and tools that have been researched for the modular platform architecting process, like the Design Structure Matrix and the Quality Function Deployment (Simpson et al., 2014). While these and other academic authors have published methodologies and approaches to optimize the platform architecting process, there is no evidence that the automobile industry is following any of them to develop new BEV-dedicated platforms.

Along with electrification, software development, connectivity, and new technologies are raising the vehicle’s complexity. In order to manage this complexity throughout the architecting process, conventional methodologies are not enough as they focus only on one domain (Góngora et al., 2012; Krog, Suden, et al., 2022). Model-Based Systems Engineering (MBSE) has been adopted in several industries over the years and is considered a promising approach for the automotive industry. Krog et al. suggest the use of MBSE during the vehicle concept development to achieve a holistic Vehicle Systems Architecture (VSA) that considers software, electrical and electronic, and mechanical or geometric domains (Krog, Suden, et al., 2022; Krog, Şahin, et al., 2022). By following this approach, the information used across the teams in a company would be centralized in a model rather than divided into individual documents. This makes it easy to integrate requirement databases and improve the traceability of changes. Furthermore, a platform can be developed with only one model to support variants in a product line (D’Ambrosio & Soremekun, 2017).

This thesis will survey the architecting processes OEMs and Tier 1 suppliers follow on their new BEV-dedicated platforms and analyze data from an MIT MBSE course survey. Specifically, it will answer the two research questions:

- Do we expect OEMs and Tier 1 suppliers to use a different process to architect EVs, as compared with ICE vehicles?
• *Does the shift towards EVs, with more clean-sheet designs and newer OEMs, suggest that adoption of MBSE is more likely as a modeling advance, or do we expect that the relative simplicity of EVs is unlikely to create a pull for MBSE adoption?*

These questions will be answered within two phases. The first phase will answer the first question by analyzing data collected during interviews with architects from OEMs and Tier 1 supplier companies to understand the differences and similarities between firms.

The second phase will answer the second question by analyzing responses obtained surveying participants of an MBSE course delivered by MIT. The analysis will serve to understand the level of MBSE adoption in the industry and compare the status of MBSE between the automotive and other industries.
Chapter II

2 Literature Review

The objective of this chapter is to provide the reader with an overview of the research that several authors have done regarding the architecting process of a vehicle and related topics such as modularity and model-based systems engineering. In preparation for chapters three and four, some concepts are presented here: Automotive platform, automotive platform architecture, modular platform, architecting process, and Model-Based Systems Engineering.

2.1 Automotive platform

Usually, when a new product is introduced to the market, there is only one version that the early adopters use, and if successful, the product makes its way toward other segments and markets. Once this product becomes more popular, new competitors arise and launch their products, and the original producer needs to offer more to the market to compete. Companies must usually diversify their products and create different versions to satisfy various market segments and remain relevant. Creating these variants increases a product's complexity and might increase engineering and manufacturing costs.

To be able to manage the increasing complexity of their products in the most efficient way possible, companies have adopted a Platform strategy, which consists of making components and processes common across several products with the objective of reducing costs, increase efficiency, enable mass production and thus, reduce manufacturing time (Gonzalez-Zugasti et al., 2000; Küpper et al., 2021; Sihem Ben Mahmoud-Jouini, 2010).

This strategy is used for a wide range of products, from smartphones to airplanes. In the case of the automotive industry, the objective is to have a platform on which many vehicles
can be based, from sedans and trucks to utility vehicles. Usually, the components of a vehicle platform are the underbody structure, the powertrain, the suspension, and other driveline elements. Despite the fact that these components are shared, if a platform strategy is done correctly, all vehicles using the platform will be differentiated and offer unique characteristics to the customer (Brylawski, 1999; Küpper et al., 2021).

Some examples of automotive platform strategies come from legacy automakers. Ford developed the Fusion and the Lincoln MKZ on the same platform. The same happened with the Chevrolet Camaro and Cadillac ATS by GM and the Audi A3 and Golf by VW (Walters & Helman, 2023).

Despite all the advantages a platform strategy can provide, it is necessary to carefully balance the commonality of components and the differentiation among products. If customers notice insufficient differentiation between products, their willingness to pay for a more premium car would decrease.

2.2 Automotive platform architecture

The architecture of a product or system can be defined as the descriptive form in which system elements are organized, including the interactions among them and the functions they perform to achieve an outcome as a whole (Crawley et al., 2016). Every system has an architecture regardless of its size; what can vary is the number of elements in the system and, thus, its complexity. In the case of a current car, the number of elements goes beyond thousands, which makes it a highly complex system.

One possible way to describe and analyze an architecture is by decomposing it into different levels, which can be further decomposed into sublevels. This decomposition is equivalent to what is known in systems engineering as system, subsystem, and component levels. Additionally, it is possible to decompose a system according to its functions, its
components or the interactions among components, which can be energy, material or information (Gorbea Díaz, n.d.).

Vehicles, particularly the most recent ones, have more than one architecture depending on the domain. There is a hardware architecture that includes the physical components, a software architecture that entails the lines of code or software modules, and also the Electrical and Electronic (E/E) architecture, which is formed by both hardware and software components (Askaripoor et al., 2022; Eder et al., 2018; Mudhivarthi et al., 2023). Even though they are usually referred to as separated architectures, recent literature proposes they are treated and considered together as a cyber-physical system (Zellmer et al., 2023).

Based on the considerations mentioned before, it is possible to define the vehicle platform architecture as the way in which vehicle modules are organized and interact with each other. (List of elements that are part of the vehicle platform).

The development of Battery Electric Vehicles (BEV) raised a new challenge for legacy automakers, which had been manufacturing Internal Combustion Engine (ICE) vehicles for decades. Whereas many of the components of a vehicle platform are shared between a BEV and an ICE vehicle, others are specific. To get to the market with an electric proposal, OEMs could modify their existing platforms for ICE vehicles to develop BEVs or start a completely new platform exclusive to BEVs. Both approaches are detailed below.

### 2.2.1 ICE-modified platform

The increasing regulations from governments worldwide, along with the rise of BEV-focused startups, put pressure on OEMs to start the development of BEVs. Two options were available: modifying existing ICE platforms to integrate BEV elements and remove ICE components or starting a platform from a clean sheet. This is not a trivial decision as the investment and the risk of not meeting the market demand are high. Moreover, legacy OEMs need to find a balance between producing ICEVs, which are profitable, and BEVs, which are demanded by the market. The cost of producing a BEV is higher than that of an ICE, primarily
due to the battery pack cost. On top of that, car companies must continue investing in other features necessary for consumers like connectivity and autonomy. *(Electrifying Insights: How Automakers Can Drive Electrified Vehicle Sales and Profitability | McKinsey, n.d.)*

Modifying an existing platform used for ICEVs presents many advantages for automakers. First, although changes to the assembly lines are necessary, they are not as drastic and do not require a significant investment compared to creating a new production line for a new platform. Moreover, in terms of design, carmakers could keep most of the vehicle platform and remove the engine, the transmission, the fuel tank, and fuel lines to package BEV elements like the motors and the battery. Even though these adaptations would require time, getting to the market with an electric vehicle was much faster. As shown in Figure 2.2-1, BEV and ICE powertrain components are packaged in the vehicle to support all variants.

Lastly, and possibly the most important advantage for OEMs, is risk mitigation. While EV sales have proliferated, it is uncertain whether the market will keep the same growth rate. An ICE-modified platform allows companies to adjust production volumes with relatively minimal effort if BEV demand falls. *(Els, 2019)*

As it is to expect, all these advantages come with a downside. An ICE-based BEV may have poor performance and a low range because of its battery size. The battery cannot be bigger because of the limited space caused by the ICEV design. In addition, a battery’s weight alters the vehicle’s dynamics, and vehicles can be limited to specific drivetrains.

Toyota followed this strategy with its RAV4 in 1997 and later in 2012, using the RAV4 ICE platform and integrating an electric powertrain provided by Tesla *(Smet, 2024)*. Among other OEMs that decided to pursue this strategy are BMW with the Cluster Architecture (CLAR) platform, Jaguar Land Rover with the Modular Longitudinal Architecture (MLA), the PSA group, now Stellantis, with its Efficient Modular Platform (EMP2), and Volvo with the Compact Modular Architecture (CMA). These multi-energy platforms can accommodate ICEVs, hybrids, and BEVs. *(Els, 2019; Gauthier, 2018; Holmes, 2018; Modular Multi-Energy Platforms, n.d.; Platform Sharing, 2022)*
2.2.2 BEV-dedicated platform

The second alternative to satisfy the electric vehicle market and the CO2 emission reduction regulations is to develop an entirely new BEV-dedicated platform. This fresh canvas offers OEMs the opportunity to design an efficient, high-performance, and flexible platform capable of accommodating several body styles, from sedans to SUVs.

A BEV powertrain is quieter and simpler than an ICE, thanks to its fewer moving parts and lower maintenance costs. Also, from a design perspective, a BEV purpose-built platform enables the removal of redundancies that are present in a modified ICE platform.

The battery geometry is the main reason a BEV-dedicated platform can deliver a better performance in terms of range. Opposite to an ICE platform, a pure BEV platform does not have the transmission, the exhaust, and the center tunnel to accommodate the driveline.
Therefore, there is enough room to package a rectangular battery, 25% larger than one in an ICE-modified platform, as shown in Figure 2.2-2 (Trends in Electric-Vehicle Design | McKinsey, n.d.). Consequently, the vehicle’s energy capacity increases and a more extended range can be achieved. The battery pack also provides the flexibility to build vehicles with different energy requirements and the same battery dimension, only changing the number of active cells. Another benefit is the possibility of customizing the drivetrains, offering front-wheel drive, rear-wheel drive, and all-wheel drive configurations. (Elektroautos: Trends in Electric Vehicle Design | McKinsey, n.d.)

Batteries of native electric vehicles require less compromise and allow for greater flexibility.

Source: A2Mac1; McKinsey Center for Future Mobility

*Figure 2.2-2 Battery comparison between a modified ICE platform and a BEV-dedicated platform* (Elektroautos: Trends in Electric Vehicle Design | McKinsey, n.d.)

As consumers expect a wide variety of BEV models, car makers need to build new plants to increase capacity. From a financial perspective, building a new BEV plant is less costly than
building a plant with both types of vehicles in the same assembly line because capital expenditure is lower (Els, 2019).

Besides the electrification of the powertrain, a BEV-dedicated platform is an opportunity to increase efficiency by improving the integration across the architecture levels. As in the Tesla Model S, hardware elements like the gearbox, the motor, and the inverter can be integrated. Also, features can be centralized in the Electronic Control Units (ECUs), reducing the number of separated microcontrollers. A centralized E/E architecture enables software development and over-the-air updates, besides reducing material and weight (Elektroautos: Trends in Electric Vehicle Design | McKinsey, n.d.).

With the growing EV sales and the zero-emission targets set in various countries, automakers will eventually phase out ICEVs. Many automakers decided to take the risk and invested in developing BEV-dedicated platforms. One of the pioneers in this move was the Volkswagen group, which invested 7 billion dollars to develop its Modular Electric Drive Matrix (MEB). This platform promises ranges from 330 km to 550 km. Cars like the ID. 3, ID. 4, and Audi Q4 e-tron are based on this platform (Els, 2019; VW’s MEB – “Tesla Inside,” 2019). The MEB design around the battery, the absence of an engine and center tunnel, and the longer wheelbase provide passengers with a flat floor and an ample cabin. For example, the ID. 3 is the size of the Golf with the interior space of the Passat (VW’s MEB – “Tesla Inside,” 2019; Zoia, 2018). In addition to this, the MEB platform leverages data processing by implementing centralized controllers, allowing over-the-air updates (Zoia, 2018).

The Volkswagen Group has developed the Premium Platform Electric for its premium vehicles, which can accommodate higher segment vehicles with better performance. The Porsche Macan and the Audi Q6 e-tron are based on this platform. (VW’s MEB – “Tesla Inside,” 2019)

Developing native BEV platforms also has some downsides. Probably the most relevant is a deceleration in the BEV adoption, which could financially affect OEMs after the investments are made.
Despite the significant investment and lack of profitability, a dedicated platform provides flexibility and performance in the long run. Arguably, fewer components make BEVs more durable as they are not exposed to wear over time.

Apart from the Volkswagen Group, other OEMs invested in BEV native platforms. Daimler created the Electric Vehicle Architecture (EVA2) for its Mercedes-Benz EQS, Renault-Nissan-Mitsubishi developed the Common Module Family (CMF-EV) on which the Ariya is based, and Toyota and Subaru designed the electric Toyota New Global Architecture (e-TNGA) for the bZ4X. (Els, 2019)

Even those companies that started their journey toward electrification by modifying their ICE platforms have announced their coming BEV purpose-built platforms. In 2016, Hyundai, for instance, offered the Ioniq, based on a multi-energy platform with various powertrains (HEV, PHEV, and BEV) before launching the Ioniq 5 on the Electric Global Modular Platform (E-GMP) with a BEV-dedicated architecture. (Willems, 2017)

2.3 Modular platform
One of the strategies for vehicle architecture that has been around since 2012 is the modularization of the platform (Lampón et al., 2019). Modularity refers to managing complex systems by separating the elements of a system into modules with standardized interfaces and identifiable functions, keeping interdependencies within the modules and not across them (Fang & Kim, 2023; Pandremenos et al., 2009; Simpson et al., 2014). This strategy allows for flexibility and versatility (Lampón et al., 2019). The standardization of interfaces is necessary to enable the interchangeability of modules and their independent optimization without affecting the rest of the system. This translates to lower costs because if no design parameters need to be modified, the cost will not propagate to the rest of the modules. This cost propagation can be used as a metric for modularity in a product (Fang & Kim, 2023).
In the automotive industry, small-scale modularity has already been applied in some subassemblies like the doors, fascias, and instrumental panels (Pandremenos et al., 2009). However, when it was applied to the platform strategy, it revolutionized it. While the idea of the conventional platform is to keep some underbody components common for numerous vehicles of the same segment, a modular platform allows compatible modules to change their dimensional parameters to accommodate models of different segments on the same platform. In other words, besides providing horizontal diversity, it provides vertical diversity (Lampón et al., 2019).

Some key benefits of modular platforms are the economies of scope and scale. The economies of scope are achieved using the same resources to produce several models, whereas the economies of scale are obtained due to the volume produced. For this reason, a modular platform strategy could benefit firms with an ample portfolio and produce high volumes or plan to do so. Smaller companies can adopt the strategy, but the benefits will not be as significant. From the production perspective, a modular platform increases efficiency by allowing manufacturing plants to share resources and transfer production from one location to another whenever necessary (Lampón et al., 2019).

The transition toward a modular platform requires resources first to architect the platform and second to modify the assembly lines so that different models can be sequentially assembled.

Some studies have compared the modular platforms of global OEMs and found that although the modularization is not the same in the type and number of modules, there are some similarities in how the platform is partitioned. OEMs like General Motors, Volkswagen, BMW, Daimler, and Volvo adopted a modular strategy in the last decade and segmented the platform into sections like underbody chassis, front floor, rear floor; or front underbody and rear underbody; or front bulkhead and engine bay, main floor and rear unit (Lampón et al., 2019). In an attempt to summarize, many of them have a front section, a middle section, and a rear section. Every section offers different options, making it possible to have several configurations on the same platform. Additionally, as part of the modular
platform definition, the geometric dimensions can be changed to accommodate segments. Carmakers made it possible to change the track width, wheelbase, and even rear overhang in some cases. This degree of modularity allowed OEMs to accommodate more than one segment on the same platform (i.e., B and C, C and D, or even B, C, D). Examples of a modular platform strategy are the platform MBQ by Volkswagen, UKL by BMW, MRA by Daimler, and SPA by Volvo (Lampón et al., 2019).

Even though modularity in the automotive industry started with ICEVs, it has continued to be implemented and even improved with BEVs. A study from 2023 that compared the modularity of ICEVs and BEVs based on the interdependency of their components revealed that although it is thought that BEV-dedicated platforms are more modular due to the fewer elements, they actually present more interdependencies among their design parameters, which makes them less modular (Fang & Kim, 2023).

Despite this, BEVs offer some modularity through the “skateboard” concept. This concept refers to the chassis with the motors, the power electronics, and the battery as the floor. Although this concept was presented in the Autonomy model by General Motors in 2002, it did never go into production. On the other hand, Tesla used the “skateboard” to design the Model S, and other OEMs like Rivian, Hyundai, and GM followed the same strategy. The skateboard design offers versatility to use the same platform to develop multiple body styles (History Of Electric Cars Using Skateboard Platforms - CleanTechnica, n.d.). New developments and players have emerged with the skateboard concept, which can shift how the economic value of vehicles is distributed. While ICEV platforms were designed around the engines, the BEV architectures prioritize the energy storage or battery. Therefore, legacy automakers’ expertise in the internal combustion engine and its powertrain has become irrelevant, and battery and other core module suppliers can claim a more significant portion of the vehicle’s economic value (Fang & Kim, 2023). For example, CATL has developed the CATL Integrated Intelligent Chassis (CIIC), which groups the battery, suspension system, braking system, and motors with the chassis. It is expected that the first vehicle based on this platform will be launched by late 2024 (Opletal, 2023).
Like in any other platform strategy, modularity has its drawbacks. The main ones are maintenance and replacement costs because whenever an element of the module needs to be repaired or replaced, the entire module would need to be substituted, which increases the cost, especially for the consumer. Moreover, there is more dependency on suppliers because they require integration capabilities to deliver components assembled into modules. Additionally, if the customization of modules is prioritized to differentiate models, modularity might cause divergence, which is the reduction of commonality (B. G. Cameron et al., 2017). Finally, a significant amount of time and cost is necessary to design a modular platform.

2.4 Architecting process

It has been mentioned what OEMs need to do to maximize efficiency to produce several models for various segments, sharing components and reducing costs. The next question is how to do it.

Numerous authors cover processes at different levels, from elaborating a family of platforms to specific procedures on how to create modules for a modular platform. Some articles even propose methods and tools for every step of these processes. This section aims to show where the platform architecting takes place in a high-level process and then what steps some authors recommend to follow within the architecting process.

Every car company has a Product Development Process (PDP). Legacy automakers have a more mature one than BEV startups. Nevertheless, all of them follow specific steps to create a vehicle. Despite the differences that may exist between companies, Liang proposes an integrated PDP with five major phases: customer input, conceptual design, detailed design and engineering, manufacturing process and production, and sales and distribution.

The third stage of this framework is divided into eight steps, the first being Product Architecture and Commonality, as shown in Figure 2.4-1. Liang identifies this step as
transforming the vehicle's functions into its forms, one of the major tasks in the process, as it is the starting point of a common platform linking the customer needs and the design specifications (Liang, 2009).

Within the architecting process, some authors suggest a series of steps to translate requirements into a platform. Hölttä-Otto et al. compiled the sequence shown in Table 2-1 (Simpson et al., 2014).

Table 2-1 Architecting process steps, adapted from (Simpson et al., 2014)

<table>
<thead>
<tr>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define market segments</td>
</tr>
<tr>
<td>Market attack plan</td>
</tr>
<tr>
<td>Customer needs</td>
</tr>
<tr>
<td>System requirements definition</td>
</tr>
<tr>
<td>Component alternatives</td>
</tr>
<tr>
<td>Generic system architecture</td>
</tr>
<tr>
<td>Module boundary definitions</td>
</tr>
<tr>
<td>Architecture roadmap</td>
</tr>
<tr>
<td>Commonality assignment</td>
</tr>
<tr>
<td>Architectural module sizing</td>
</tr>
<tr>
<td>Architecture downselection</td>
</tr>
</tbody>
</table>
Figure 2.4-1 Closed-loop product development (Liang, 2009)
This sequence has elements in common with other authors. For example, customer needs, system requirements, boundary definition, and architecture down selection are stages mentioned in other process proposals (Crawley et al., 2016).

A way to represent complex engineering systems with multiple participants is a Design Structure Matrix (DSM), which helps identify the relationships between the tasks of the process (YASSINE A A, 2001). This might be helpful for grouping tasks, optimizing sequences, or reorganizing teams.

The DSM in Figure 2.4-2 was created based on the architecting process steps in the literature. It captures the relationships that exist among the steps of the process. A clustering algorithm was also applied, resulting in four general stages of the architecting process: Goal setting, upstream influences, operations definition, and boundary and interfaces.

While legacy OEMs have followed their own architecting process to develop their platforms, the general stages mentioned below should be covered. Nevertheless, the arrival of BEVs in the automotive industry might represent a transformation point for the architecting process. Although several methods for requirements mapping, modularization, and optimization are...
present in the literature (Simpson et al., 2014), none mention changes in the architecting process for electric vehicles.

There is a possibility that the architecting approach of the engineers who transition from an ICEV to a BEV platform is highly influenced by their existing mental models, while engineers who started working on a BEV architecture from the ground up have a fresh approach that might be more focused on modularity (Fang & Kim, 2023). Although legacy processes are used as a reference, it is essential to ensure that the conditions and requirements of the legacy processes remain valid for the new development (Crawley et al., 2016).

2.5 Model-Based Systems Engineering (MBSE)

Today, the market requires vehicles to have features that involve multiple domains like electronics, mechatronics, and software, becoming cyber-physical systems (Góngora et al., 2013; Krog, Şahin, et al., 2022). Their complexity and difficulty have augmented significantly due to the increasing amount of software they contain, given trends in connectivity, electrification, and automated driving (Brankovic et al., 2021; D’Ambrosio & Soremekun, 2017). These systems of systems need a multidisciplinary process development, and systems engineering methodologies are thought of as one of the possible solutions for companies to manage complexity, improve cost efficiency, and avoid delays in their products while orienting the system development to its customer and functions (D’Ambrosio & Soremekun, 2017; Krog, Şahin, et al., 2022).

In the automotive industry, the introduction of new technologies and the high complexity are accompanied by aggressive competition that demands reduced design cycles, creating conditions for defects to skyrocket. It is no surprise that electrical and software issues lead the list of vehicle recalls (D’Ambrosio & Soremekun, 2017).

Usually, companies have flaws in their systems engineering data management and storage. If documented, the data is captured in several types of documents and stored in local drives
or other distributed repositories (D’Ambrosio & Soremekun, 2017), which fosters the creation of several versions when flowing between activities and domains (Góngora et al., 2013).

Model-based systems engineering (MBSE) is an approach used by INCOSE to formalize modeling in the systems engineering practices (Brankovic et al., 2021). System Engineering provides the principles, and MBSE applies them through a system model for a multidisciplinary development (Krog, Şahin, et al., 2022). It has gained momentum in different industries over the past 20 years (D’Ambrosio & Soremekun, 2017). This approach replaces the documents with models for data capturing. It also helps with numerous activities during the development lifecycle while enabling the reusability of models and easier integration with requirement databases and performance analysis models. Most importantly, MBSE provides a single and up-to-date source of truth on which teams can rely during requirements change, analysis, verification, and validation. These characteristics result in higher quality, increased productivity, and improved communication (Góngora et al., 2013; Krog, Şahin, et al., 2022).

Since MBSE requires a common language, the automotive industry has widely used SysML, whose diagrams use structure, requirements, parametrics, and behaviors to describe a system (D’Ambrosio & Soremekun, 2017). Additionally, it supports viewpoints definition and system decomposition, abstraction, and traceability (Góngora et al., 2013).

Four main challenges have hindered the adoption of MBSE. First, it is not easy to communicate the approach's benefits with evidence. Also, convincing upper management to allocate resources to implement the approach. Moreover, easing the transition of MBSE users by providing adequate interfaces to the data (D’Ambrosio & Soremekun, 2017), and finally, the current lack of consistency and alignment between activities, outputs, and engineering disciplines. Overall, the adoption of MBSE requires a change in organizations and their culture (Góngora et al., 2013).
Some methodologies have been suggested for implementing MBSE, specifically in automotive product development. For example, the Software Platform Embedded Systems (SPES) (Brankovic et al., 2021), the SAGACE (Góngora et al., 2013), and the RFLP (Krog, Şahin, et al., 2022).

These methodologies consist of abstraction layers, views, and viewpoints. These viewpoints are the requirements, functional, logical, and technical in the case of SPES and physical in the case of RFLP. The Requirements viewpoint models the stakeholders' requirements and goals, the Functional viewpoint covers the functions of the systems along with their inputs and outputs, the Logical viewpoint decomposes the functions into logical components, and the Physical or Technical viewpoint translates the logical elements into physical components (Brankovic et al., 2021; Krog, Şahin, et al., 2022). In the case of the SAGACE framework, the viewpoints are operational, functional, constructional, and requirements, and they are equivalent to the RFLP viewpoints (Góngora et al., 2013).

Some OEMs are already adopting an MBSE approach. Last decade, for example, Renault launched an initiative that followed the principles of architecture frameworks and used models to describe them. An architecture framework consists of elements that describe an architecture and explain the procedure to do it. The description should be consistent, homogenous, and unambiguous so that the architecture is understood across an organization. The principles of the architecture frameworks use levels of abstraction as a way to provide structure for the system’s data of specific fields such as defense (Góngora et al., 2013). In the architectural design framework followed by Renault, there are four viewpoints, and a subset of views for each of them are shown in Table 2-2. For the automotive industry, Volkswagen launched an initiative that could be the starting point of an Automotive Architectural Framework. This methodology aims to be used during the concept phase for a multidisciplinary architecture that allows creating a broad portfolio while being applicable to existing processes.
Table 2-2 Architecture framework viewpoints and views (Góngora et al., 2012)

<table>
<thead>
<tr>
<th>Viewpoints</th>
<th>Associated Views</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational</td>
<td>Maximal System Scope</td>
</tr>
<tr>
<td></td>
<td>System Environment</td>
</tr>
<tr>
<td></td>
<td>Operational Context</td>
</tr>
<tr>
<td></td>
<td>External Interfaces</td>
</tr>
<tr>
<td></td>
<td>Use-Cases</td>
</tr>
<tr>
<td></td>
<td>Operational Scenarios</td>
</tr>
<tr>
<td></td>
<td>System Working Modes</td>
</tr>
<tr>
<td>Requirements</td>
<td>Stakeholder Requirements</td>
</tr>
<tr>
<td></td>
<td>High-Level Requirements</td>
</tr>
<tr>
<td></td>
<td>System Technical Requirements</td>
</tr>
<tr>
<td>Functional</td>
<td>Functional Breakdown Structure</td>
</tr>
<tr>
<td></td>
<td>Functional Architecture</td>
</tr>
<tr>
<td>Constructional</td>
<td>Product Breakdown Structure</td>
</tr>
<tr>
<td></td>
<td>Organic Architecture</td>
</tr>
</tbody>
</table>

The Vehicle Systems Architecture (VSA) explains the architecture as part of the vehicle concept development oriented toward systems engineering and MBSE. The Requirements viewpoint of the methodology is the starting point that covers the stakeholders’ demands in different aspects of the business. Then, the VSA lies on the Functional, Logical, and Physical perspectives, as shown in Figure 2.5-1. The Functional perspective covers the marketable features based on the requirements and the technical functions necessary to deliver said features. The Logical perspective places the functions under a solution-neutral architecture that is then addressed with technical solutions from various domains in the Physical perspective. This last perspective is the closest to what has happened most of the time in car companies. It is proposed that a meta-model is created to reflect the methodology through SysML (Krog, Şahin, et al., 2022). Interestingly, this methodology relies on the iterations among the architecture and the requirements, which are desired to be removed from the development processes.

Since the VSA proposed is solution-independent, it aligns with the modular platform strategy OEMs are trying to pursue.
There are some applications of MBSE in the automotive industry, but they are mainly focused on new technologies and smaller subsystems like the Advanced Driver Assistance System (ADAS) (Krog, Şahin, et al., 2022). Therefore, it is expected that MBSE will be emphasized in the BEV development due to the scope change that electrification has caused in the car sector with new technologies and new stakeholders (Góngora et al., 2013).

The architecting process is a critical step in the concept phase of a vehicle and can determine its success or failure. More than a hundred years of experience developing ICEV seems to take the architecting process for granted. Approaches like modularity and MBSE are discussed in several articles, but only some go into detail about the architecting process. However, the advent of BEV-dedicated platforms has set a landmark in the history of the automotive industry due to the changes in vehicle architecture and its context.
Nevertheless, the literature has not covered the impacts on the process of that new architecture. Chapter three of this thesis intends to address this gap.

Furthermore, along with electrification, other technologies are being adopted in vehicle architecture, causing a significant increase in complexity. Although several articles suggest using MBSE to manage this complexity, it has not been discussed whether automakers are adopting MBSE to handle the architecting process of a BEV. This is intended to be answered in chapter four of this thesis.

The purpose of both chapters is to contribute to the existing literature and help answer both gaps to improve the architecting process of future BEV models.
Chapter III

3 ICE and BEV architecting process differences

3.1 Method

Despite the numerous studies and articles regarding vehicle architecture and the approaches used to develop these architectures, there is usually a gap between what is happening in academia and what the industry is implementing. Therefore, to understand the differences in the architecting process between Internal Combustion Engine Vehicles (ICEVs) and Battery Electric Vehicles (BEVs), it was proposed to gather knowledge by interviewing people related to the matter. The collected data was then analyzed to present the results in this chapter.

3.1.1 Data collection

Twenty individuals with years of experience in the automotive industry were identified as appropriate for the interview. It was necessary that the interviewees were familiar with the vehicle architecture, regardless of the domain (e.g., E/E architecture, software architecture, etc.). These engineers work for Original Equipment Manufacturers (OEMs), Tier 1 suppliers, and Autonomous Vehicles (AV) companies. They work in different domains and levels in their organizations. Their names and the companies they belong to were anonymized. However, some population characteristics can be found in Table 3-1.

The interviewees received a questionnaire with 26 questions covering topics from architecture and the architecting process to error tolerance in the architecture evaluation and architectural decisions. The complete list of questions can be seen in Appendix A. The interviews were about one hour long, and the interviewees were free to skip any questions if they were unfamiliar with a particular topic. The interviewer created notes based on the answers to be organized and classified before the analysis.
3.1.1 Demographics

Twenty interviews were conducted with automotive experts, most with experience in the architecting process. The characteristics of the interviewees are presented below to have a better understanding of the profile of the people who were interviewed.

<table>
<thead>
<tr>
<th>Company type</th>
<th>Companies</th>
<th>Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legacy OEM</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>BEV OEM</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Tier 1 supplier</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>AV developer</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The specific roles were Systems Engineer, Systems Architect, Architecture Chief Engineer, and Systems Engineering Leader / Manager, among others.

These individuals were selected based on their experience with systems architecture and the automotive industry.

3.1.2 Data analysis

The participants' responses were organized and categorized based on the questions’ framework shown in Figure 3.1-1. The exploratory questions were open and provided qualitative answers. The interviewer summarized the unexpected and surprising statements and organized them into themes. The questions tied to dependent and independent variables gave both quantitative and qualitative responses. The quantitative responses were quantified, whereas the qualitative answers were categorized. After the classification, the dependent and independent variables were analyzed to find correlations, and the themes were examined, looking for interesting associations with the variables or other phenomena. This section briefly describes the variables and themes included in this study as well as the methods and tools used for the analysis. The insights and findings are presented in the results section.
3.1.2.1 Themes
This study covers two types of themes. The first type is current themes, which were proposed before the interview based on relevant topics for the research. The second type is the new themes, unexpected statements discovered during the interviews, especially from the exploratory questions. The interviewer used the highlighted statements from the interview notes to build the themes. The themes are listed in Figure 3.2-1 and described in this section. The results section covers the insights and potential associations between themes, variables, and other behaviors.
3.1.2.1.1 Current themes
The current themes are those identified as key aspects to answer the research questions before the interviews.

**Architecting process benefits and flaws**

This theme concerns the respondents' understanding of the process of selecting an architecture, the aspects that work well, and the aspects that need improvement according to their experience. This process may change between an ICE and a BEV.

**Level of difficulty in the vehicle design**

This theme is related to the respondents' experience and perception of the complexity of designing a BEV vehicle. The number of components, new technologies, and manufacturing challenges are some of the factors that lead to an increase in the difficulty of designing a car. These factors may vary from an ICE to a BEV.
Architectural decisions

Rather than specifying the architectural decisions made when defining a vehicle platform, this theme is about the respondents' approach toward architectural decisions, how they are managed in the process, and how they have chosen competing decisions.

Iterations

Iterations are inevitably present in the architecting process and this theme is about the stages in which the respondents have encountered more iterations. Besides the stage, it is interesting to understand whether the iterations are initially part of the plan or unexpected.

3.1.2.1.2 New themes

Four new themes were identified from the interviews. Even though they were not considered initially, they are essential to this thesis since they reflect what is happening in the industry and help answer the research questions.

Zone architecture

One of the architecture domains in a vehicle is the E/E architecture. This theme is about a recent approach taken by car manufacturers to redistribute the functions or features in the vehicle by having only one control unit per zone rather than allocating controllers based on vehicle functionality (wherever that functionality takes place).

Model-based systems engineering (MBSE)

Although MBSE is a topic that has been around for a while, its adoption by different industries has been slow, which surfaced as friction in the interviews. MBSE data from a separate dataset will be analyzed in Chapter Four.

Software content

One of the evident changes in vehicle architecture in recent years is the increment in the lines of code they use. New features require additional modules, which add software
modules to the vehicle's functionality. Besides new features, some mechanical ones are being replaced with electronic units that need software to work.

**Architecture definition: hardware versus software**

This theme was widely mentioned during the interviews and has been a popular topic in recent years. As electrical and electronic components previously replaced mechanical elements in the vehicle, the amount of software necessary to perform vehicle functions has increased significantly to the point that mechanical and electronic components are used as actuators for the software to perform its functions.

**Organizational structure**

Besides the technical aspect of the architecture process, the process and the teams involved are also causal in explaining outcomes.

**Architectural changes difficulty**

Once a vehicle platform architecture is defined, architectural changes can significantly impact the whole system. Changing one of its elements might or might not propagate change on interfacing modules depending on how architecture is defined. The difficulty level in making an architectural change in a BEV might differ from that of an ICEV.

3.1.2.2  **Dependent and independent variables**

The 26 questions (Appendix A) were classified into three categories. One category is the independent variables, which are those that might cause an effect on other variables. The second category is the dependent variables, which the independent variables might influence. A third category is the exploratory questions, which helped identify new themes that were unknown before the interviews. The purpose of this classification is to identify potential correlations between variables. To determine the correlation between the responses, the Chi-squared method was applied, considering most of the data was nominal.
Depending on the nature of the questions, the variables provided different types of data. Although all questions were open, the data was classified based on the interviewees’ responses; some of the responses were binned to form groups. The type of data obtained for each variable is captured in Table 3-2.

Besides the Chi-squared test, the participants’ responses were used to build a table, where the columns were the variables and the rows were the participants. A manual analysis was performed by filtering each possible response per column and identifying the homogeneity of answers in the rest of the columns. When more than 50% of the filtered responses were the same in a particular column, that relationship was registered to be discussed in the results. For example, when filtering the response 5% to 10% in the Expected error column, 80% of the answers in the Planned iterations column were Yes. Therefore, this relationship was identified and included in the results as an interesting finding.

Before the analysis, a hypothesis was made about which independent variables influence which dependent variables. The expected dependencies are shown in Figure 3.1-3. The independent variables are the colored words in the middle of the figure, and the independent

<table>
<thead>
<tr>
<th>Independent</th>
<th>Type</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of company</td>
<td>Nominal</td>
<td>Autonomous/Electric/ICE/Tier 1 supplier</td>
</tr>
<tr>
<td>Methodology</td>
<td>Nominal</td>
<td>Some tools/Product Development Process/MSSE/No methodology/Agile</td>
</tr>
<tr>
<td>Architecting process time</td>
<td>Continuous</td>
<td>Number of months</td>
</tr>
<tr>
<td>Experience launching BEVs</td>
<td>Discrete</td>
<td>Number of BEV</td>
</tr>
<tr>
<td>Separated decomposition</td>
<td>Binary</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Carried over requirements</td>
<td>Continuous</td>
<td>Percentage</td>
</tr>
<tr>
<td>Reference architectures</td>
<td>Binary</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Component incompatibilities tracking</td>
<td>Binary</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Tradespace exploration</td>
<td>Discrete</td>
<td>Number of candidates</td>
</tr>
<tr>
<td>Key interfaces list</td>
<td>Nominal</td>
<td>Yes/No/WIP</td>
</tr>
<tr>
<td>Planned iterations</td>
<td>Binary</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dependent</th>
<th>Type</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected challenge</td>
<td>Nominal</td>
<td>Same difficulty/ICE is harder/BEV is harder</td>
</tr>
<tr>
<td>Expected change in the luxury segment</td>
<td>Ordinal</td>
<td>Scale from 1 to 10</td>
</tr>
<tr>
<td>Expected error</td>
<td>Continuous</td>
<td>Percentage</td>
</tr>
<tr>
<td>Stages with higher rework</td>
<td>Nominal</td>
<td>Early phase/First prototypes/New technology/Component level/New suppliers</td>
</tr>
<tr>
<td>Architectural change</td>
<td>Nominal</td>
<td>Same/BEV more smoothly</td>
</tr>
<tr>
<td>Expected BEV dominance</td>
<td>Nominal</td>
<td>Year</td>
</tr>
</tbody>
</table>

Table 3-2 Types of variables and responses
variables are the black words on both sides. The dependencies are color-coded dotted lines with an arrow at one of their ends that indicates an input, whereas the lack of the arrow indicates an output. For example, the dependent variable BEV Dominance on the bottom right corner has three inputs: the independent variables Company Type, Experience launching BEVs, and Architecting Process Time. This means that the hypothesis is that the expectation of the interviewees about the year in which BEV will comprise 50% of the sales is tied to the type of company they are from, the number of BEVs their company has launched, and the time their architecting process takes. Similarly, it is expected that the number of candidates the participants think are necessary before selecting an architecture influences the level of change they expect in the coming generation of luxury sedans.

*Figure 3.1-3 Expected relationships between dependent and independent variables. Independent variables are in the middle, and dependent variables are on the sides*
3.1.2.2.1 Independent variables

Most of the independent variables are related to the past or current work of the interviewees. Aspects like the existence of standardized processes, discipline to follow them, documentation, and traceability are included in these variables.

Type of company

This variable refers to the type of company for which the interviewees work. Their companies vary from Original Equipment Manufacturers (OEM), Tier 1 suppliers, and Autonomous Vehicle (AV) development companies. Some OEMs are recent and dedicated to BEV only, whereas others are legacy OEMs that used to focus on ICEVs.

Methodology followed during the architecting process

This variable is included to understand automotive companies' methodologies for developing vehicle architecture. The methodology may be tied to the performance of the process, delays, iterations, and others.

Architecting process time

The time to develop an architecture can be altered by factors like the time to market or unaccomplished targets. A BEV-dedicated platform usually takes longer than an ICE-shared platform (Erriquez et al., n.d.). The architecting time may be related to the complexity of the architecture.

Experience launching BEVs

The experience a company acquires after launching an electric vehicle may be reflected in other aspects—for example, faster development for future platforms, fewer unplanned iterations, and improved commonality among cars.
Separated decomposition: form and function

The decomposition of a system can be done at different levels but can also be divided into form and function decompositions. A vehicle platform can be decomposed into elements of form, such as the suspension, chassis, and powertrain, among other components. It can also be decomposed into functions like maintaining stability, providing support, and generating power. The respondents were asked whether they have a functional decomposition separated from the decomposition of form.

Carried over requirements

Both the architecting process and the engineering process are driven by requirements. How different are these requirements between ICEs and BEVs? This variable is a percentage of the percentage of ICE requirements that are expected to be carried over to the BEVs.

Reference architectures

Looking at a reference architecture when developing a new one can benefit the outcome since mistakes can be avoided, and explored approaches may reduce risks.

Component incompatibilities tracking

Tracking the compatibility between components or modules could be related to preventing iterations in the advanced stages of the process.

Tradespace exploration

The number of candidates considered before selecting the final architecture of the platform may be related to unexpected performance or costs.

Key interfaces list
Tracking the interfaces among the architecture components, as part of the interface management, could help improve the modularization of the platform and avoid incompatibilities later in the process.

**Planned iterations**

The iterations in the architecting process occur when a step of the process is followed more than once. Planning iterations is a strategy to create a more realistic development timeline and allocate resources promptly.

3.1.2.2 Dependent variables

The dependent variables might be correlated to or a consequence of the independent variables. This section briefly describes the dependent variables and states the hypotheses between them and the independent variables.

**Expected challenge overall**

This variable is included to measure the difficulty level the respondents expect in the BEV platform architecture compared to that of an ICEV. The participants can expect different levels of challenge depending on how familiar or experienced they are with the architecting process. Reference architectures and more carried-over requirements could be signs of fewer changes and, therefore, less expected change. Similarly, the type of company they are from and the number of BEVs it has launched might increase familiarity with BEV development and reduce the anticipated challenge overall.

**Expected change in the luxury segment**

The luxury market is an interesting segment in the BEVs because of the more significant number of features - and thus, complexity - these cars have to differentiate themselves from other segments. Respondents were asked about the level of change they expect in the new generations of luxury BEV sedans to gauge whether the respondents believe BEVs or luxury features will be more difficult to design. The hypothesis is that those participants who suggest a limited exploration of the tradespace or have a reference architecture will expect
a slight change in the luxury sedans. Also, depending on the type of company interviewees are from, they might or might not have expertise in the luxury segment.

**Expected error**

During the architecting process, the candidate architectures are evaluated against specific metrics. This variable measures the expected error bars considered when assessing a BEV architecture to gauge whether companies feel the change in architecture comes with more uncertainty in design. The initial assumptions were that experience through the number of launched BEVs, carried-over requirements, and reference architecture reduces the uncertainty and, thus, the error tolerance expected. At the same time, controls like building a list of key interfaces, planning for iterations, and tracking module incompatibility can mitigate uncertainty and lower the expected error tolerance.

**Stages with higher rework**

As the independent variables section mentions, iterations occur in the architecting process. However, it is interesting whether these iterations happen during the same stages and in the same amount for BEVs compared to ICEVs. Respondents were asked about the architecting process stages with more iterations to measure a difference in the stage with more iterations when developing BEVs. The hypothesis is that the stages with more iterations can change depending on mitigation actions like a key interfaces list, a function-based decomposition, a module incompatibility tracker, or a structured methodology. Also, the allocated time for the architecting process may rush processes and cause more iterations. If iterations are planned at certain stages, then the iterations can be shifted from one stage to another.

**Architectural change**

An architectural change happens when an element of the platform has to be replaced, removed, or added. Depending on the element and its interfaces with the rest of the system, an architectural change may affect a vehicle's timing, cost, and performance. The
interviewees were asked about when they participated in an architectural change to measure whether architectural changes would run more smoothly in BEVs. The initial proposition was that almost all independent variables correlated with the difficulty of an architectural change. The two exceptions were carried-over requirements and planned iterations because they do not influence the difficulty of an architectural change.

**Expected dominance of EVs**

One way to measure the dominance of EVs in the market is through the units sold as a percentage of the total sales. Therefore, the respondents were asked to provide the year they expected the EV sales to be 50% of the total car sales. This might suggest a high difficulty expected if participants pointed out a far year or a low difficulty if they were convinced that 50% of sales would happen sooner. The hypothesis was that company type, their experience launching BEVs, and the architecting process time could influence the confidence of the interviewees toward this BEV dominance.

### 3.2 Results and discussion

Two parts comprise the results from the interviews and the analysis. In the first part, we discuss the differences found across the automotive companies’ architecting processes through the associations between dependent and independent variables. The second part of the results covers the identified themes to provide observations about the architecting process and the challenges the companies will face in the coming years as new BEV models are developed.

**3.2.1 Architecting process differences among automotive companies**

This section presents the insights and findings on the potential relationships between dependent and independent variables to explain the differences between automotive companies.
Since the creation of the automobile, many companies have emerged to satisfy the customer’s needs and offer various products with different styles, capabilities, and purposes. Original Equipment Manufacturers (OEMs) work closely with hardware and software suppliers to develop new models and maintain their presence in the market. Although many practices and processes have been adopted by several automakers (Assembly line and Toyota Production System), each of them has its own strategy to differentiate its product from those of competitors. The purpose of this section is to present the differences found in the practices of the interviewed professionals and how these practices may influence the performance or sentiment of the company. Although the responses from the interviewees are not representative of their firms, it is possible to argue that the individuals’ familiarity with the architecting process provides a fair sense of the companies’ approach.

As mentioned in the previous section, the Chi-squared test was applied to the variables trying to identify correlation. Figure 3.2-1 summarizes the results of this test. There are only three combinations of variables for which the significance level (P) was below 0.05, and the null hypothesis of no correlation can be rejected: The type of company with the use of reference architectures and the expected change in the luxury segment with both the tracking of incompatible components and the list of key interfaces. The details of these findings are discussed below in these variables sections.

![Figure 3.2-1 Chi-squared test results](image-url)

**Figure 3.2-1 Chi-squared test results**
After analyzing the variables, it was found that many of the expected dependencies between independent and dependent variables had no evidence to be sustained. This means that the relationship between them did not pass the Chi-squared test, and there were no findings through the manual analysis (filtering). Other dependencies were confirmed by the Chi-squared test or were identified as findings through the manual analysis. On top of that, the study proposes that there are relationships not only between independent and dependent variables but also between the independent variables themselves, either through the Chi-squared test or the manual analysis. These insights are represented in Figure 3.2-2 and further explained for each variable below. Arguably, it is only possible to talk about correlation between the variables that passed the Chi-squared test. Correlation between two variables means they are closely related, and a change in one will affect the other and vice versa. For this study, the correlation between two variables confirms that the variables are directly associated. For example, the Reference Architecture and the Type of Company passed the Chi-squared test, and the interpretation is that the legacy or ICEV OEMs have a Reference architecture. In contrast, those not legacy OEMs, like BEV-dedicated OEMs or suppliers, do not have a Reference Architecture.

As mentioned before, the manual analysis yielded some relationships between variables that, although they did not pass the Chi-squared test, were interesting to discuss in the variables section and included in Figure 3.2-2. The confirmed relationships by either of the analyses are represented with solid lines. For easy identification, those dependencies confirmed by the Chi-squared test are bolded. Moreover, new relationships identified as interesting in the manual analysis are represented with dotted lines. Finally, those relationships that neither the Chi-squared test nor the manual analysis confirmed were removed from Figure 3.2-2.
3.2.1.1 Independent variables
Although some variables were established as independent at the beginning of the study, the analysis of the responses suggested relationships among these variables, either confirmed with Chi-squared or as curious observations resulting from the manual analysis explained in Section 3.1.2.2. This section presents each independent variable and the findings about its possible relationships with other variables. According to the Chi-squared test, the Type of company and the Reference architecture are the only two correlated independent variables.

Type of company

Potentially influence: Reference architectures, Expected challenge, Carried-over requirements and Expected error
Potentially influenced by: None
One of the variables that has much influence on other variables is the type of company for which the participants work. As mentioned before, the interviewees' backgrounds are diverse; they come from OEMs, Tier 1 suppliers, and Autonomous vehicles (AV) development. Moreover, those from car manufacturers can be divided into legacy OEMs and relatively young EV companies.

**Methodology followed during the architecting process**

Potentially influence: Key interfaces list  
Potentially influenced by: Company type and Experience launching BEVs

There is a clear difference among the methodologies followed by the companies. Whereas larger organizations have a well-established product development process that includes the architecting and the engineering processes, smaller companies are still trying to craft their own development process. According to the responses, having an established methodology helps the team know the steps they must follow. However, some of the respondents see that as a barrier when it comes to new product development. Not every product can follow the same steps. Out of 13 answers to this question, around 50% claim to follow a specific methodology like Agile or their own product development process. The other 50% mentioned that they either do not follow a methodology at all or that some of the teams have implemented tools and initiatives that are not yet connected with other teams. The analysis showed that BEV-dedicated companies do not have a structured methodology when architecting a platform. This is expected due to their level of maturity. Legacy OEMs have existed for more than 100 years, over which time they have developed and improved their methodologies.

Furthermore, there is a relation between the number of BEVs launched and the methodology. Those OEMs which have launched more than seven vehicles followed a methodology. It can be concluded that experience and maturity foster the adoption of methodologies to architect platforms.
Architecting process time

Another aspect that varies significantly among the respondents is the time it takes to develop an architecture. The 17 answers to this question suggest a range between 1 and 60 months. Although some people claim it can take a few months, most answers point toward between 24 and 60 months to complete an architecture. One of the respondents even stated that the architecting process never ends because the architecture keeps being modified. There are three interesting factors to highlight from the difference of these responses. The first is the maturity and focus of the company. Even though newer OEMs might not have decades of experience developing cars, they do not face the challenge of adapting an existing architecture to an electric vehicle. They had the chance to start from a fresh piece of paper. For this reason, the responses from people working at more recent companies tend to state shorter times.

The second point is the respondents' experience. The ones that have worked closely with subsystems or components rather than the vehicle itself provide a more optimistic timeline. Those involved in vehicle-level architecture talk about years when referring to architecture.

Finally, the third factor that might influence the difference in responses is that not every person has the same understanding of the architecting process; some see it as the entire development process until the product is complete. Others identify the process only from the goal-setting phase to the selection of the architecture.

Experience launching BEVs

Presumably, launch after launch, carmakers improve their products and processes. Having a longer list of developed electric vehicles might give an idea of the maturity and expertise
of the company. Around 60% of the answers to this question show that the companies have launched 5 BEVs or less. This is related neither to the type of the company (ICE vs BEV) nor to the time the company has been in the market. Not all legacy automakers have launched several EVs. The data indicates that the more architecture candidates are generated, the more vehicles the company has launched. 60% of those who recommend having five possible architectures or more come from professionals whose companies have launched more than seven vehicles. It is conceivable that creating multiple possible architectures reveals different benefits in each of them that result in a new product to satisfy a different market. It is also possible that some OEMs aim to keep their presence in various market segments by launching multiple BEVs, and therefore, they require the generation of numerous architecture candidates.

**Carried over requirements**

Potentially influence: Tradespace exploration and Error tolerance  
Potentially influenced by: Company type

Overall, there is a clear expectation from the industry professionals that the percentage of requirements carried over from the ICE vehicles is high. Around 60% of the answers obtained suggest that between 50% and 70% of the requirements that currently exist for the ICEV are followed to develop BEVs (Figure 3.2-3). Curiously, many respondents said that the percentage of requirements that change is related to their domains. For example, the interviewees whose jobs were in the software area of the company stated that while many requirements were carried over, the software-related ones were the ones changing. This also happened for interviewees from the electrical and testing departments and might be due to their limited awareness of the requirements other departments manage. The type of company is a variable that has some influence on the expected rate of carried-over requirements. The responses of those professionals from legacy OEMs were between 60% and 90% of the requirements from an ICEV carried over to a BEV. Those working for legacy OEMs are perhaps more familiar with the general requirements of a vehicle and can easily identify the portion that is changing now that they develop BEVs. Conversely, this could be
tied to the mental models crafted by legacy automakers that may bias the opinion about a new architecture (Fang & Kim, 2023).

Figure 3.2-3 Percentage of carried-over requirements according to respondents

**Separated decomposition: form and function**

Potentially influence: Key interfaces list and Tradespace exploration
Potentially influenced by: Experience launching BEVs

There is no right or wrong answer to how companies approach the decomposition of their systems. Teams may benefit by linking functions automatically to specific components or keeping them separated. The former is a component-oriented decomposition, meaning that as soon as the vehicle is decomposed, a component is already assigned to perform a function, limiting the exploration of other modules that can perform the same function. On the other hand, the latter is a function-oriented decomposition, which means that the vehicle is first decomposed into functions, and modules are assessed before being selected to perform a function. Some interviewees mentioned that the teams felt more comfortable...
with a form decomposition because they knew precisely the module they had to work with, whereas giving them a function could cause ambiguity and provide a feeling of lack of guidance.

On the other hand, working with a solution-neutral decomposition that shows only the functions of a system can be beneficial to avoid constraining the design from the beginning. There is room for innovation in form when the function is unrestricted. The 16 responses to this question were equally divided between the people who separate their decomposition and those who do not. The analysis of these responses showed that those respondents whose companies have launched eight or more BEVs do not decompose into functions and then assign modules. Possibly, these companies have enough confidence to proceed with a new development without having to decompose the functions due to their experience with all the previous vehicles.

Furthermore, suppose all the vehicles generated are intended to share several modules. In that case, it is convenient to have a decomposition of functions already showing the modules necessary to perform specific actions. Therefore, it is unnecessary to separate the decompositions.

**Reference architectures**

Potentially influence: Expected error  
Potentially influenced by: Company type  

Companies will likely use a reference architecture while developing a new or modified architecture. 60% of the answers to this question state that a reference is used, either a previous architecture of the same company or architectures from competitors. The Chi-squared test shows a strong relationship between using a reference architecture and the type of company, as shown in Figure 3.2-1. 83% of the people who stated that they follow a reference architecture during new developments work at a legacy OEM. In contrast, the ones that mentioned that they do not follow a reference architecture come from BEV-dedicated OEMs, Tier 1 suppliers, or AV development companies. Given the number of
architectures that legacy OEMs have created, it is understandable that they use a previous architecture as a reference. An interesting inquiry for this practice is how limiting this can result for teams whose objective is finding a completely new architecture. A reference might be a source of bias for the team.

**Modules incompatibilities tracking**

Potentially influence: Tradespace exploration and Expected change in the luxury segment
Potentially influenced by: None

Almost 60% of the respondents who answered this question said that their companies tracked the components that are not compatible with each other in some way, either with a list on a spreadsheet or a more sophisticated tool like a software application. Some mentioned that having a list of incompatible components works as a filter to dismiss some architectural combinations. The analysis suggested that this variable influences the expected change in the luxury segment and the tradespace exploration. The details of these findings are discussed under the dependent or influenced variables.

**Tradespace exploration**

Potentially influence: Stages with higher rework and Experience launching BEVs
Potentially influenced by: Incompatibilities tracking, Carried-over requirements, Separated decomposition and Planned iterations

The tradespace exploration and the number of candidates that make it to the final stage are similar across the respondents. 12 out of 17 responses suggest that there should be between 2 and 5 candidates before deciding on the final architecture, 3 being the most recurrent answer. Many respondents recognized that even though the entire tradespace should be explored ideally, they are limited by resources and time. Therefore, working with commonly used configurations and options becomes necessary. One of the interviewees mentioned a significantly different approach to this problem: delaying the decision for the architecture as much as possible to avoid dismissing good options very early in the process. According to the analysis, this is the independent variable with the most influences from or
relationships to other variables. For example, those who say more than ten candidates should exist before selecting an architecture separate their functional and formal decompositions. This separation may enable new proposals of forms to perform the functions, which increases the number of possible combinations, and therefore, more possible architectures exist. In addition, 66% of the respondents who claim more than 50% of the ICEV requirements are carried over to BEVs suggested between 2 and 4 candidates. Since most of the requirements are not changing, most parts will be shared, and therefore, only a few candidates will result from a tradespace exploration. Conversely, 50% of the people who indicated that ten or more candidates are necessary also mentioned that less than 50% of the requirements are carried over. This means more changes in BEVs, more opportunities for exploration of the tradespace, and more necessary candidates to fulfill the new requirements.

Another variable related to the tradespace exploration is the tracking of incompatibility between components in the architecture. Those who mentioned that more than ten candidates are necessary do not track component incompatibility. This suggests that they probably generate many more candidates because many will be rejected due to incompatibilities during the evaluation. A list of incompatible components could work as a filter, resulting in fewer candidates. This is supported by the fact that 86% of the respondents who track incompatible components suggested between 2 and 4 candidates. They may be more aware of the limitations of component compatibility and, therefore, aim for fewer possible architectures. Finally, the interviewees who do not plan for iterations in their architecting process tend to recommend between 2 and 4 candidates. Arguably, since no time is allocated for iterations, teams are forced to work only on some architecture candidates. In other words, time constrains the number of proposed candidates.

**Key interfaces list**

Potentially influence: Stages with higher rework and Expected change in the luxury segment
Potentially influenced by: Separated decomposition and Methodology
A list of key interfaces or a different way to ensure their traceability seems common among enterprises. More than 80% of the 15 answers to this question indicate that there is a list or a way to track the key interfaces of the vehicle. Also, one of the interviewees admitted that they are in the process of creating a list. From the three architecture domains, mechanical, electric/electronic (E/E), and software in a vehicle, only mechanical and E/E interfaces are mentioned by the respondents. Nevertheless, four admit that the software interfaces are not being tracked yet. There might be a relation with the recent vehicle software increment; the number of code lines has increased in the past few years. The study showed a relationship between this variable (Key Interfaces List) and other variables related to process discipline: Use of a Methodology and Separated Decomposition. The respondent who admitted not following any methodology during the architecting process was also the only one who stated not having a list of key interfaces, which might be related to a lack of procedures in general or a lack of discipline in the team. Similarly, all those who separate their decompositions of form and function have a list of key interfaces. It is easier to identify key interfaces if there is a functional decomposition separated from the components since the criticality of functions is evident.

**Planned iterations**

Potentially influence: Expected error, Tradespace exploration and Expected dominance of BEVs
Potentially influenced by: Incompatibilities tracking, Architecting process time and Expected challenge

Most companies, suppliers, or OEMs plan for iterations during their development process. 75% of the interviewees stated that they plan for iterations and allocate time and resources for them. Some of those who work in BEV companies admitted that this was not their first approach but happened later as a lesson learned. Interestingly, some teams do not include iterations in their development processes yet because the stakeholders do not accept the idea of iterating. Although BEV and AV companies are more recent than legacy OEMs, five out of seven respondents who work for them state that iterations are already planned in their process. Arguably, the other two will eventually incorporate iterations into their work plans.
The professionals who claimed the architecting process to be short (between 1 and 3 months) also mentioned that they plan iterations as part of their process. They work on an architecture briefly and then modify the base architecture until they reach the set targets. Moreover, 83% of the professionals who do not track incompatibilities plan for iterations. It is likely that since they do not identify incompatibilities between components, they find out in later stages of the process that rework is needed. This may increase the number of iterations they go through, and now they plan for those iterations. Companies, in which that is the case, might find an opportunity to incorporate some practices and reduce the number of iterations. Finally, the analysis showed that planned iterations are the only independent variable influenced by a dependent variable - the expected challenge. 78% of the interviewees who claim that designing a BEV is more complicated than an ICE also plan for iterations. This might be interpreted as a way of preparation. They plan for iterations because they think the challenge is immense, and allocating enough time for it is better. This relationship can be seen at the right of Figure 3.2-2, going from expected change to planned iterations.

3.2.1.2 Dependent variables
This section explains the findings from the analysis about the influence of the independent variables on the dependent variables. According to the Chi-squared test, only the Expected change in the luxury segment is correlated with two independent variables: The List of key interfaces and the Tracking of module incompatibility. Additionally, each independent variable section includes curious observations from the manual analysis explained in Section 3.1.2.2.

Expected challenge overall
Potentially influence: Planned iterations
Potentially influenced by: Company type and Experience launching BEVs

Interestingly, the expected challenge of developing BEVs against ICE vehicles is equally split. Out of 20 answers, 45% stated that BEV development is more complex than ICE
vehicles, 45% stated exactly the opposite, and 10% claimed it is the same difficulty level. The main reasons for those arguing that BEVs are more challenging to develop are the lack of expertise in the BEV components and the software these vehicles require. Those who think ICEVs are more complicated to design highlighted that the number of pieces in a BEV is much less than in an ICEV, making the design less complex. Not having an engine is a sign for them that the complexity is significantly reduced.

Most interviewees claiming it is easier to develop BEVs were from BEV-dedicated companies. In contrast, engineers at legacy OEMs see BEV development as more complicated. Arguably, this is linked to the methodology followed by the companies to develop their architectures. An established process development might be limited or constrained to be applied to a different type of technology. One of the independent variables expected to influence this variable is the type of company.

To some extent, there is a relationship between the responses. Those who stated that developing an ICEV is as difficult as a BEV are professionals who do not work for an OEM. They work for either a Tier 1 supplier or an AV company. As stakeholders who are not entirely responsible for the architecture development, they have a different opinion (ICEVs and BEVs have the same difficulty level) than the ones working at OEMs. A second relevant variable is the experience of the companies launching BEVs. The analysis implies that those who have launched eight or more vehicles claim BEVs are more complex to develop. It would be logical to think they must be right since they have more experience developing BEVs. However, it is worth mentioning that these responses also come from legacy OEM professionals. As mentioned before, ICEV-focused OEMs have struggled to build BEVs and have adapted existing platforms to reach the market soon.

Other variables like reference architectures or planned iterations did not result in being of influence for the expected challenge.
**Expected change in the luxury segment**

Potentially influence: None  
Potentially influenced by: Incompatibilities tracking, Reference architecture, Company type and Key interfaces list

The respondents do not expect the luxury segment to be changing dramatically. They were given a scale from 1 to 10, where 1 is a slight change, like a change of material, and 10 is a significant change, like a clean sheet design. 56% of the answers are five or below, and around 19% are nine. Most respondents who provided higher numbers work at larger automakers. The type of company and reference architectures were the two expected variables confirmed by the analysis.

70% of the respondents who expect significant change (6 to 9) work in legacy OEMs. OEMs previously dedicated to ICEVs have had to focus on differentiating a premium car from a conventional one. For them, there is a significant difference between the two products. However, recent BEV makers do not market differences among their products because they are already expected to be premium (for BEVs sold outside of China). Moreover, 80% of the people who expect little change in the luxury segment (3 to 5) indicated they have reference architectures. The analysis hints that having a reference architecture is advantageous because automakers do not have to change many components and just modify a small portion of the architecture.

In addition to these findings, as shown in Figure 3.2-2, the Chi-squared test revealed a strong influence from the variables module incompatibility tracking and key interfaces list. 86% of the people who expect more considerable changes in BEV luxury sedans (6 to 9) also track component incompatibility. This might mean that having this list gives them better visibility of coming incompatibility challenges that will require more changes in this segment. Similarly, 89% of those who expect lower change (3 to 5) have a list of key interfaces. This might be related to a modularity strategy. If the interfaces are strategically managed, changing one component might not cause others to change. Therefore, some modules can
be changed in the luxury segment without significant modifications to other elements. Interestingly, participants with a list of key interfaces do not necessarily track module incompatibilities. This is because they might track only the interfaces of a particular domain, which differs from the domain of the incompatible modules.

**Expected error**

Potentially influence: None
Potentially influenced by: Reference architecture, Company type, Carried-over requirements and Planned iterations

The expected error tolerance in the metrics to evaluate an architecture is similar for most respondents. Although the interviewees recognized that the error tolerance depends on the type of attribute being assessed, 75% of the responses are between 5% and 10%. The study demonstrated an independent variable that was not expected to influence the expected error: the type of company. Interestingly, the responses that go beyond those values to 20% and 40% are linked to people working in the autonomous vehicle domain, where technology is not mature yet and teams are still working to reduce error. The three expected independent variables impacting expected error are carried-over requirements, reference architectures, and planned iterations. Those pointing out that 60% to 90% of the requirements are carried over from ICEV to BEV expressed that the expected error is between 5% and 10%. In contrast, a lower percentage of carried-over requirements are linked to higher error tolerance. Since a higher rate of carried-over requirements means that only a few elements change for a BEV, the error is expected to remain low. Previous modules already used in ICE should present a low error. In contrast, a lower percentage of carried-over requirements would be tied to a higher expected error because more elements are new.

Furthermore, 67% of the professionals who use reference architecture claimed an expected error of between 5% and 10%. Similar to the requirements, a reference architecture is a sign of a baseline that, if followed, does not require a significant change; therefore, a high error tolerance is unexpected. Finally, 80% of the interviewees who expect 5% to 10% error also
plan iterations in their architecting process. This could imply that performing iterations should provide a more mature design and a more refined outcome with a lower error. However, there is not enough data to demonstrate the statistical significance of this statement.

**Stages with higher rework**

Potentially influence: None
Potentially influenced by: Tradespace exploration and Key interfaces list

All the interviewees acknowledged the existence of iterations throughout the development process, but they suggested that most of the iterations happen once the first physical prototypes are available. 7 of the 13 responses to this question indicate that most of the iterations happen at this stage. Something to notice is the difference between software and hardware iterations. Most interviewees mentioned that Agile is the methodology used for software development and that they experience iterations constantly, even weekly. The respondent who mentioned that iterations are higher when a new technology is implemented also admitted that the key interfaces list was in progress. One plausible reason for this is that the lack of a list of interfaces does not allow the team to optimally define the best strategy, which means that a slight change to the architecture can impact other components and have considerable iterations. Also, those who said that the stages with more iterations are the early stages suggest that the number of architectural candidates should be 2 or 3. This might be a perspective under which several iterations are performed at an early stage to deliver only a few concepts. Therefore, only 2 or 3 candidates are recommended.

**Architectural change**

Potentially influence: None
Potentially influenced by: Key interfaces list

When it is necessary to modify an architecture, there is an apparent belief that an architectural change in an ICE vehicle is as smooth as in a BEV. 10 out of 12 responses to
this question support this idea. Even though the respondents do not think it is more difficult to perform an architectural change in an ICE or a BEV, they do expect more architectural changes to happen in the BEV since they are not as mature as ICE vehicles. According to the analysis, the key interfaces list variable is related to the architectural change variable. 90% of the interviewees who identified the magnitude of architectural changes between ICEV and BEV to be the same have a key interfaces list. This list indicates maturity, giving the teams a more informed, high-level view of the system. Then, the team will know that architectural changes in BEVs can be managed as smoothly as in ICEVs architecture.

**Expected dominance of BEVs**

Potentially influence: None  
Potentially influenced by: Tradespace exploration and Planned iterations  

The expectations of automotive professionals vary significantly. They point to different years for the EVs to constitute 50% of the sales in the United States. From the 18 answers to this question, approximately 45% expect this to happen between 2034 and 2040. It is worth mentioning that their prediction is based on the policies put in place for EVs rather than on what the customer wants. From their point of view, things like the infrastructure, the charging time, and the high cost are factors that need to change so that customers want to purchase an EV and not just because the government requires it. None of the expected independent variables for the dominance of EVs was sustained by the study. Instead, it showed curious observations regarding tradespace exploration and planned iterations. Two-thirds of the people who recommended having more than ten architecture candidates think that 50% of sales in the U.S. will be BEV by 2034. In other words, teams that generate a significant number of candidates might think that many configurations could be released to satisfy the market and increase BEVs sales.

Furthermore, people who said 50% of sales would be BEV between 2030 and 2035 plan iterations. These professionals might have a more mature knowledge of the timing to develop a vehicle architecture. They might have gone through lessons learned that make
them confident that sales can reach 50% not after ten years but not before the end of this decade either.

Ultimately, it is interesting that some expected relationships between the dependent and independent variables work differently. Moreover, unexpected links between variables exist, as shown in Figure 3.2-2.

3.2.2 The architecting process: advantages and challenges

This section covers the current and new themes identified in the interviews and their potential associations with the variables in Section 3.2.1 to explain phenomena and behaviors occurring in the automotive industry that can represent advantages or challenges during the architecting process of BEVs.

Within a BEV's Product Development Process, the platform's Architecting Process sets the ground for several models. While carmakers have progressed significantly in catching up with the electrification and new technologies to update their platforms, there is still a long way to go, where they will face expected and unforeseen challenges. Throughout the interview's exploratory questions, it was possible not only to know the status of the current themes widely known in the BEV development but also to discover new themes that brought insights to this research.

3.2.2.1 Current themes

Architecting process benefits and flaws

As discussed in Chapter Two, the architecting process is essential in developing a product and has a significant influence on the performance of its emergence. Listening to various experts in the automotive industry helped understand those things that are beneficial during the architecting process and others that degrade the efficiency of the process. Surprisingly, most aspects mentioned by the interviewees are related to the organization and the team
members' behavior and not to technical aspects like it was expected before conducting the interviews. One of the most common topics is the team members' understanding of their responsibilities; if everybody knows what to do, the tasks should run smoothly. Another essential point is to understand the requirements of the platform architecture. This means the teams must precisely know the goals and targets, as this will direct their work. A third important point is to count on experts in the firm. Every company must procure professionals knowledgeable about the technologies that will be part of the vehicles.

On the other hand, there are flaws that the interviewees identified in the current architecting process, and that could be improved. The most common is the communication among teams. This affects the process negatively because every team works on optimizing a component, and during the integration problems arise because of incompatibility. There must be effective communication among the teams to ensure that all components will fit when put together. As one of the interviewees mentioned, “We don’t want to build the best component; we want to build the best car.” A second aspect is the limitation the teams experience due to the established processes and procedures. When introducing a new technology, engineers want to try a different approach to make it work, but they find a barrier if that is not part of the procedure, which makes them feel constrained to innovate and improve.

Some variables discussed in the previous section support the benefits and flaws of the architecting process. For example, following a methodology has been crucial for legacy OEMs to achieve efficiency; a structured architecting process with planned iterations avoids delays and favors the position of a company in the market. Also, the discipline in the processes, which can be indicated by tracking module incompatibilities and listing key interfaces, are determinants for iterations later in the process and the difficulty of making an architectural change.
Level of difficulty in the vehicle design

Over the years, vehicles have expanded their functions. While their primary function is to take passengers from one point to another, nowadays, drivers are assisted by cameras, sensors, and radars to preserve their safety. They can enhance their entertainment while driving thanks to the advanced connectivity with which cars are equipped. These and other features entail enormous efforts by the engineering teams. A new function can be translated into a couple of lines of code or a completely new module packaged in the vehicle with new interfaces to other components. Through the interviewees' answers, they expressed interesting ideas about the difficulty of designing a BEV against an ICE vehicle. There is a general thought that developing a BEV-dedicated platform is more manageable than creating one for ICE vehicles due to the number of components. There are fewer moving pieces in a BEV, and they have no engine, and elements like motors and inverters are well-known machines.

Nevertheless, the respondents point out that the difficulty of developing BEVs does not lay in the number of pieces or the electric components but in the new technologies that are coincidentally integrated into electric vehicles, like the Advanced Driver Assistance System (ADAS), the Over The Air (OTA) capability and the connectivity and software required for this technologies. It is clear that these features are exclusive to electric vehicles; however, electric vehicle consumers expect their vehicles to have all kinds of technological features. Conversely, an ICE driver may still accept a reduced content in an ICE vehicle.

The Expected challenge and the Expected change in the luxury segment are variables closely related to this theme. Interviewees from legacy OEMs find it harder to design BEVs, whereas those from BEV-only companies find it more manageable. This may be because of the mental models teams working on ICEV have; they want to adapt those models to a new product type, which can be challenging. Those starting a BEV architecture from the ground up create new mental models and find it easier to develop this kind of architecture. Additionally, through the expected change in the luxury segment, it is possible to realize that...
some aspects of a structured architecting process give the interviewees the confidence to expect less change in a vehicle and, possibly, less difficulty developing it.

**Architectural decisions**

As part of the architecting process, it is essential to go through the selection of architectural decisions to obtain a final configuration that complies with the targets and fulfills the firm’s goals. It was expected that automobile professionals had experienced analyzing several options for each decision and selecting between competing decisions. However, some of the answers may be surprising to the readers. Most interviewees admitted that they do not explore the solution space when working with architectural decisions, mainly due to the limited time they have to select the following architecture. It is intriguing to know what the vehicle architectures would look like if the solution space were explored exhaustively.

Regardless of the level of exploration, it is done with the architectural decision options. Once the teams have put together a certain number of candidates, they will select a final architecture, a process with different approaches depending on the company. Most teams assess the candidates, choose one of them, and discard the others to move on to the next steps of the process. However, one of the interviewees mentioned, “You should delay the decision as much as possible,” and then explained that some teams avoid selecting an architecture as long as they can and start with the following steps to find out further in the process the options that best fit the design. One of the respondents believes it is impossible to have a candidate that satisfies all the targets set for the architecture, so it is always the discretion of upper management to decide whether the need is to have the best cost, the best performance, or the quickest to market.

The Tradespace exploration and the Architectural change variables relate to this theme. Listing key interfaces and having a function-oriented decomposition ease the exploration of the tradespace and generate more candidates before selecting an architecture. Also, architectural change, meaning changing an architectural decision, may be influenced by identifying the key interfaces to define modules better and avoid change propagation.
Iterations

As mentioned in the variables section, iterations are part of developing highly complex products like automobiles. It was expected that every company would experience iterations during its development process. However, the difference was found in whether they planned for it or not. There are two aspects worth mentioning. The first one is that, contrary to reducing iterations, interviewees say that with the content and features that the customers demand, the iterations in the process increase, especially if a new technology is being introduced. A new technology can cause many problems if it is decided to be implemented and it turns out that it is not mature enough to be deployed. The second point is that one of the interviewees is convinced that the Agile methodology, which implies constant iterations, is unsuitable for the automotive industry hardware. Unlike software, hardware is not as fast and easy to modify, so that it may be costly and time-consuming. Software, on the other hand, seems to go through weekly iterations, according to many of the respondents. Interestingly, most respondents agreed that the iterations happen mainly after the first physical prototypes, even when the teams can leverage simulations to perform tests in advance. No one provided initiatives or efforts to reduce the number of iterations in hardware, except for one interviewee, who assures that the implementation of digital twins will significantly decrease the issues found during the physical tests as most of the problems will be captured virtually, allowing the teams to modify the design promptly.

This theme is related to the Planned iterations independent variable and the Stages with higher rework dependent variable. The time allocated for the architecting process can be short because companies plan several iterations to improve the baseline design. Also, missing a list of key interfaces might generate additional rework in some process stages. This has served recent BEV-only companies in planning for iterations as a lesson learned.
As discussed in Chapter Two, there are many architectural frameworks, and the automotive industry has not only adopted specific frameworks but also developed its own variations. When asking the interviewees about the differences in the architecting process between the companies they had worked for, an interesting topic arose: the zone or zonal architecture. This type of architecture has been mainly proposed for electric and electronic architecture as a response to the increase in the number of modules in the vehicle. The zonal architecture proposes to divide the car into zones (Askaripoor et al., 2022) and integrate all the functions that need to be performed in each zone in one single module connected to actuators and sensors. This approach has several advantages since it reduces the problem of packaging many modules in a reduced space. As one of the respondents pointed out, the space gained from removing the ICE elements is destined for customer comfort and convenience, not for the engineering team to package modules more easily.

As expected, the zonal architecture reduces not just the number of modules but also the wiring that connects modules with sensors and actuators. The reduction of elements has a positive impact on material cost and weight. However, developing the integrated modules requires more time and higher costs than off-the-shelf solutions. If updates to these new modules can be done by changing the software only, a zone architecture can be leveraged using over-the-air updates. Arguably, a zonal architecture approach can be achieved through the architecting process during the clustering and modularization of components. A cluster of functions likely becomes one zonal module.

The independent variables List of key interfaces and Separated decomposition are tied to this theme. A zonal architecture requires that the functions of the systems are not instantly linked to a specific component; instead, functions are put together in a different form, a new module. Moreover, key interfaces change in a zonal architecture. Interfaces from several microcontrollers might be reduced with only one centralized module in a zone. On the other hand, the zonal architecture affects the dependent variable Architectural change because
to change one of the functions or features, the entire zonal module would need to change, making it more challenging and costly to make changes later in the architecting process.

**Model-based systems engineering (MBSE)**

As part of the evolution of systems engineering, many people in academia and the industry bet on Model-based systems engineering as the solution to the increasingly complex systems humans have created. Systems engineering is a concept that has not yet been entirely adopted in the industry; therefore, using a model is an even more significant challenge. Although Model-based systems engineering will be discussed in detail in Chapter Four, it is worth mentioning that it was a topic discussed in several interviews. Some interviewees even had the implementation of MBSE at their companies as their primary job.

Many surprising points resulted from the discussions about MBSE. A significant percentage of the professionals agreed that MBSE is a valuable approach for the automotive industry and could be used to make their workflows more efficient. However, they also expressed concern about its adoption. One of the aspects they mentioned is the lack of awareness of the MBSE benefits among the teams and the need for training to implement the approach successfully. These factors prevented teams from adopting or even being interested in using models for work.

Furthermore, those who have been able to adopt MBSE to some extent claim that the approach is not being correctly used, but it is being confused with the use of software. As one of the respondents explained, MBSE is a powerful tool only if the models are created with the correct information. Therefore, it is not enough to learn how to use the software but to understand the approach. Another interviewee manifested their disagreement in getting software licenses for people to use them without making sure teams really understand the theory.

Due to its integration advantage, MBSE can influence variables like the List of key interfaces, Carried-over requirements, Module incompatibility tracking, and Separated decomposition. All these variables can be integrated into one model, improving efficiency. Simultaneously,
MBSE may impact the Expected errors thanks to its benefits to verification and validation by keeping requirements up to date and facilitating the testing tasks.

In summary, model-based systems engineering is a valuable tool that companies need time and resources to deploy and adopt successfully. Chapter four will cover the landscape of MBSE across industries and its effect on the automotive industry.

**Software content**

Even though the word software was not used in any interview questions, every responder mentioned software in more than one of their responses. While it was expected that the interviewees alluded to software at some point, some statements they made were surprising. First, there is a clear association that professionals see between software and the difficulty of architecting a vehicle. Phrases like “computer on wheels” and “software-defined” vehicles were used to refer to the complexity of developing a vehicle nowadays. They mentioned this because of the software required to achieve today’s vehicles’ functionality. For instance, the electronic units in current premium vehicles depend on more than 100 million lines of code (Zellmer, 2023).

References architectures and Expected challenge are variables that may be affected by the increasing software content in vehicles, especially in BEVs. First, modifying and deploying a reference software architecture across multiple models is easier. On the other hand, as mentioned before, the challenge increases with the rise of lines of code in the vehicle modules. This difficulty has created the need for more specialized engineers and a stronger foundation of software engineering within vehicle companies.

**Architecture definition: hardware versus software**

Software is not only increasing in vehicles, but it is also taking over the importance mechanical elements had in the past, creating software-defined vehicles. During the interviews, two respondents mentioned that the OEMs have underestimated software engineering, which has been one of the main reasons for program delays. They suggest that
Software not only deserves closer attention in the next generation of vehicles but also must be considered during the architecting process as much as hardware and E/E components, just like authors Zellmer and Cesena suggest (Cesena, 2022; Zellmer et al., 2023).

Software-defined vehicles influence the Key interfaces list variable by adding new interfaces to the vehicle. As mentioned in the previous section, OEMs have just started tracking these interfaces. Also, the Stages with higher rework dependent variable can change because the iterations in software happen much more constantly than in hardware. Additionally, the Architectural changes may vary because changes that used to involve changing hardware in a software-defined vehicle can be changed only by updating a module’s software via over-the-air (OTA) technologies.

**Organizational structure**

In the literature, some authors mention the influence of the organizational structure of companies on their products (Daniilidis et al., 2012). Also, Conway’s law points out that an organization’s structure will strongly influence the structure of the product it develops (Herbsleb & Grinter, 1999). While the interviewees were expected to refer to technical aspects of what goes right or wrong in the architecting process, most of them alluded to organizational aspects as key during the development of vehicle architecture.

Many interviewees suggest that the teams should be structured in the same way the architecture is modularized because this would allow a team to make architectural changes more easily. Additionally, in terms of interfaces, if the most critical ones are managed inside the same team, the interface will likely not have a problem during integration with other components. One of the responders suggested that the architect should have certain authority among the engineering teams to guide them towards the entire system’s performance rather than that of the component. If the organization is too flat, engineering teams might not make an effort to implement the architect’s vision but what is more convenient for a particular team instead.
The way in which an organization is structured can be influenced by the Type of company variable. BEV-only companies transitioning out of the startup phase keep a less hierarchical structure than legacy OEMs. Even the Separated decomposition variable can impact this theme. Teams may be organized according to modules in a component-oriented decomposition or functions, following a function-oriented decomposition.

**Architectural changes difficulty**

It might be a common belief that once an architecture is selected, it must not change because this would generate iterations and impacts on the vehicle that could be translated into additional costs and delays. Surprisingly, there are different opinions among the interviewed experts. Some of them support this idea and say that the architecture should be carefully crafted to remain unchanged and avoid problems. On the other hand, some professionals argue that the architecture should keep evolving and that the teams should be able to manage the architectural changes.

This can be linked to the idea that depending on the modularization of the platform, an architectural change will or will not be more complicated. Some respondents link the difficulty of an architectural decision with a direction from upper management that is not aligned with what they think is the best; others suggest that an essential component in the difficulty of an architectural change is how vertically integrated the product is. They suggest that if suppliers develop the affected components, it will take more time than the changes on in-house components due to communication and the coordination it takes to handle a modification between two companies.

As mentioned in the previous section, interviewees claim that the challenge involved in an architectural change does not depend on whether the vehicle is a BEV or an ICEV but on other aspects related to the architecting process approach. For example, the Key interfaces list variable can substantially affect this theme because how the interfaces are managed impacts the difficulty implied when an architectural change has to be made. The
participants who follow a key interfaces list confirmed the same difficulty in an architectural change for both ICEV and BEV.

### 3.2.3 Conclusion and discussion

In conclusion, this chapter provides insights that help answer the first research question.

*Do we expect OEMs and Tier 1 suppliers to use a different process to architect EVs, as compared with ICE vehicles?*

According to the experts interviewed, the architecting process should be the same for both BEV and ICE vehicles. Even though the propulsion system changes, the steps to an architecture are expected to be the same. It is important to mention that even though the electrification of the powertrain does not demand a different architecting process, other complexity drivers, like the increasing number of features and the software-defined vehicles, need more efficient methodologies to manage the complexity. MBSE is a potential candidate due to the benefits it provides to make the transition toward BEV-dedicated platforms smoother. Along with the answer to the research question, it was possible to gain some insights that helped better understand the surrounding aspects of the architecting process.
Chapter IV

4 Model-Based Systems Engineering (MBSE) adoption in the automotive industry

4.1 Method
As discussed in Chapter Three, one of the approaches that have captured the attention of several industries is Model-Based Systems Engineering (MBSE). Although the literature covers several cases and initiatives in the automotive industry for the adoption of MBSE, it is not clear to which degree it has been adopted so far. At the core of this study is understanding if MBSE adoption has increased over time and its evolution in the automotive industry by analyzing seven years of data from a survey part of an MBSE course.

4.1.1 Data collection
4.1.1.1 Characteristics of the survey
The obtained data comes from several surveys made during an MBSE course. This course is part of the MIT xPro program “Architecture and Systems Engineering: Models and Methods to Manage Complex Systems,” which consists of four courses targeting Systems Engineering professionals in different career levels. The course “MBSE: documentation and analysis” is the third of four courses, and it has been delivered two or three times a year since 2017. The average number of professionals enrolled in this course is around 500, from industries like aerospace, defense, automotive, and manufacturing, among others.

The course duration is four weeks, and each week covers one of the following topics: What is MBSE?, Building an MBSE Model, Critiquing an MBSE Approach, and Managing the Model. Throughout the four weeks, the participants answer 15 questions to assess how familiar they are with the topic and to understand how much it has been adopted in their industries and companies, as well as the tools or approaches they have used to implement it in their
activities. The participants' answers to these questions are anonymized by removing any personal identification information and providing an ID instead. This ID helps link the responses of each participant through the questions (B. Cameron & Adsit, 2020).

Up to this point, the course has been delivered 19 times, generating 241 CSV files and 5,379 responses. All this data has been gathered in master files to track the same participant's responses.

4.1.2 Data analysis

The analysis of the data is divided into two phases with different objectives. The first part consists of analyzing the data throughout time, looking to understand the changes in the response over the years, which might provide some insights about whether the adoption of MBSE had increased among the industries and whether the practices of the professionals have matured over time. Also, it shows the priorities and emphasis of companies undergoing a transformation toward MBSE.

The second phase entails comparing the adoption of MBSE in the automotive industry versus other industries to identify whether automakers are using more models in their vehicle development. If they are, some answers might give insight into how they have applied the methods in the processes. If they are not, some responses could explain why it has worked better for other industries.

The combination of findings between these two phases aims to help answer the second search question of this thesis: *Does the shift towards EVs, with more clean-sheet designs and newer OEMs, suggest that adoption of MBSE is more likely as a modeling advance, or do we expect that the relative simplicity of EVs is unlikely to create a pull for MBSE adoption?*
4.2 Results

4.2.1 The proliferation of MBSE from 2017 to 2024

MBSE has existed for decades, but firms have not widely adopted it. Several companies are still trying to incorporate a Systems Engineering mindset, and only the more mature ones are likely to look at MBSE as a possible solution to complex products and processes. This section shows the evolution of MBSE adoption through 15 graphs divided into five topics. First, the work approach companies currently follow to develop their products, then MBSE usage to understand its adoption over time, and then MBSE perception, which gives information about how participants see this approach. Moreover, the roadblocks companies face in adopting MBSE and the expectations from the professionals about the peak of MBSE transformation.

Work approach

Arguably, MBSE is more beneficial for companies with highly complex products, for which it is easy to make mistakes and inefficiencies when handling numerous elements and interactions. The work approach of the companies provides a general idea of the level of maturity in their processes and their familiarity with tools and models that could serve as the first approach to MBSE.

One of the elements of a company's work approach is how they capture the data coming from their systems or products. Currently, most companies capture this data in files stored locally or shared in the cloud. However, firms migrating to MBSE might have started capturing data through models, which are claimed to be easier for sharing information and keeping teams up to date without the need to manage file versioning.

When the participants were asked how they capture the system data, they were given options to indicate if they use mostly documents or models.

Figure 4.2-1 shows a significant increase in respondents who predominantly use models to capture data from their systems over time. While in the first quarter of 2017, around 10% of
the respondents indicated the data was managed mostly through models, by the first quarter of 2024, that percentage has increased to approximately 15%. An interesting further study would be to identify the main drivers of this growth rate. Is it possible that companies do not own the tools to capture data through models or that they find a benefit in using documents over models?

Survey respondents were asked about the most sophisticated query they had written to understand how they usually proceeded. Based on Figure 4.2-2, the respondents mostly followed two approaches over time: putting data into spreadsheets or using databases like SQL. Only some have not written queries and have asked a coworker to do it instead. It is interesting to see the decrease in the use of MS access from around 20% in 2017 to nearly 10% in 2024: those users have probably migrated to SQL. Additionally, there has been an increment over time in the number of people who have used SQL themselves, which indicates not only that people are being trained to use this tool but also that professionals have become more familiar with using queries over time.
Overall, most participants' knowledge about queries seems somewhat mature as they use SQL. However, the data in spreadsheets continues to be the highest response in most of the year quarters, which is aligned with Figure 4.2-1 about how most companies capture data.

Figure 4.2-2 Approaches toward queries by percentage

One dimension of the maturity of a company’s approach to MBSE is through participants' familiarity with queries, so each possible response was assigned a number from 1 to 5, with 1 being the least sophisticated and 5 the most sophisticated, as shown in Table 4-1. Then, the numbers were averaged per course. However, the results in Figure 4.2-3 suggest no trend regarding the level of maturity over time.
Table 4-1 Levels of familiarity with queries

<table>
<thead>
<tr>
<th>Number assigned</th>
<th>Level of familiarity with queries</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>I've used databases like SQL</td>
</tr>
<tr>
<td>4</td>
<td>I've used simple databases like MS Access</td>
</tr>
<tr>
<td>3</td>
<td>I've put data in spreadsheets</td>
</tr>
<tr>
<td>2</td>
<td>I've asked my co-workers to run queries, but I haven't written a query myself</td>
</tr>
<tr>
<td>1</td>
<td>I've manually sorted through a series of documents</td>
</tr>
</tbody>
</table>

Figure 4.2-3 Average level of maturity per quarter

The use of models is at the heart of MBSE, and firms that develop complex products are likely to work with models at some point regardless of their adoption of MBSE. Teams can either start a model from a clean sheet of paper or modify existing models to achieve a specific purpose.
It was expected that the less familiar professionals are with model creation, the more probable they will use an existing model, which might reduce the ambiguity of the process. Looking at Figure 4.2-4, except for a couple of outliers, the confidence of participants to create new models has slightly increased. Over 35% of the respondents in the second quarter of 2019 stated that their companies would make a model from the ground up, and over 40% of the respondents supported this statement by the first quarter of 2024. Since it is either one option or the other, the use of existing models has slightly decreased over time. This is aligned with the idea that the adoption of models in Systems Engineering has increased in academia and industry; more students are introduced to models and can implement them once they are in the industry after graduation. Simultaneously, companies that have created Systems Engineering positions in their organizational structure look for people who can develop new models. Additionally, the pace with which technology is evolving and the supporting environment for start-up creation have opened the door to the need for new product or process models that cannot necessarily be based on existing ones.

Figure 4.2-4 Change in the percentage of approaches over time
To explain the results obtained in Figure 4.2-4, participants were also asked for the reason for their previous answers. According to Figure 4.2-5, year after year, most of the participants claim that rebuilding their numerous existing models cannot be justified, and therefore, participants continue tying existing models together. Interestingly, there has been a switch between two of the reasons from the third quarter of 2021. MBSE, being so specific to be captured in off-the-shelf tools, became the third reason, while the difficulty of tying models together across different modeling environments was the least mentioned reason. It is possible that in recent years, the implementation of MBSE has happened in novel technologies, and it is not easy to find tools capable of supporting those applications.

![Figure 4.2-5 Reasons to follow a clean sheet approach or a tied existing models approach](image)

**MBSE usage**

Every time the course is delivered, the participants are asked if their organization uses an MBSE approach. Figure 4.2-6 contains the resulting percentages from the first quarter of 2017 to the first quarter of 2024, meaning seven years. Over this period, there has been
evident growth in the number of organizations that use MBSE, from 30% in 2017 to above 50% in 2024, which means a growth rate of around 1.37% per course run with a coefficient of determination ($R^2$) of 0.6. Based on these results, it is possible to argue that Model-Based Systems Engineering has grown over the past seven years.

![Figure 4.2-6 MBSE usage in organizations](image)

Those who stated that their companies are not yet using an MBSE approach were asked how open their companies would be to adopting MBSE. Figure 4.2-7 shows that although many companies are not using this approach right now, they might use it in the future.

A transition toward MBSE would happen gradually, as reflected in the graph. Most participants stated that their companies might start the MBSE adoption in non-mission critical areas, which is a way to run pilots and assess results and benefits before deploying further. Over time, the number of professionals supporting this statement increased by around 1.5% annually. On the other hand, it is possible to see a decrease of around 0.99%
per year in the percentage of people who pointed out that their companies would not adopt MBSE. With this in mind, it is possible to argue that more firms are open to adopting MBSE in their processes, and that might be the reason they support professionals to take the “MBSE: documentation and analysis” course: to start the implementation with non-mission critical projects or initiatives and eventually make MBSE part of their core projects.

Figure 4.2-7 Applications which companies would be open to try

When adopting MBSE, companies can deploy it in specific projects in determined areas of the firm or in large programs that eventually transform the entire organization. Deploying it on a single project might depend on its complexity; if it is highly complex, MBSE is an approach that firms can leverage. It is also helpful if it is desired to test this approach in an isolated way before looking for a broader implementation. Then, this project would become a pilot.
Additionally, some professionals acquire knowledge of MBSE during their academic trajectory. Once they enter the workforce, they see the benefits of using this approach in their activities, even if the companies they work for have not adopted it. This might benefit the organization if coworkers notice the advantages of using MBSE. Nevertheless, it can be overlooked and used only by some professionals without spreading through an organization. Figure 4.2-8 shows no trend over time, and the percentages remain similar - the project-by-project basis is the most popular, with over 40% every quarter. In contrast, the individual approach is usually the least popular and remains under 20% most of the time.

Looking into why to adopt MBSE, companies might have different priorities. The transformation toward MBSE is a long path that can take years, and companies willing to go through that transformation should establish the most critical aspects to transform first. The participants were asked to rank their companies' priorities in the MBSE transformation on a scale from 1 to 5, where 1 is the highest priority and 5 is the lowest. As indicated in
Figure 4.2-9, most participants referred to process and workflows, as well as methods and models, as the top priorities. On the other hand, both the organizational culture and structure were selected as the lowest priorities. It is interesting to notice that process and workflows have been ranked higher over time, whereas the organizational aspects have been ranked lower every time. This might indicate that when companies started initiatives to incorporate MBSE in their processes and activities, they considered different areas to transform. However, throughout the years, firms might have focused the implementation on more technical and practical areas.

Similar to the priorities of the companies, there are some tasks on which MBSE is emphasized. Participants were asked to rank six options according to their company’s goals for MBSE. They ranked the goal with the most emphasis as 1 and the goal with the least emphasis as 6. The results were averaged and captured in Figure 4.2-10; the lower the average, the more emphasis on the goal. According to the results, MBSE is mainly used to
have a common understanding of the system, fostering teams collaboration. This is one of the benefits of using models; the same model is used by all teams in an organization and is linked to the second highest ranked objective, the ease of communication across teams thanks to a single and updated source of truth. On the other hand, having easy access to documentation to improve lifecycle activities is by far the lowest activity identified as an area of emphasis for MBSE.

![Rank your organization's emphasis on MBSE](image)

**Figure 4.2-10 Company goals for MBSE**

**MBSE perception**

Once the participants have completed the course and become familiar with the topic and its benefits, they are asked if they think MBSE should be implemented in their organizations. Figure 4.2-11 demonstrates that the percentage of survey respondents who point out that their companies should not implement MBSE has been constant. The main difference in the graph is between those participants whose answer is yes and those who state that their
companies are already implementing MBSE. While the former has slightly decreased at -0.64% over time, the latter has grown 0.54% every course run, as expected based on the previously shown data on MBSE adoption. The graph also shows a slight increase in participants who do not know whether MBSE should be implemented. However, the coefficient of determination is less significant to confirm a linear growth rate.

![Graph showing MBSE implementation](image)

*Figure 4.2-11 Opinion on MBSE Implementation*

One of the enablers of the transition to MBSE is the maturity of its tools. This maturity will make this approach reliable and compelling to companies, attracting them to explore its benefits and eventually migrate their processes. The MBSE maturity makes it appropriate to warrant actions and decisions within an organization. According to Figure 4.2-12, when participants were asked if MBSE was mature enough to warrant actions, most of them pointed out that the maturity of the approach is enough to create models using a standard language, which is closely related to what professionals identified as one of the main
emphasis of MBSE in Figure 4.2-10 - a single and up-to-date source of information. Interestingly, making models parametric for reuse and patterning has been consistently identified by the lowest percentage of participants.

As it was mentioned before, reusability is essential in the automotive platform architecting process, as the objective is to avoid starting from zero for the development of every vehicle.

Participants who are not sure about implementing MBSE have slightly decreased over time, while those who claim MBSE is mature enough to execute models and facilitate verification, as well as make models parametric and facilitate reuse, seem to grow marginally. Nevertheless, the coefficient of determination is not significant enough to confirm these changes are linear in time.

![Figure 4.2-12 MBSE maturity levels](image)

One of the industries that has successfully leveraged the use of MBSE is the Aerospace industry. Some factors, particular to this industry, are enabling this. The course participants,
including those working in aerospace companies, were asked about the factors that have made the Aerospace industry a leader in MBSE. As shown in Figure 4.2-13, although there has not been a significant change over time, it is clear that across the years, project and product complexity has consistently been identified as the feature that influences the high adoption of MBSE in the aerospace industry. This is expected since MBSE is usually endorsed in products with significantly high complexity.

![Figure 4.2-13 Aerospace features to become a leader in MBSE](image)

**Figure 4.2-13 Aerospace features to become a leader in MBSE**

**Roadblocks**

It has been discussed what benefits and opportunities an MBSE approach can provide to different industries and companies. Also, it has been demonstrated that Systems Engineering professionals show interest in the methodology and have a positive attitude toward transforming their processes. Then, why has MBSE not yet been adopted widely?
It is being said by professionals in the automotive industry that there are many obstacles to incorporating MBSE into the current product development process. One of the reasons is that teams do not find in models the same advantages or benefits they currently have. The participants were asked about which model qualities they think are more difficult to achieve in MBSE, and they were given 17 options to choose from.

The responses support the idea that professionals are still skeptical about the benefits of models. Figure 4.2-14 shows the highest and lowest qualities according to the respondents to avoid a busy graph. It is possible to see that participants perceive the model’s credibility as the most challenging quality to achieve over the years. The second most complicated quality to achieve is the model’s elegance, which might be linked to the fact that complex products or processes need a sophisticated model that can hardly be seen as elegant. If models are not trusted within an organization, they will hardly be used in daily activities.

Intriguingly, the options that fewer participants have selected over the years are “Validation” and “Availability of interfaces” as qualities that are easier to achieve in models. If it is possible for these professionals to validate their models, why would the models lack credibility? In the face of the unknown, participants may prefer to go with what is known, even if they have enough information to believe something new will work. It is probably a matter of risk aversion, which can be good to avoid things going wrong but can also be limiting to finding better solutions.
Probably the main reason that prevents MBSE from being welcomed by teams in an organization is the challenge of convincing stakeholders that it is worth it to migrate to this approach and change the way they currently operate. Participants were asked about the factors preventing teams from being convinced about the benefits of MBSE.

While it was expected that the unclear value was part of most of the responses, it is surprising to see that the most significant percentage every time the course has been delivered is the same: the lack of guidance on how to implement MBSE shown in Figure 4.2-15. Under the assumption that this is the main barrier for people to see the value of this approach, then ideally, the deployment of constant and in-depth training should suffice to accelerate the adoption of MBSE across industries, which leads to the questions of whether there are enough professionals knowledgeable and experienced enough to continue the dissemination of the methodology. It is intriguing why the guidance on MBSE implementation has not improved over the past seven years. Literature refers to initiatives and pilots that have surged in different companies trying to implement MBSE. However, the way in which learning and knowledge propagation happened is not mentioned. An investment is required to acquire the MBSE know-how, and possibly, these resources have
been limited to some individuals expecting them to become experts in the matter and lead the transformation in their firms. These individuals may guide the transformation but not necessarily train others with the MBSE theory; therefore, knowledge remains somewhat isolated.

![Graph showing reasons why MBSE does not convince professionals](image)

*Figure 4.2-15 Reasons why MBSE does not convince professionals*

**Expectations**

As with new technologies, when methodologies are developed, there is speculation about their success; they can be expected to revolutionize the industry or only be trials that fail over time. Professionals’ perspectives about MBSE have likely changed throughout the years. It is very interesting to see in Figure 4.2-16 that professionals keep an optimistic perspective that MBSE will be a hit in the mid-term. Those asked in 2017, 2018, and 2019 seemed optimistic about 2020 and less positive about 2030. Nevertheless, as years pass by and we approach 2030, the optimism for this year to be the hit for MBSE increases. On the
other hand, the percentage of survey respondents that claim 2025 to be the year has decreased as we approach that date.

It would be interesting to know the metrics to assess whether MBSE is a hit or not in the future and understand how close the forecast was with professionals familiar with Systems Engineering.

Figure 4.2-17 shows the weighted average percentage of the participants throughout seven years. Notably, 2020 has had the highest rate, followed by 2025 and 2030. It is possible that 2020 was the furthest year people could choose for the first surveys, which is why the percentage is so high. This is probably because it is more common for people to refer to years by multiples of 5 or 10 years. When the option of 2025 became available, most of the responses moved to that year, and 2030 was probably not an option in 2017 because it was very far away. However, survey respondents began to see it as a possibility as it came closer.

![Figure 4.2-16 Predicted year for MBSE to become a hit](image)

*Figure 4.2-16 Predicted year for MBSE to become a hit*
4.2.2 MBSE trends in the automotive industry

This section presents the same questions for the subset of survey respondents in the automotive industry; around one-fifth of the participants who took the “MBSE: documentation and analysis” course (Figure 4.2-18). This is equivalent to more than 1000 professionals, of which almost 60% work in an OEM and around 6% work in a Tier 1 supplier (Figure 4.2-19). Moreover, the participants represent 9 of the Top 25 automotive OEMs, like Ford, Hyundai and Volkswagen. Therefore, the collected knowledge is assumed to be significant in reflecting the perspective of the automotive sector.
Figure 4.2-18 Percentage of participants from the automotive industry

Figure 4.2-19 Distribution of survey respondents within the automotive sector
Additionally, Figure 4.2-20 shows the regions represented by OEMs and Tier 1 suppliers. More than half of the companies in the data are from North America, mainly the United States. The lowest representation is from Asian companies.

![Region of origin of OEMs and Tier 1 suppliers](image)

Figure 4.2-20 Region of origin of OEMs and Tier 1 suppliers

As was presented in the previous section, the responses to every question will be displayed through graphs, and the findings will be discussed.

**Work approach**

The complexity of the vehicle development process has been discussed throughout the chapters of this thesis; the amount of data involved needs to be handled efficiently. As Figure 4.2-21 shows, the automotive industry captures this data mostly using documents like the rest of the industries. However, the percentage of professionals capturing the data in models is higher than that of other industries, reaching almost 20%. This might be a good
indicator that MBSE is more likely to happen since more people are familiar with the use of models already.

Nevertheless, the following question provides a different perspective. Even though more professionals are using models to capture data in the automotive industry, only a few are familiar with databases like SQL compared to other sectors. Figure 4.2-22 shows that while in other industries SQL is used by around 35% of the participants, those in the auto sector are just above 20%. More than 40% are still putting data in spreadsheets, and almost 15% are manually sorting documents, practices that are less common in other industries according to the percentages shown. This shows a potential opportunity for higher adoption of databases, which might improve how data is managed in the car industry.
Chapter two helped understand the focus of automakers to achieve commonality across vehicles to improve the efficiency of their processes and reduce cost. Most interviewees supported this idea in Chapter Three, claiming that new architectures and platforms usually have a reference development to base on. Before the rise of BEV-dedicated platforms, developing a platform from a clean sheet of paper was not usual. However, nowadays, the electrification of mobility and the fast advancements of technologies in the auto sector might push car companies to work on clean sheet designs and move faster. Figure 4.2-23 shows that whereas over 40% of other industries build models from the ground up, the automotive sector remains conservative, with around 30% of professionals working on entirely new designs. Considering that the data used in the graphs includes participants from 2019 to 2024, this percentage may be higher in the coming years due to the current BEV-dedicated platforms being designed. Given the difference in the number of participants in each sample, a z-test was performed, obtaining a p-value of 6.72e-12, which confirms the percentage difference of the survey respondents building models from the ground up is statistically significant.
Regarding the previous question, respondents were asked about the reasons for using either existing models or a clean sheet design. Supporting the idea mentioned before, Figure 4.2-24 shows that professionals in the auto sector think that the number of existing models is such that working on an entirely new model would be unjustified. This statement might change now that the market demands new platform architectures, which would justify a new design. On the other hand, other companies highlight how productive clean sheet software can be, which might explain why almost 50% of participants work on models from the ground up.

Figure 4.2-23 Comparison between modeling approaches
MBSE usage

After exploring the differences in the work approach of the automotive sector compared to other industries, the level of adoption that MBSE has achieved on both sides is presented.

According to Figure 4.2-25, there is a significant difference in the usage of an MBSE approach. Opposite to around 45% in other industries, about 60% of participants in the automotive industry claim that their companies are already using MBSE.
Despite the variation shown in Figure 4.2-25, the growth rate between the automotive and other industries is significantly different. Surprisingly, Figure 4.2-26 shows that there has not been growth in the adoption of MBSE in the automotive industry, while according to Figure 4.2-27, the growth in other industries is around 0.87%. This might mean that from 2020, more professionals in the automotive industry use MBSE than in other sectors. However, the adoption has not increased; therefore, other industries might eventually surpass the usage in automotive. Later, this section presents the challenges the automotive industry faces in continuing MBSE adoption.
Figure 4.2-26 Change in MBSE use in the automotive industry over time

Figure 4.2-27 Change in MBSE use in other industries over time
Out of the approximately 20% that claimed their companies are not using MBSE, more than 90% believe their companies might try. Like in other industries, in the auto sector, most companies would prefer to implement MBSE in a sandbox environment that would not affect mission-critical areas. Nevertheless, the percentage of other companies willing to try mission-critical applications is higher than that of automotive companies, which might be related to the industry’s risk aversion (Figure 4.2-28). The long-time development of automobile projects is likely one reason to avoid such a risk with a different approach.

![Figure 4.2-28 Comparison of level of company’s openness to MBSE adoption](image)

While it has been discussed whether the car industry is using MBSE and to what extent, it is still necessary to know the approach companies follow in implementation. Figure 4.2-29 shows how MBSE is distributed, and interestingly, car companies are mainly pursuing a general implementation through programs that lead to a more extensive transformation. About 45% of the participants using MBSE follow this approach compared to just above 30% in other industries, in which almost 50% of the MBSE initiatives are on a project-by-project basis.
Based on this, it is possible to argue that automotive companies already plan to transform their processes to an MBSE approach and not just pilot projects to see how they result. Whether the transformation will conclude and when that will happen remains unsolved. More importantly, the transformation toward MBSE might be linked to the changes happening along with electrification. As mentioned in Chapter Two, the development of BEV-dedicated platforms is challenging the mental models of legacy automakers and might be part of the large MBSE adoption programs occurring in OEMs. As mentioned by some authors, BEVs have brought additional stakeholders and technologies to the scene, and conventional methodologies and tools might not be enough to manage the increasing complexity (Brankovic et al., 2021; Góngora et al., 2013). Here is where MBSE can play an important role.

Going one level below with those companies already using MBSE, participants were asked about their companies’ priorities during the adoption of MBSE. They ranked five aspects using 1 as the highest priority and 5 as the lowest priority. In Figure 4.2-30, it is possible to see the consistency of priorities across all industries, including automotive. The top priority is process and workflows, meaning the sequence of tasks to reach a target. The difference
observed between both sectors is the lowest priority. Opposite the other industries in which organizational structure is the lowest priority, the automotive industry gives the least importance to organizational culture, which is related to the informal relationships in the working environment. Formal and informal organizational aspects are the lowest priorities inside and outside the car industry, probably because they are not closely related to the complexity of the product itself. Overall, there is no significant change in priorities between the automotive and other sectors.

![Organization's priorities ranking in the MBSE transformation](image)

*Figure 4.2-30 Comparison between MBSE transformation priorities*

To understand in detail what the automobile companies' specific objectives are with adopting MBSE, it is necessary to go one more level below and know the emphasis companies put on MBSE. Figure 4.2-31 provides six possible goals companies are likely to pursue with MBSE. Participants ranked these objectives and assigned 1 to the one with the most significant emphasis and 6 to the one with the least emphasis. While other companies center their attention on having a shared system across teams that improves collaboration,
the auto sector emphasizes cost and cycle time reduction through understanding problems. This might not be a surprise given that the automobile market is highly dynamic, and in recent years, fierce competitors such as Tesla, BYD, Rivian, and Lucid have entered the market to develop BEVs. Launching new vehicle models faster and with lower costs is necessary for OEMs to remain in the market.

Facilitating collaboration across teams is the second objective for the automotive participants, while for other industries, it is having a single and updated source of information to improve communication. This objective is the fourth in the list of automakers. These differences are interesting and suggest that the emphasis of MBSE in the automotive industry is more focused on cost efficiencies and documentation rather than improving how teams communicate through a single system.

![Comparison between company's goals with MBSE](image)

*Figure 4.2-31 Comparison between company’s goals with MBSE*
MBSE perception

Regardless of whether MBSE has already been implemented in their companies or not, participants were asked whether they thought their firms should implement MBSE. Surprisingly, even if the course the professionals are taking is about MBSE, some pointed out that MBSE should not be implemented. What is important to notice in Figure 4.2-32 is that the percentage of the automotive industry professionals that think MBSE should be implemented or have already implemented it is slightly higher than the one in other industries. However, in general, there is a positive attitude towards adopting MBSE.

Even though MBSE is growing, its level of maturity can be perceived differently among the industries and therefore, the actions it can achieve vary. Across sectors, it is clear that most participants think that the maturity of MBSE is enough to create models using a common language. However, in the auto sector, one-quarter of the respondents are not sure of the maturity of this approach. This is a higher percentage than those who think the system models can be integrated using MBSE, which is the second choice in the rest of industries (Figure 4.2-33). The skepticism shown by automotive industry participants is likely related to the MBSE value proposition not being communicated (D’Ambrosio & Soremekun, 2017). It is possible that in other industries, this value is better communicated due to the nature of the product or process, causing less skepticism among the survey respondents.
As mentioned before, the aerospace industry has become a reference for the transformation to MBSE. Despite the difference in production volume, the similar complexity between aircraft and vehicles could make MBSE a good fit for both industries. The features that participants identified to make aerospace the industry leader for MBSE are shown in Figure 4.2-34.

There is no difference between the automotive and other industries in the perception of these features; the complexity of aerospace remains the primary feature, making aerospace the leader in MBSE.
MBSE has existed for over a decade, yet only some industries and companies have adopted it. Even if organizations identify it as a promising approach, some challenges must still be addressed to increase adoption. Many aspects can characterize a model. However, MBSE might only be able to satisfy some of them. The participants were asked to identify those that were more difficult to achieve, and their responses were quantified in Figure 4.2-35. Both model credibility and elegance are the most challenging qualities to achieve. However, in the auto industry, it seems there is more skepticism since the percentage of model credibility is higher.

Conversely, validation and verification are considered the least challenging qualities for MBSE to achieve. Nevertheless, the availability of interfaces seems to be even easier than
being verifiable for other industries. Overall, the challenges are consistent across different sectors, including the automotive.

One of the most complex challenges MBSE has faced is to show benefits to the stakeholders who are skeptical about its implementation. There are several reasons why it is not an easy task to convince people about the benefits of MBSE, and Figure 4.2-36 shows what professionals think are the most common reasons. The main one is the lack of guidance on implementing this approach, just like the other industries. After identifying the unclear value of MBSE as the second reason, the car sector refers to the difficulty of finding best practices. At the same time, the rest of the industries claim the concepts of MBSE are too high-level. The car industry may find it more difficult to find best practices than other industries because, based on the previous sections, the auto industry is ahead of others in terms of MBSE implementation. Other industries might use best practices from the automotive industry or other leading sector. Despite these slight differences, after performing a z-test of the percentage differences, it is possible to conclude that they are not statistically
significant. The only exception is the difference in the lack of MBSE implementation guidelines, with a p-value of 0.036. Nevertheless, this is the top selection, regardless of the industry.

![Image showing reasons why MBSE might not be convincing]

*Figure 4.2-36 Comparison between reasons why MBSE might not be convincing*

**Expectations**

Finally, the experts' forecast might give insight into what will happen in the coming years. Figure 4.2-37 demonstrates that professionals in the automotive sector remain optimistic, with more than 50% stating that MBSE is already a hit and over 20% predicting it will be by 2025. Below 50% of the participants from other industries consider MBSE a current hit, and around 25% expect it to be by 2025. Overall, around 80% of all sectors are positive that MBSE will be a big hit by 2025.
4.2.3 Conclusion and discussion

It is essential to understand the limitations of this study. While the number of survey respondents is enough to obtain insights about Model-Based Systems Engineering in the industry, participants signed up for the course to learn MBSE, meaning their responses may differ from those of MBSE experts. Moreover, participants may not have access to all the data and projects in their companies, which may hide valuable information about MBSE-related initiatives. This is confirmed in those questions for which many participants stated they ignored or were unsure about the answer. Additionally, regarding demography, most survey respondents work for American companies, which may skew the answers to a specific region rather than provide a global outlook.

The first phase of this chapter showed that MBSE implementation is not only happening but growing year after year; more professionals are becoming familiar with models and using them instead of documents. Most companies use it in projects that do not impact critical areas, and they focus on processes and methods. Participants are optimistic about MBSE becoming a hit by the decade's end, but some challenges must be solved. The most relevant
problem for adopting MBSE is the lack of guidance on its implementation. Suppose the
growth rate of the MBSE adoption continues to be positive. In that case, in the next decade,
the maturity level of the methodology and its tools will likely have reached a point that eases
the transformation companies are pursuing to manage complexity.

In the second phase of this study, the analysis showed that the automotive sector has a
higher adoption of Model-Based Systems Engineering. It has created large programs to
deploy MBSE and not just launched isolated pilot initiatives, demonstrating commitment
and maturity to transform its processes and methods as its top priority. Opposite to other
industries, carmakers put MBSE emphasis on cost reduction and the improvement of cycle
times to face the increasing competence of the market.

As one of the leading industries in MBSE, the lack of guidance in implementing the approach
and the credibility of models are roadblocks that the automotive sector must face to
continue with the adoption. Although the level of MBSE implementation is higher than in
other companies, for the automotive industry, this level has not grown in four years, nor has
the guidance or training on MBSE to achieve the transformation. These are two key factors
that must be solved to expand MBSE implementation. Fortunately, professionals in this
sector remain optimistic about the implementation of MBSE in the coming years and
continue enrolling in courses to learn more about the methodology and apply their
knowledge in their companies.

As mentioned in Chapter Two, using MBSE to develop platform architectures has provided
important insights into the automotive industry. It is clear that even though BEVs have fewer
pieces, the level of multidomain integration they require due to the increasing software,
connectivity, and autonomy cannot be addressed with conventional methodologies. The
platform architecture process, which happens in the early phases of vehicle development,
can highly influence the design's success in later stages. Therefore, a structured
methodology must be used during this process. As discussed in this chapter, the aerospace
industry is leading the use of MBSE due to its high complexity. A similar complexity
demanded by BEV-dedicated platforms and software-defined vehicles will require a mature
and reliable methodology that works with other approaches like modularity to deliver vehicles on time and efficiently. In a time of disruption, when new platforms and architectures have to be redefined, MBSE has a promising opportunity to play a role in transforming the vehicle development process through the redefinition of the Architecting Process.
Chapter V

5 Conclusion and Future Work

5.1 Conclusion

This thesis aims to address two research questions:

- *Do we expect OEMs and Tier 1 suppliers to use a different process to architect EVs, as compared with ICE vehicles?*

- *Does the shift towards EVs, with more clean-sheet designs and newer OEMs, suggest that adoption of MBSE is more likely as a modeling advance, or do we expect that the relative simplicity of EVs is unlikely to create a pull for MBSE adoption?*

Chapter I presented the motivation for studying the vehicle platform architecting process, its differences between Internal Combustion Engine Vehicles (ICEVs) and Battery Electric Vehicles (BEVs), and the Model-Based Systems Engineering (MBSE) methodology as an alternative for architecting BEV-dedicated platforms. Then, chapter II explored the literature and the perspectives from which numerous authors have discussed both the architecting process and the MBSE methodology. It also defined key concepts to set the stage for Chapter III. Chapter III covered the first analysis by interviewing experienced automotive industry professionals about their experience in the architecting process and its differences when developing ICEVs and BEVs. This study's objective was to answer this thesis's first research question. Finally, Chapter IV performed the second analysis by studying data collected from professionals who have enrolled in an MIT MBSE course over the last seven years. This study aimed to answer the second research question.

Chapter V aims to integrate the information gathered from the literature and the findings from both analyses to answer the research questions.
1) *Do we expect OEMs and Tier 1 suppliers to use a different process to architect EVs, as compared with ICE vehicles?*

The fundamentals of the architecting process between both types of vehicles are not expected to change. However, there will be nuances between architecting a BEV and an ICEV derived from new technologies accompanying BEVs.

According to the literature and the interviews with experts from the automotive industry, the architecting process followed to develop ICEVs should remain the same as that of developing BEVs. The steps are essentially the same: gather requirements, translate them to functions, decompose the system according to those functions, and perform architectural decisions to propose a set of concepts, evaluate them, and select an architecture to continue the engineering process for detailed design. The fewer moving pieces of the electrified powertrain make BEVs appear simpler to design. Nevertheless, technologies like connectivity and autonomy entail the presence of new modules, the creation of new interfaces, and a substantial amount of software that skyrockets the complexity of a vehicle. This complexity increases the difficulty of the BEV architecting process, demanding different methodologies and tools capable of integrating the hardware, electric & electronic, and software domains.

According to the interviews, specific strategies some companies follow during the architecting process have resulted in benefits. Actions like tracking the incompatibility between modules, identifying key interfaces, and planning iterations reduce the perception of difficulty experienced by professionals designing BEVs. Therefore, it is reasonable to say that process maturity and discipline can ease the transition toward architecting BEVs. The mentioned methodologies, tools, and actions are the nuances that differentiate the BEV and the ICE architecting processes.
2) *Does the shift towards EVs, with more clean-sheet designs and newer OEMs, suggest that adoption of MBSE is more likely as a modeling advance, or do we expect that the relative simplicity of EVs is unlikely to create a pull for MBSE adoption?*

The development of new BEV-dedicated platforms opens the possibility for MBSE to grow its adoption to help automakers manage the increasing complexity. However, this will happen only if existing challenges are addressed, especially the increment of guidelines on implementing MBSE.

The implementation of MBSE in various industries has grown at a rate of around 4.11% year over year. It has mainly focused on processes and workflows to provide a shared system that improves team communication. On the other hand, its growth is hindered by the limited credibility of its models. An improved strategy to guide enterprises on implementing MBSE and a better articulation of the value proposition of the methodology are essential to continue its adoption.

In the case of the automotive industry, MBSE is an alternative that has yet to be exploited. Although the automotive industry has a higher rate of MBSE adoption than other industries, it’s penetration has not grown over the past four years, and the models used are existing rather than new ones. On the bright side, evidence suggests that MBSE is being implemented in programs that target a larger transformation. Given the transition toward electrification and software-defined vehicles, it is reasonable to assume that these programs aim to address these new challenges.

Like other industries, the models lack credibility, which is tied to one of the two significant challenges in MBSE adoption – the unclear value of the methodology. The other and more relevant challenge is the lack of guidelines on its implementation.

MBSE is a potential solution to handle the highly complex clean-sheet designs of BEVs due to the benefits that have been proven on a small scale. However, a more extensive adoption requires investment in professionals’ training, software tools, and a change in the collective mindset and organizational culture.
5.2 Future research opportunities

The findings and conclusions obtained in this thesis resulted in thought-provoking questions that, although outside of the scope of this study, are appealing to research.

The first study of this research related to the architecting process can be complemented with detailed data from specific case studies from automakers. A detailed architecting process map and metrics to assess the resulting platforms from legacy and BEV-only OEMs could provide precise differences and their impact on the resulting architecture.

The second study related to MBSE adoption can be continued by researching the exact processes in which automakers are implementing MBSE to understand whether the benefits of this methodology are being used in the architecting process of ICEVs or BEVs. Also, to decode the biggest challenge for the MBSE implementation, it is essential to research the reasons for the lack of guidelines: how the knowledge of the MBSE experts is being disseminated in organizations, and why have guidelines not been created? Additionally, the insignificant growth rate in adopting MBSE in the automotive industry is intriguing and can be investigated to identify specific roadblocks.

Finally, other methodologies, different from MBSE, that can be implemented in the architecting process can be studied to understand if there are better fits depending on the vehicle type or the architecture domain.

The pace of technology advancements in the automotive industry is exponential and can impact the entire product development process. Research on making the architecting process more efficient in the face of these advancements will always be necessary.
List of questions performed during the interviews

Q1. How do you define architecture?

Q2. Please describe the architecting process on a high level.

Q3. What role do you play in the architecting process?

Q4. What do you feel works well during the architecting process?

Q5. What do you feel does not work well during the architecting process?

Q6. What differences in the architecting process do you identify from previous companies or roles?

Q7. Do you think the Battery Electric Vehicle (BEV) architecting process should be different than the Internal Combustion Engine (ICE) process?

Q8. Do you follow any methodology to develop BEVs architecture?

Q9. Roughly what fraction of the total person-months (time) is the architecting process?

Q10. How many BEVs has your company released for sale historically, not counting trim levels?

Q11. What is your perception of the difficulty of designing BEVs compared to ICEs: is this basically a simple integration, or are there a lot of moving pieces with unknown interactions?

Q12. On a scale of 1-10, 1 being a minor change like seat material, and 10 being the most demanding clean-sheet design, how difficult do you expect new BEV luxury sedans to be?
Q13. Do you maintain a functional decomposition separate from the Bill of Materials and the Modules list during the architecting process? Would this change for EVs?

Q14. What fraction of requirements do you expect would carry over from ICE designs to EVs, and what fraction of requirements will be new to BEVs?

Q15. Tell me about a time when you incorporated a new technology into a vehicle. What process did you use to integrate that technology?

Q16. Tell me about a time when you traded between two competing decisions. (ex: what voltage vs battery size?)

Q17. Do you have a small number of corner-case vehicle configurations you manage or estimate against during the architecting process?

Q18. Do you identify and track which architectural decisions are incompatible (e.g., this electric motor does not work with this battery type)?

Q19. How many different candidate BEV architectures do you think should be considered when building a new EV? Is that the same number as are considered for ICEs, in your experience?

Q20. What would you judge are the error bars during architecture evaluation for your metrics: +/- 1%, +/- 5%, +/- 10%, +/- 20%, +/- 50%?

Q21. Is there a list of key interfaces that is maintained for each architecture?

Q22. Are there areas of a BEV vehicle that could be better integrated into a next-generation architecture? Do they cause bottlenecks during the design process?

Q23. In which stages of the ICE architecting process do the teams usually encounter rework? Do you expect the timing to be the same, earlier, or later, on BEVs?
Q24. Tell me about a time when you managed the changing of an ICE architectural decision within a vehicle program. Do you expect that similar magnitude changes will run more smoothly or less smoothly on a BEV program?

Q25. Do you deliberately structure iteration (rework) into the development process? Do you expect that similar rework will run more smoothly or less smoothly on a BEV program?

Q26. In what year do you personally think BEVs will comprise 50% of US sales?
7 References


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