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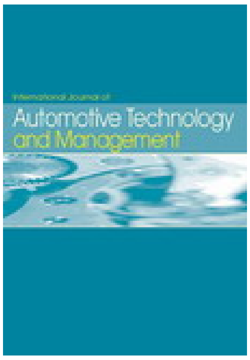

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Prototyping in motorsports: exploring manufacturer-supplier collaboration in Formula One

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Abstract: Formula One is at the forefront of technological advances in the automotive and motorsport industries. The sport serves as a testing ground for cutting-edge technologies that often find their way into mainstream automotive applications. The development process is accompanied by pressure to innovate, regulatory constraints, and time and cost constraints. In this context, prototyping plays a special role in accelerating development success. This study explores the complex interplay between OEMs and suppliers and the dynamics in the prototyping process between OEMs and suppliers in the F1 supply chain using a case study approach based on archival data and an online survey. The aim is to learn from the unique interplay of requirements and pressure to succeed in order to optimise prototyping processes beyond F1. Using the 2022 season racing teams as an example, the complex supplier relationships and regulatory influences on development are explored. The factors that contribute to successful collaboration and those that hinder progress are highlighted. The results offer practical implications for OEMs and suppliers outside of Formula One on how to use the prototyping phase as a catalyst for successful product development.

Keywords: prototyping; collaboration; vertical relationships; product development.

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1 Introduction

In a constantly evolving automotive landscape characterised by fierce competition and technological change, OEMs face the challenging task of developing products efficiently with limited budgets and time constraints, while maintaining quality and safety standards (Elverum and Welo, 2015). On top of that, regulatory requirements are limiting design freedom. This balancing act becomes even more challenging with the need for advanced technologies and increasing complexity due to the proliferation of vehicle software (Xie et al., 2020; Ashjaei et al., 2021). Against this backdrop, OEMs are faced with the daunting task of navigating a domain where variant diversity and complexity seem limitless. These challenges require a fundamental reassessment of research and development (R&D) processes to address the prevailing technology and resource gaps (Jáki and Halmosi, 2022). This study focuses on the central role of Formula One (F1) racing teams in addressing these challenges. Partnerships between OEMs and F1 teams facilitate the development, testing, refinement, and validation of breakthrough innovations. F1's extreme racing conditions provide a unique testing ground for optimising critical automotive technologies, with a particular focus on engine efficiency, aerodynamics and lightweight materials. This collaboration is a mutually beneficial exchange. F1 teams gain access to OEMs' technical expertise and resources, enabling them to build on their competitive advantage. In turn, the OEMs gain invaluable opportunities for innovation and technology transfer, enabling them to strengthen their position in the rapidly evolving automotive industry (Skeete, 2019).

While previous studies have examined the entire new product development (NPD) process (Suurmond et al., 2020; Wynstra et al., 2010; Martinez Sanchez and Perez Perez, 2003), this study focuses on the merger dynamics between suppliers and OEMs in the prototyping phase of the development process in F1. Prototyping is the process of developing an approximation of the final product. In this process, any entity of interest can be defined as a prototype for the development team, different forms of prototypes such as concepts, test components, and functional pre-product versions included (Ulrich and Eppinger, 2016). Following the principle of trial and error, technological innovations can be developed and tested in the shortest possible time and with the least amount of development effort.

However, the development of a new vehicle can only be achieved with the use of additional resources or the purchase of components or modules. Therefore, suppliers play a crucial role in this process. Whereas in the past, the contract focused only on delivery, today, the suppliers' knowledge and involvement in the process are also of interest (Stock et al., 2021; Wang and Hu, 2020). This study aims to answer the following question: "What are the key dynamics and challenges within the F1 supply chain, and how can original equipment manufacturers (OEMs) and suppliers navigate these complexities to achieve successful collaboration?"

A case study approach was chosen to answer the research question. The analysis of prototyping in F1 provides a unique perspective on innovation, performance optimisation, and interdisciplinary collaboration between OEMs and suppliers. In addition to an intensive study of the regulatory constraints of the Fédération Internationale de l'Automobile (FIA), an online survey of OEMs and suppliers was conducted to gain deeper insights into the motorsport ecosystem.

Overall, this paper analyses the implications of F1 R&D collaboration between OEMs and suppliers in the prototyping phase. It extends the knowledge-based view of prototyping and argues that two dimensions are crucial in practice: regulatory influences and the form of collaboration. It shows three types of collaboration, which differ in the degree of involvement: self-development, purchased development and partnered development.

This paper contributes to the literature in two ways. First, it is one of the first to focus on analysing the impact of regulatory-influenced R&D collaborations on the critical prototyping phase. Second, this paper contributes to the literature on R&D collaborations between suppliers and OEMs by explaining the added value of such partnerships from both perspectives and showing how they have changed. A distinction is made between the fundamental theories of the prototyping phenomenon and its real-world implementation. The term 'collaborative prototyping' is introduced to present a more comprehensible framework for managers aiming to enhance their grasp of utilising R&D collaboration during the prototyping phase.

This paper is organised as follows. First, it briefly discusses F1 and prototyping as a phase of NPD. Second, the research design and structure of the case study conducted and the results of the case study are outlined. Finally, considerations for future research on prototyping and the dynamics in the relationship between OEMs and suppliers are highlighted and the limitations of the case study are presented.

2 Theoretical background

F1 is a racing series sanctioned by the FIA. Participating teams design and develop cars that have to meet the technical specifications of the F1 regulations. It stands for performance, innovation, and technical mastery through the development of sophisticated racing machines. The advanced technologies developed in F1 often lead to breakthroughs in the automotive industry as technologies are validated, and use cases are proven (Skeete, 2019). Whereas championships can measure the results of F1 engineers' work to date, the development path to a title is fraught with constraints. For example, the pressure to innovate with fewer resources and less time is a challenge for engineers in all industries – these are just three (time, cost, innovation) of many challenges engineers face every year (Jenkins, 2010). In addition to the constraints imposed on race teams by specifications and limited resources, the governing body of F1, the Fédération Internationale de l'Automobil, significantly influences the development process (Marino et al., 2015). For example, the introduction of a budget cap in 2021 was intended to make competition in sports more sustainable and balanced. This cap has made it even more important for suppliers and OEMs to collaborate efficiently on R&D.

Crucially, F1, with its global platform, acts as an ecosystem for collaboration between different companies in the automotive industry as well as research institutions. This convergence promotes the exchange of expertise, new technologies as well as the evaluation of best practices. With these insights, the automotive industry is driven into new areas of innovation and development. Due to fierce competition, the automotive industry is in a constant state of flux. Balancing efficient product development with limited budgets and compressed timelines without compromising quality and safety standards often leads to difficult hurdles (Elverum and Welo, 2015). These fundamental challenges, which have always existed, are exacerbated by advanced technologies and the complexity factor, which continues to increase due to the growing amount of vehicle software (Xie et al., 2020; Ashjaei et al., 2021). Whereas in the past the hardware of a vehicle contributed to customer satisfaction, today it is primarily the software that is becoming the key differentiator (Liu et al., 2022). This opens up new business models for OEMs and suppliers to meet market needs and customer expectations (Zhao et al., 2022) and requires a rethinking of R&D processes to bridge technology and resource gaps (Jáki and Halmosi, 2022). In addition, uncertainty must be minimised by involving stakeholders as early as possible in the NPD process (Barrane et al., 2021; Tuli and

Shankar, 2015). A distinction must be made between internal and external stakeholders (Gheshmi, 2019; Ahmadi-Gh and Bello-Pintado, 2021).

Internal measures can include fostering cross-functional collaboration between design, engineering, manufacturing, and supply chain teams (Agren et al., 2022). Moreover, agile development methodologies, such as rapid prototyping or iterative development processes, can help enable rapid feedback loops and speed decision-making to reduce time to market (Marion and Fixson, 2021). Furthermore, reducing the reliance on physical prototypes in the early stages of development through simulation tools, virtual prototyping, and digital twins (Madni et al., 2019; Leng et al., 2021; Lo et al., 2021) can accelerate the development cycle and optimise designs.

However, such internal measures cannot be considered in isolation, as suppliers are increasingly involved. While in the past, the supplier was responsible for the proper delivery of parts, the level of involvement and knowledge is increasingly shifting in the automotive industry today.

Research has widely discussed early supplier involvement (Mikkelsen and Johnsen, 2019). Previous research has shown that supplier involvement significantly improved NPD performance (Zirger and Maidique, 1990; Eisenhardt and Tabrizi, 1995; Clark, 1989; Lawson et al., 2015). In addition, suppliers are a source of innovation and technological expertise, acting as idea generators and they are influencing various aspects such as project and manufacturing cost reduction, improved functionality, and enhanced manufacturability (Birou and Fawcett, 1994; Bonaccorsi and Lipparini, 1994; Ragatz et al., 1997; Lau et al., 2010).

These advantages must be leveraged to meet the diverse challenges of the automotive industry. However, successful collaboration between suppliers and OEMs often fails due a lack of understanding of the supplier identification and integration process (Petersen et al.). This situation requires an analysis of all phases of the NPD process to understand the current situation and to identify optimisation potentials in the collaboration. Therefore, the prototyping phase is examined in this study.

The prototyping phase is crucial in NPD (Lauff et al., 2018; Wall et al., 1992; Elverum and Welo, 2014). Prototyping is an experimental process phase of creating multiple versions or models of a product during the development phase. In this process, these models are created and refined sequentially based on feedback, testing, and improvements until the desired specification is best met. In contrast, a prototype refers to a specific, individual model or version that is created within the prototyping process. The definition of a prototype varies due to its wide range of applications. According to Lim et al. (2008), a prototype represents a design idea before the existence of the final product, for example. Supporting this view, Wall et al. (1992) define a prototype as the first object of its kind. At the same time, Houde and Hill (1997) include all forms of design idea representations, regardless of the medium, including existing objects. Beaudouin-Lafon and Mackay (2012) provide a more specific definition, highlighting the importance of tangibility and excluding abstract descriptions requiring interpretation.

Many studies show the diverse use of prototypes within the development cycle. According to Lauff et al. (2018), prototypes facilitate communication, aid in learning, and decision-making at any stage of the design process. Furthermore, Yu et al. (2018), Liao et al. (2009), and Houde and Hill (1997) emphasise the opportunities that prototypes offer for testing and showcasing features. Wall et al. (1992) make a broader statement, emphasising the testing and utilisation of technology to answer questions. In addition, Otto and Wood (2001) address the significance of prototypes throughout the process, using them to gain insights and ensure project progress with minimal effort. Although the importance of prototypes is clearly emphasised in research, their use in practice has been largely unexplored (Elverum and Welo, 2016). While previous research has considered supplier involvement from a holistic perspective across NPD (Chae et al., 2020; Petersen et al.), there is limited research on effective involvement in individual phases of the NPD (Martinez Sanchez and Perez Perez, 2003). As this literature review shows, the automotive industry faces several challenges that it cannot overcome without access to additional resources. The early involvement of suppliers in the prototyping phase and the associated access to knowledge can help to overcome these complex challenges. This study examines this challenge using F1 as an example. While the automotive industry is dealing with challenges ranging from sustainability to performance enhancement, F1 is both an inspiration and a driver. The sport's focus on adding hybrid powertrains and other environmentally friendly technologies is a pathfinder for the automotive industry. The symbiotic relationship between Formula 1 and automotive OEMs underscores the potential for progress and innovation. Analysing prototyping in F1 provides a focused and specialised perspective that can provide insights into rapid innovation, high-performance engineering, and collaborative strategies that might not be evident in the broader automotive landscape.

F1 teams continuously develop and refine their prototypes throughout the racing season. With rapid iteration cycles and time, cost, and regulatory constraints that do not allow for expansion, dynamic relationships, and impacts can be uniquely analysed and evaluated.

3 Research design

The F1 is a dynamic environment strongly influenced by external requirements – customers, politics, and competitors. The involvement of suppliers plays an important role, as they act as an additional resource but also bring knowledge and experience to the development teams. This paper aims to find out how the role of suppliers has changed. To this end, a combination of documents from the FIA, official information from F1 teams, and an online survey of OEMs and suppliers was used. This approach integrates quantitative and qualitative methods to gain a comprehensive understanding of the dynamics despite the inaccessibility of internal development data.

3.1 The case: Formula One

Formula One, often referred to as F1, is one of the world's most popular and widely watched racing series. Historically, F1 has its roots in the early 20th century when racing became popular in Europe. The governing body of international motorsports, the FIA, was founded in 1946 and created the first F1 World Championship in 1950. Over the years, F1 has undergone many changes, such as its technical regulations and worldwide popularity.

The history of F1 shows a remarkable journey from the early days of establishing a new racing format to a high-speed race that produces cutting-edge technologies. The different aspects of F1 become apparent when looking at the organisational structures, the technical regulations, and the dynamics of the relationships between suppliers and OEMs.

3.2 Data collection and analysis

F1 is known for its cutting-edge technology, rapid innovation and development cycles, and complex supplier-OEM relationships. Unlike traditional industries, F1 is subject to strict regulations by the Federation Internationale de l'Automobile. In contrast to the conventional automotive industry, OEMs that own a F1 team as a holding company also supply other teams with engines, for example. These unique characteristics make F1 an exciting environment to study the interplay between suppliers and OEMs. To this end, information about the engine manufacturer was collected from the F1 team websites. This was then correlated to show the relationships between OEMs, suppliers, and race teams. As part of the study, supplier relationships were assessed concerning the engine supplies for the 2022 season.

In addition, a structured survey was developed to gather insights from suppliers and OEMs. The questionnaire was designed to collect quantitative data on supplier and OEM relationships, challenges, benefits, and perspectives. Key suppliers, including those providing engine components, aerodynamic solutions, and specialty materials, were invited to participate in an online survey highlighting various aspects of the collaboration. Furthermore, existing partnerships were identified by searching the teams' websites. The companies identified were researched via LinkedIn, and employees of these companies were contacted directly.

As R&D departments are very protective and personal information is not published on websites, 63 people were contacted. Of these, 21 responded to the online survey. The participants were R&D employees, who gave insights into their collaboration processes with OEMs. Two criteria were used to select suitable participants for the case study to obtain a holistic impression. Firstly, employment with a F1 supplier or OEM was a prerequisite. Second, the focus was on the department. The respondents had to be employed in R&D/design for the study. The survey was divided into three sections. The first section asked for basic information about the company, the respondent's position, and the time spent there. In addition, it was essential to learn at what level the respondents are involved in the development process and what services they offer as a company.

The second section focused on the relationship and cooperation between OEMs and suppliers today and in the future and how this is perceived. Due to non-disclosure agreements, it was impossible to look at the contracts, so respondents were asked about the duration of relationships and changes and the reasons for them over the past ten years. In addition, general questions were asked about the perceived value of the collaboration, especially in light of the technological disruptions we are currently experiencing and how this might impact outsourcing/in-house development at the OEM.

The third section focused on prototypes, their definition, and their use in NPD. The purpose of prototypes and where they are used in the product development process were of particular interest. The survey concludes by asking who is responsible for prototyping and which part of the R&D collaboration is responsible for testing the solutions. The responses were analysed using statistical software. Descriptive statistics, such as frequencies and percentages, were used to summarise the survey data and identify patterns in supplier-OEM collaboration. Qualitative data from documents and information provided by the FIA and F1 teams were coded. Using the powertrain as an example, a deductive approach was utilszed to analyse the data in terms of contractual relationships. The results from all data sources were consolidated and discussed concerning previous research to provide a comprehensive understanding of supplier-OEM relationships.

4 Findings

4.1 Racing teams and their engine suppliers in the 2022 season

F1 teams often have complex relationships with holding companies or parent organisations. These relationships can affect various aspects of a team's operations, including funding, resource allocation, and strategic supplier decisions. It is important to note that the level of interaction between a holding company and an F1 team can vary significantly from team to team. Some teams have more autonomy in their operations, while others are closely integrated into the larger corporate structure of the holding company. The Table 1 shows the ten racing teams competing for victory in the 2022 season and their associated suppliers, using engines as an example.

F1 engines are produced in very limited numbers, often to meet the specific needs of a few teams. These engines are highly specialised and designed for maximum performance within the constraints of the regulations. They are strictly controlled by the sport's governing body to ensure a level playing field and limit costs. Teams must adhere to specific design parameters and performance limits to encourage innovation within certain limits. Engine suppliers play a critical role in the overall competitiveness of the teams. A well-performing engine can give a team a significant advantage on the track.

The uniqueness of F1 is also reflected in the relationship between the teams and their suppliers. In total, four suppliers supplied engines to ten teams. In the case of the Mercedes-AMG Petronas F1 Team and Scuderia Ferrari, the parent company also supplied competing teams. For example, Mercedes-AMG High Performance Powertrains is a wholly owned subsidiary of the Mercedes-Benz Group, which is the parent company of the racing team. At the same time, Mercedes-AMG High Performance Powertrains also supplied the same engine to William Racing, the McLaren F1 Team, and the Aston Martin Aranco Cognizanz F1 Team. The BWT Alpine F1 Team was supplied exclusively by the Renault Group. The two Red Bull racing teams, Scuderia AlphaTauri and Oracle Red Bull Racing, will be supplied by Red Bull Powertrains, which is part of Red Bull GmbH. In the case of Ferrari, the OEM supplied its racing team directly: Scuderia Ferrari, Haas F1 Team, and Alfa Romeo F1 Team ORLEN. In total, four engines were used in the 2022 season, all from suppliers that were either OEMs or represented in F1 through a subsidiary.

The specifications for how an engine must appear have been set by the FIA. For example, only 4-stroke reciprocating engines were allowed. In addition, all engines had to have six cylinders arranged in a 90°V configuration, and the standard cross-section of each cylinder had to be circular. Overall, all six cylinders had to have the same capacity (Fédération Internationale de l'Automobile, 2021).

Additional regulations were made in Appendix 4 of the FIA technical regulations. It states that a so-called 'engine freeze', i.e., a complete development stop, has been imposed on the engine manufacturers from the 2022 season.

This means that for the 2022 to 2025 season, only powertrains consisting of components that were classified as homologated at the time of their introduction are allowed to be used. The most recently submitted and confirmed homologation document applies (Fédération Internationale de l'Automobile, 2021). In terms of the relationship between the OEM and the supplier, this means that the race team will be tied to its supplier for this period of time and will not be able to change. This flexibility restriction is also contractually linked to high costs for the OEMs, which cannot be reduced by switching suppliers, for example. It is also clear that suppliers in the engine sector are rare anyway and are based on development cooperation. However, the suppliers' business models are also affected. They may have to adjust their staffing and resources to accommodate the engine freeze and find new ways to add value to their partner teams during a period of constrained development. In addition, the engine freeze may reduce F1's relevance to road vehicle technology. As described at the outset, technological advances in F1 have provided insights that have influenced technologies used in road cars. This influence and the associated lessons learned are limited by an engine freeze.

Table 1 Racing teams and their engine suppliers

Engine supplier	*Race team*	*Owner*
Mercedes AMG High Performance Powertrains	Mercedes-AMG Petronas Formula One Team	Mercedes-Benz Group
	Williams Racing	Dorilton Capital
	McLaren F1 Team	McLaren Group
	Aston Martin Aramco Cognizant Formula One™ Team	Aston Martin
Renault	BWT Alpine F1 Team	Renault
Ferrari	Scuderia Ferrari	Ferrari
	Haas F1 Team	Haas Formula LLC
	Alfa Romeo F1 Team ORLEN	Islero Investments AG
Red Bull Powertrains	Scuderia AlphaTauri	Red Bull GmbH
	Oracle Red Bull Racing	Red Bull GmbH

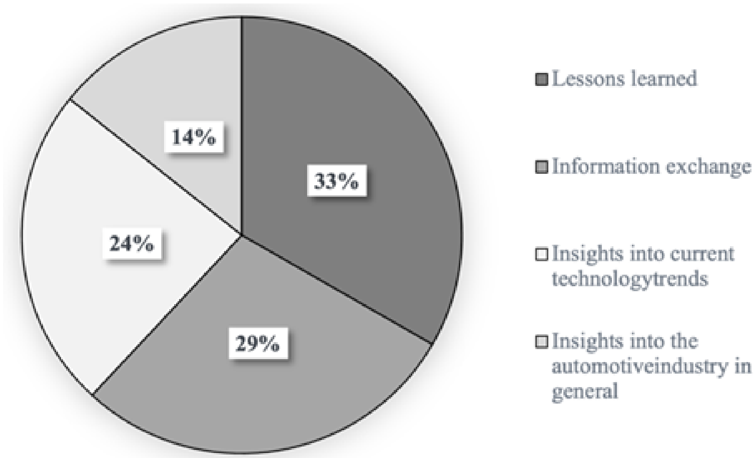
In summary, while an engine freeze in F1 can help control costs and maintain competitive balance, it also significantly impacts innovation in the sport. It also poses new challenges to the OEM-supplier relationship. Co-development of other components and areas of the car becomes even more important, for example, to improve performance through new innovative technologies in aerodynamics.

4.2 Results of the online survey

As part of the case study, OEMs and suppliers in the F1 ecosystem were surveyed to assess the current and future collaborative model. Of the total number of respondents, 63.6% were employed by a supplier and 36.4% by an OEM in F1 at the time of the survey. While all are involved in R&D, their roles vary. In addition to test engineers, hardware and software developers were also surveyed. To ensure anonymity, no personal or company-related data was collected that would allow conclusions to be drawn about the company.

Collaboration between suppliers and OEMs brings several benefits. The chart below shows the percentage responses of the 21 participants in the online survey to the question: What advantages do you see in the collaboration? (see Figure 1).

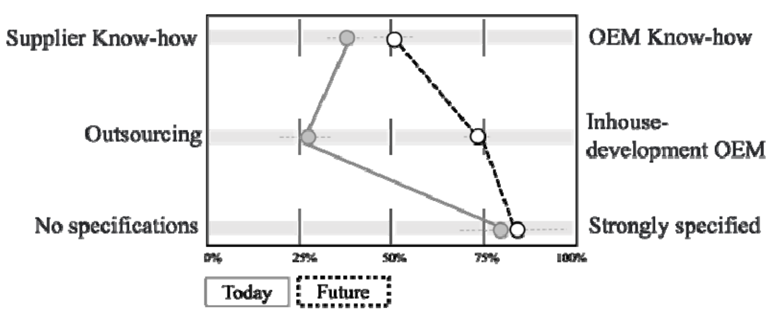
Figure 1 Advantages of collaborations between OEM and supplier



These benefits include various aspects of knowledge sharing, innovation, and industry expertise. This close interaction allows the supplier and the OEM to share their experiences and learn from each other's successes and challenges. By leveraging shared knowledge, errors are reduced, and the development process is accelerated.

Today, contractual frameworks provide protection and an environment for mutual learning, whereas in the past, access to knowledge was minimal. In addition, collaboration enables the exchange of essential information between suppliers and OEMs. This information includes market knowledge, product knowledge, and fundamental processes and strategies. The aspect of knowledge sharing related to technological advances was highlighted separately. This insight into cutting-edge technologies allows both parties to remain competitive and incorporate innovative solutions into their products.

Figure 2 Evaluation of the cooperation between supplier and OEM



Furthermore, collaborations often provide a broader perspective on the motorsports industry beyond the specific project. Suppliers and OEMs can gain insight into regulatory changes, their required solutions, customer preferences, and industry-specific challenges. This understanding contributes to strategic decision-making.

In summary, collaboration between suppliers and OEMs has a positive impact in many ways. It creates an environment of shared learning, fosters open communication, drives innovation through technology trends, and improves the overall understanding of the motorsports industry of each other and in general. In addition to the key benefits, the online survey also looks at the collaboration models in F1 in general.

The results clearly show that a shift from outsourcing to suppliers to in-house development at the OEM is expected in the future. The chart below (see Figure 2) shows the rating of the 21 participants in the online survey based on a Likert scale on the subject: Please evaluate the collaboration model between supplier and OEM today and in the future.

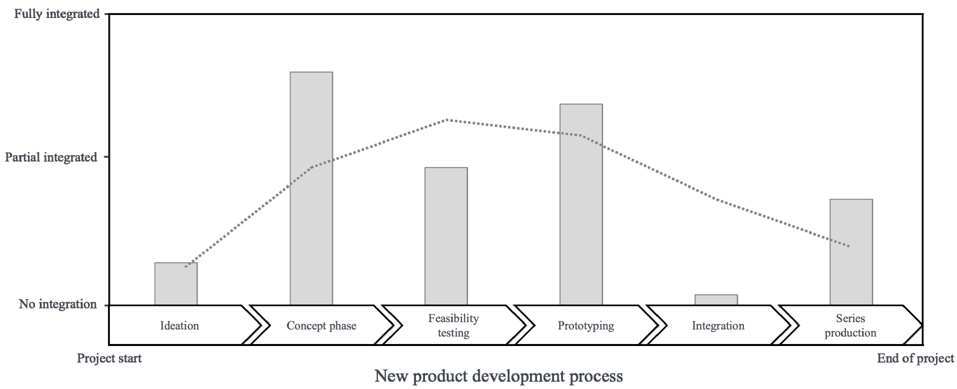
The analysis of the evaluation of the cooperation models clearly shows that product and technology-specific knowledge is increasingly located at the supplier. Participants in the online survey attributed this to the shortage of skilled workers and the simultaneous technological change in terms of connectivity and software-controlled vehicles. However, according to the respondents, this trend will shift back to the OEM in the future. This will also have an impact on outsourcing. While today's development is increasingly carried out by the supplier, a significant change is expected that will lead to more in-house development on the part of the OEM.

Nevertheless, the basis for collaboration will remain virtually unchanged. This means that the specifications that define the collaboration and the project-specific approach will continue to be very important. This is unsurprising, as precise specifications and guidelines are essential for successful and productive collaboration. They promote clarity, alignment, quality, and efficient resource allocation, ultimately contributing to the collaboration's success and achieving desired outcomes. It was also asked how the OEM/supplier relationship could be further developed to become more balanced. It became clear that the length of the relationship is a key factor in ensuring efficient collaboration over the long term without a loss of knowledge. Building long-term relationships fosters trust, which is essential for balanced collaboration and promotes a collaborative and sustainable partnership. Direct communication is also crucial.

Too many interfaces and IT-related barriers limit efficiency and create a breeding ground for misunderstandings. For example, open and transparent communication channels must be established so that developers on both sides can communicate directly and collaborate. As soon as customer-specific requirements and unique solutions are requested, collaborative development is essential to ensure cost and time efficiency. This requires early involvement and a common understanding of the product, the project, and its objectives. To determine at what point such integration occurs, respondents were asked to indicate the point in the NPD process (see Figure 3). The evaluation of the results has shown that in most cases, the integration takes place at the concept stage, or as soon as the prototyping stage begins and the concept is mature enough for initial testing. Both points or phases are indicative of the progress of a development project. The product and component requirements are evaluated and specified in the concept phase. Suppliers can provide valuable input on the concept's feasibility, manufacturability, and cost-effectiveness. It also ensures that all stakeholders agree on product-specific requirements and expectations. This reduces the likelihood of misunderstandings and minimises the risk of costly changes. On the other hand, involvement in the prototyping phase is aimed at testing and troubleshooting solutions that have already been developed.

Suppliers can provide practical feedback on functionality, manufacturability, and optimisation opportunities, leading to improvements and refinements. Fundamental changes to an already defined concept are difficult to make and can delay the project.

Figure 3 Average rating of supplier integration in each NPD phase



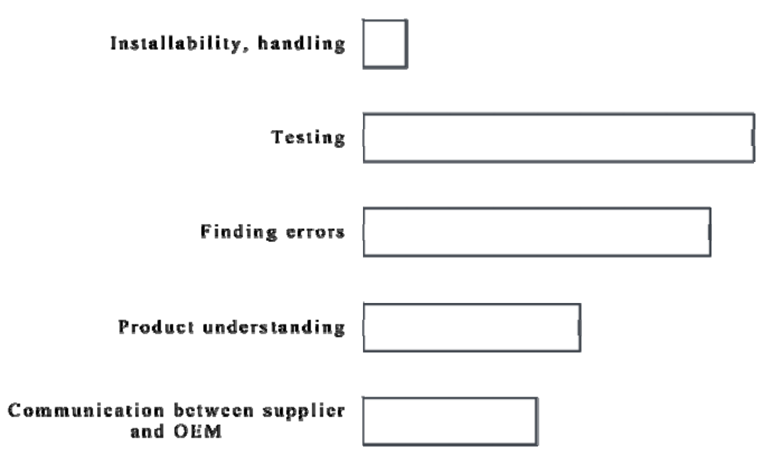
Overall, a balanced relationship between suppliers and OEMs requires trust, open communication, and the other party's involvement as appropriate to the project.

4.3 Prototyping

The respondents explained that a prototype is a first attempt to represent a final product. However, the focus is primarily on geometry and not on the final feel. Nevertheless, a prototype must be mature enough to be tested. Therefore, an early-stage idea or concept that is not ready for testing is not considered a prototype by respondents. The form of presentation and the use of different types of prototypes were also discussed. Virtual prototypes and related testing in the form of simulations can be used before a physical prototype. However, in a highly complex field such as motorsports, a physical prototype cannot yet be entirely replaced by a virtual one.

The utility of prototypes in engineering design was also evaluated. The following chart (see Figure 4) shows the percentage of the 21 respondents who answered this question: *What do you use prototypes for*?

Figure 4 Intended use of prototypes



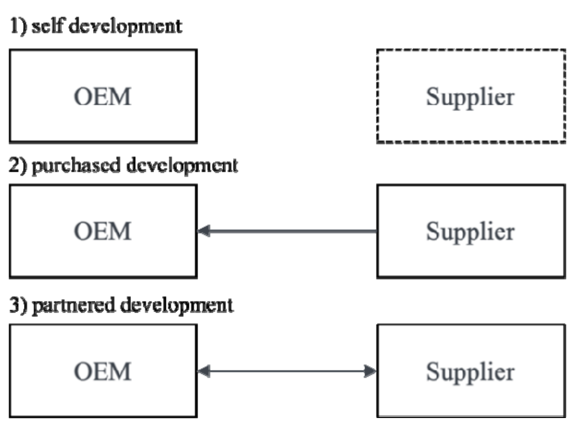
According to respondents, prototypes serve two primary functions: testing and debugging. Testing determines how well a product's intended functions and features work in the real world. This includes evaluating whether components work together as expected, systems function smoothly, and the product as a whole performs its intended tasks. In addition, a prototype can serve other purposes that were only sporadically mentioned, such as promoting product understanding, verifying buildability, and promoting communication between supplier and manufacturer. In about 64% of development projects, the supplier develops the prototypes, which are then tested by the OEM. In contrast, only 18% of co-development projects involve pure in-house development and testing at the OEM.

In conclusion, prototypes are an essential part of OEM-supplier collaboration. Prototypes accelerate the development cycle by enabling rapid testing and adjustments and by highlighting potential risks and challenges that may not have been apparent in the concept phase. Furthermore, the survey results show that a prototype must be as close as possible to the production part. In the early stages, the focus is on geometry and materials (mechanical and physical properties), followed by haptics and manufacturing technology. Prototypes enable iterative testing and adjustments that allow the supplier and OEM to address design flaws, inefficiencies, or performance issues early in the development process. Identifying these issues in the prototype phase allows for proactive mitigation and minimises the impact on the final product. This is important because prototypes are primarily used to validate assumptions and find potential bugs that need to be fixed iteratively.

5 Discussion

The results of the case study have shown that the form of collaboration needs to be rethought. In order to ensure fruitful relationships between OEMs, their racing teams and suppliers in the future, new frameworks must be created that simplify collaboration and break down corporate boundaries.

Figure 5 Types of relationships



While the early involvement of suppliers is widely discussed in research (Mikkelsen and Johnsen, 2019), and the advantages are also emphasised (Zirger and Maidique, 1990; Eisenhardt and Tabrizi, 1995; Clark, 1989; Lawson et al., 2015). Nevertheless, a simplified differentiation between the individual cooperation models is missing.

5.1 Types of relationships

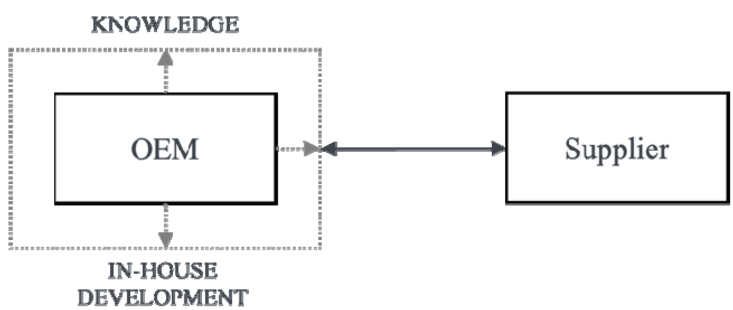
Based on the findings from the different sources, we define three types of relationships between OEMs and suppliers (see Figure 5).

Self-development is characterised by the fact that suppliers are not involved in the early stages of development; instead, everything is developed in-house by the OEM or the race team. In the case of *purchased development*, direct integration into the platform takes place.

This is a classic buyer-supplier relationship. In the case of *partnered development*, the supplier is involved in the development and contributes its knowledge to the products. The definition of requirements and the iterative adaptation of the product or component are carried out collaboratively.

The results of the case studies have shown that we are facing a paradigm shift. The role of suppliers has changed over the past decade. Driven by trends such as connectivity and a growing shortage of skilled workers, suppliers have become more involved in NPD, especially at an earlier stage. As a result, knowledge is no longer centralised at the OEM but distributed across company boundaries. The future looks regressive in this respect. According to the experts surveyed, in-house development will once again play a more critical role, as will knowledge building at the OEM (see Figure 6).

Figure 6 Model of collaboration



This does not mean, however, that the role of the supplier, which was previously highly integrated, will be reduced to a buyer-supplier relationship without any integration. This would be the case if technological innovation and the associated level of complexity were to stagnate. Increasing product requirements, such as safety and security, customer demands, and political mandates, such as climate targets, require a collaborative relationship. This is especially important during the critical phases of NPD. The prototyping phase plays a central role in testing specifications and requirements, iterating, and continuously optimising the product to increase its maturity.

5.2 Introduction of 'collaborative prototype'

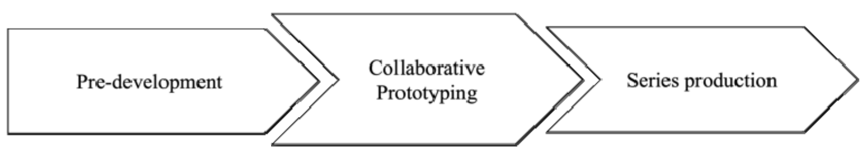
The importance of prototypes in NPD is not only emphasised in research (Lauff et al., 2018; Wall et al., 1992; Elverum and Welo, 2014) but also confirmed in the context of the conducted study. While previous research uses various criteria for the classification of prototypes (Wall et al., 1992; Lim et al., 2008; Houde and Hill, 1997; Beaudouin-Lafon and Mackay, 2012), the results of the study show that especially the aspect of geometric fidelity and the possibility of error identification are essential criteria to be able to use the prototype phase efficiently for validating assumptions and identifying errors. Based on the results, we introduce the concept of a collaborative prototype. It is defined as follows:

> "A collaborative prototype is a tangible or virtual representation of a product, component, or system developed by individuals or teams across organisational boundaries. The goal of a collaborative prototype is to ensure that all relevant specifications and mechanical requirements are considered during the prototyping process."

The prototype is no longer developed by the supplier and then sent to the OEM for testing but represents a joint development effort that combines the expertise of both parties. This facilitates cooperation in the symbiotic construct of F1, but can also lead to improved cooperation in the traditional automotive industry.

To achieve this, the NPD process is consolidated and divided into three phases: pre-development, collaborative prototyping, and series production (see Figure 7).

Figure 7 Collaborative prototyping in the NPD



This approach speeds up iteration loops and makes defects more discoverable. While in the pre-development phase, all assumptions are made based on management specifications and technical regulations, in the second phase, all development is carried out, which is not subject to any restrictions in the target image and is also clearly separated from series production. Therefore, the collaborative prototyping phase starts when all the rigid criteria (such as budget, supplier selection, and limits) are defined.

Based on this, two categories of suppliers can be classified: *the prototype supplier and the production supplier*. While pre-development remains in-house at the OEM and is based on essential knowledge, the prototype supplier supports feasibility and technology development. Due to the shortage of skilled workers, existing resources must be used more efficiently through new collaboration models. Once development is complete, the production supplier supports volume production.

Therefore, successful collaborative prototyping requires four essential preconditions that help achieve the desired results:

- Clear requirements

  Clearly define the purpose, functionality, and performance goals at the beginning of the collaboration so that all stakeholders understand the scope and intended goal of the project.

- Accessible communication

  Allow all parties to communicate directly without contractual restrictions to ensure goal-oriented exchanges at the working level.

- Assigned responsibilities

  At the beginning of the collaboration, defining who is responsible for each stage of the development process is crucial. This includes the timing of integration, development, and testing.

- Defined set of conditions

  Realistic schedules, budget constraints, and possible regulatory influences must be clearly communicated at the beginning of the project. This is the only way to accurately estimate effort and define expectations.

Fundamentally, joint R&D is essentially based on trust. Long-term relationships can help build this trust. In addition, knowing the other party is important for effective and efficient collaboration. Long-term collaboration can help speed up the development process because working methods and process requirements or constraints are already known. The results of the case study have shown that such a relationship is essential to address the challenges in the triple between OEMs and the associated race teams and suppliers in the future.

6 Limitations and further research

The study of supplier-OEM relationships in F1 is limited by restricted access to proprietary information in R&D. Some sensitive data, such as contracts between OEMs and suppliers or details of technical collaborations, are not publicly available and are subject to non-disclosure agreements, limiting the depth of the analysis. In addition, the sample size of suppliers and OEMs participating in the survey is limited. This affects the generalisability of the results. Another limitation is the dynamic nature of F1. Due to changing technical challenges and regulations, long-term shifts and trends in the relationship between suppliers and OEMs cannot be definitively described but are based on assumptions derived from the case study results. In addition, the influence of external factors, such as the economic situation or the emergence of new technologies or technical requirements, cannot be made tangible. As part of future research, a longitudinal study over several seasons or years is recommended to provide even deeper insights into the evolution of supplier-OEM relationships in F1. Analysing changes over a more extended period makes it possible to identify factors that influence collaboration and patterns that make for successful partnerships. Comparative studies in other industries would provide a broader perspective on supplier-OEM relationships. Examining how these dynamics differ in different contexts allows for generalisability and unique insights and best practices, and it would be valuable to investigate the impact of specific technical and regulatory changes on supplier-OEM relationships. In addition, analysing the impact of specific technical and regulatory changes on supplier-OEM relationships would provide insight into how regulatory changes affect collaboration strategies, innovation priorities, and performance dynamics. Addressing these limitations and exploring further research opportunities would improve the understanding of supplier-OEM relationships in F1 and facilitate the development of strategies to promote successful collaboration and foster innovation.

7 Conclusions

The relationship between suppliers and OEMs is a critical aspect that significantly influences the success and performance of teams on and off the track. In F1, collaboration plays a central role in the development and improvement of various components. Unlike in the traditional automotive industry, OEMs are strongly intertwined with race teams, suppliers and also with each other, for example in powertrain sharing. Race teams benefit from collaboration through knowledge, insight and information that can significantly speed up the development process by, for example, avoiding undesirable developments. While outsourcing plays a central role today, respondents expect more in-house development in the future, necessitating optimisation of collaboration at critical stages of NPD. In Formula 1, this includes the prototyping phase. In particular, the maturity level is crucial to be able to achieve fruitful test results, to find bugs early on, but also to optimise product understanding. In this thesis, a case study was conducted to investigate and analyse the complex dynamics of supplier-team relationships in the context of F1. An in-depth study of the F1 ecosystem and a survey revealed that pure buyer-supplier relationships are no longer appropriate.

The automotive industry in general and Formula 1 in particular are constantly in flux. This is nothing new. However, the regulations that govern product development are becoming increasingly stringent. While development in Formula 1 has been subject to regulations from the very beginning, the requirements in the automotive industry are becoming more and more precise. The simultaneous increase in complexity and shortening of development times also poses a major challenge to the shortage of skilled workers. In recent years, this necessity has also led to increased involvement of suppliers in the development of products or components. However, corporate boundaries still make joint development difficult. The study showed that this dynamic interaction is important, but still needs improvement. By dividing the development process into three phases and introducing the term ‘collaborative prototyping’, we hope to provide food for thought for further research. A fine-grained division of processes is essential within the company, but also leads to constraints that are detrimental to a fruitful OEM-supplier relationship.

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