Czech Technical University in Prague

Founding of a student research team developing an autonomous electric vehicle

Diploma Thesis

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Field of Study: Innovation Management

Consultant: prof. Ing. Oldřich Starý, CSc.

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CÍL PRÁCE: Cílem DP je popsat vznik studentského týmu eForce Driverless, včetně použitých manažerských metod a následného technického návrhu. Práce bude vypracována v anglickém jazyce.
PŘÍNOS PRÁCE: Přínosem je ojedinělý popis vzniku unikátního multidisciplinárního projektu na ČVUT. Praktickým výstupem je pak dlouhodobé fungování nového studentského výzkumného týmu o desítkách členů a potenciálně více, než milionovým rozpočtem.
OSNOVA: (1) Introduction (2) Autonomous mobility (3) Formula Student (4) Team eForce Prague Formula (5) Driverless team formation (6) Technical design of the vehicle (7) Future plans and sustainability

Seznam doporučené literatury:

(1) TROTT, P. Innovation management and new product development. Pearson education, 2008.
(2) Formula Student Germany, FSG Strategic Announcement. formulastudent.de, October 24 2019 [online].
(3) DHALL A. Real-time 3D Pose Estimation with a Monocular Camera Using Deep Learning and Object Priors on an Autonomous Racecar. Eidgenössische Technische Hochschule Zürich [online], September 28, 2018.

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While this thesis is an original work itself, it describes outcomes of a highly complex collective effort. Such outcomes can be achieved by no single person and many individuals' efforts have contributed to the final result as described here. I would like to use this opportunity to personally thank those that contributed significantly whether to the creation of this text or to the creation of eForce Driverless.

First and foremost, I would like to thank *Oldřich Starý*, my thesis supervisor. He provided me with the perfect mix of guidance and freedom, which I needed to coordinate my thesis writing with actual work on the project. His kind remarks, guidance and diligent approach to scheduling the completion of my thesis helped me tremendously and granted me valuable experience I will keep applying in my future endeavours.

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This year, the Formula Student season was severely disrupted by the COVID-19 pandemic. The inability to work on the vehicle in our workshop and the cancellation of all races was a serious blow to our morale. Therefore, I would like to thank the Formula Student Online initiative, specifically *David Oort Alonso* and *Sijmen Huizenga* from the Delft Driverless / MIT Driverless Formula Student teams for developing a driverless formula simulator that could be used in an online competition and that we are planning to further use as our main vehicle simulating environment. I have personally had the privilege of contributing to the project in a minor way by working on depth cameras implementation and am happy to have been able to cooperate on this wonderful project with such talented people.

I would also like to thank all those who participated in the eForce Driverless project so far and without whom we would not go as far as we did. I value all members efforts greatly, but I would like to specifically name those, whose contributions made the project progress significantly:

- *Ondřej Šereda*, for co-founding the team with me and playing a key role in driving forward the hardware implementations as well as integrating the new driverless team with its older electric counterpart
- *Marek Boháč*, for stepping up to manage the day-to-day functioning of the team in Prague while I was working remotely from Belgium on Erasmus. For this he seems to have sacrificed a significant amount of time, dedication and possibly even a bit of his sanity – but I am sure the end result we have achieved collectively is worth the effort
- *Tomáš Roun*, who singlehandedly drove the software development remotely from CERN while doing his day-to-day responsibilities
- *Daniel Štorc*, for stepping up and evolving from a newcomer to the most active member in the team within barely a year and inspiring others to push beyond their perceived limits
- *Matěj Zorek*, for joining eForce Driverless and helping it with machine learning and path finding algorithms even though his home faculty is physically and academically quite detached
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- *Tomáš Kazda,* for greatly helping eForce Driverless with all mechanical issues and designing the electronic steering system, even though he is a fresh graduate and did this entirely out of passion for the new project on top of his regular duties
- *Josef Med,* for leading the eForce organisation overall and being a great team captain
- *Ondřej Štogl,* for significantly helping to coordinate activities between the driverless and electric teams while working on static disciplines

Finally, I would like to thank those that supported me throughout my studies. This includes my family, who had steadily supported me throughout the past five years, but the biggest thanks go to my girlfriend, who had to endure not only the highs, but also the lows very profusely and from a deadly vicinity during all this time. She has a lion's share in me completing all my duties.

Declaration

I hereby declare that I have written the submitted thesis myself and I quoted all used sources of information in accord with methodical instructions about ethical principles for writing academic theses.

In Prague on August 6th, 2020

…………………………………………..

Marek Szeles

Abstract

After existing for nine successful years, the eForce FEE Prague Formula Student team, active at the Faculty of Electrical Engineering CTU was looking for a new challenge for its tenth season. One of the options to move forward and expand activities was to initiate the development of a new autonomous racecar concept. This move would be revolutionary, as no Czech team had attempted this before. Apart from the opportunity, it also offered heavy risks – if the initiative were unsuccessful, the team could lose a financial investment it could not afford. Combined with a possible loss of support from sponsors and the University, as well as a loss of motivation of team members, this would mean a serious existential risk.

This thesis follows the story of eForce Driverless – the first Czech research project to develop a full-scale electric racecar. It documents the evaluation and planning that preceded the decision to go forward with the project, then the implementation stages, as well as its future outlook. As the author is a founding member of the new team, and served as its first captain, this thesis offers a unique outlook on how a complex and innovative interdisciplinary research team may be sustainably created and managed, from its inception to long-term operations.

Keywords

Innovation Management, Engineering management, Leadership, Formula Student, Autonomous Driving

Anotace

Po devíti letech úspěšné existence se studentský tým eForce FEE Prague Formula, sídlící na Fakultě elektrotechnické ČVUT, rozhodl ve své desáté sezoně pokořit novou velkou výzvu. Jedna z jasných možných dalších aktivit pro tým bylo iniciování vývoje nového autonomního vozidla. Tento krok by byl bezesporu revoluční, jelikož se o nic podobného v Čechách dosud žádný tým nepokusil. Kromě příležitosti s sebou tato možnost ale nesla i významná rizika – pokud by se iniciativa nepovedla, tým by pravděpodobně přišel o finanční investici, o kterou si nemůže dovolit přijít. V kombinaci se ztrátou podpory od sponzorů i od univerzity, stejně tak jako ztrátou motivace členů týmu by případný neúspěch mohl být likvidační.

Tato práce sleduje příběh eForce Driverless – prvního českého výzkumného projektu vyvíjejícího elektrická závodní vozidla v životní velikosti. Práce popisuje proces vzniku od samého začátku, kdy probíhaly evaluace a plánování před zahájením projektu, dále samotnou implementaci, a nakonec také výhled do budoucna. Autor je zakládajícím členem tohoto týmu, a nabízí tedy unikátní vhled z první ruky na proces, při kterém vzniká komplexní a inovativní interdisciplinární výzkumný tým a jak jej lze dlouhodobě udržovat.

Klíčová slova

Řízení inovací, Řízení inženýrských projektů, Leadership, Formule Student, Autonomní řízení

Překlad titulu

Založení studentského výzkumného týmu na vývoj autonomní elektroformule

Contents

1. Introduction

Formula Student is one of the most respected and challenging student engineering competitions in the world. This competition is also one of the largest, being attended by participants the world over, and being organized by experts from leading automotive, motorsport, aerospace and other technology firms.

To most outside observers – and possibly to many of the younger participants- it may seem that the competition's added value and challenge comes from the vehicle construction. While this is undeniably the thematic centrepiece of the whole enterprise, experienced participants, alumni and organizers alike will surely agree that the real challenge comes from the organisation of teams of people with different expertise to achieve one functioning output system. The fact that this system is a racing vehicle with certain specifications is secondary. Since such vehicle represents a system that could be developed by no participant alone, even if hypothetically given unlimited time, the primary challenge remains the organisation and efficient management of such teams.

The competition has three classes: A traditional Combustion Vehicle class, which started back in 1980s, an Electric Vehicle class introduced in 2010 and most recently a Driverless Vehicle class, introduced in 2017. In the Czech Republic, one of the teams that competes in the competition – and the only electric team – is called eForce FEE Prague Formula. In 2018, it was considering entering the new Driverless category as well and develop an autonomous vehicle as the first team in the Czech Republic.

This thesis follows the full story of this endeavour – from its inception and feasibility evaluation, through its implementation all the way to the works on long-term sustainability. First, the project and the competition are described in further detail to get a better overview about the problem at hand. Then, the initial situation in 2018 before the foundation of eForce Driverless is assessed. This is done both in the scope of the organisation at the time and as a feasibility study of the soon to be founded project and its associated risks. Thirdly, the actual implementation of this project is expanded upon and contrasted with the initial plans and expectations. To further add upon the academic value of this thesis, I elaborate in detail the current approaches to topics such as organisational design and the management of innovation and discuss what could be applied when working on similar projects – in other words, I will empirically validate these theories through application on the project at hand. Lastly, the project is evaluated in terms of long-term sustainability and suggestions are proposed as to how to improve the project in the future.

This proposed structure hints at the main aims and goals of the thesis. The main goals to be achieved in the text are the following:

- Firstly, the aim is to map out and describe the current academic understanding of innovation and engineering management, as well as relevant theories that are being considered in the field.
- Secondly, it is intended to describe the decision process preceding the foundation of eForce Driverless – how and why it was decided by eForce to go forward with this project – through a feasibility study.
- Thirdly, the thesis will contain a rigorous organisational and technical description of the project outcomes as of summer 2020, along with the timing of the deliverables output, if relevant.
- Lastly, the goal is to provide academically supported recommendations for the newly founded team to remain sustainable and ultimately successful in the competition.

Furthermore, the interlinked research questions I am trying to answer in this text are the following:

- To what degree was the eForce Driverless project successful?
- Could its success be explained or supported by some of the contemporary theories of innovation management?
- If the theories are applicable, what could be done to further bolster the efficiency and sustainability of the project?

As it can be seen, this thesis is broadly scoped and describes a wide variety of topics. This is only possible thanks to the fact that the subject at hand was contributed to by tens of extremely talented and motivated individuals that were acknowledged in the preface. I hold a strong conviction that this possibility to include a wide area of topics and still go in-depth is potentially one of the strongest and most interesting points of this thesis and I am grateful to have had the possibility to study at Czech Technical University in Prague, where such diverse teams and challenges are possible in the first place.

While the technical aspects of the project are inherently a collective effort and are described only in the highest level of detail in this thesis, some further documentation is included as an attachment for those that are curious to learn more about the actual engineering challenges that had to be overcome. A direct comparison may be made between this document and my Bachelor Thesis on a similar topic. In this context we may to conclude that while this document is less practical, it also describes a more complex collective effort and the results speak for themselves. The technical aspects are further documented in attachments, and more focus is brought onto the academic theory of management in the main body of this thesis.

2. Theoretical Background

Before we can step further to the analysis of the engineering project itself, it is important to define the theory behind the academic fields this thesis is concerned with. Since the thesis is being written at the Masaryk Institute of Advanced Studies at Czech Technical University, the theory centres around two distinct subfields of management – management of innovation and engineering management.

It is worth mentioning that both of these fields are mostly being analysed in academic literature as part of a for-profit business environment. This is a critical difference and a potential diverging variable in the case of eForce Driverless, which is based on volunteering and a non-profit basis. Not all approaches can therefore be automatically assumed to be applicable.

2.1. Innovation Management

Innovation Management is a specific subclass of project management. It allows managers and workers in an organisation to understand and intentionally research and develop disruptive processes that change the preestablished functioning of the organisation. In Innovation Management, the key ambition is to come up with new concepts and utilize them to further the organisation's goal as a whole.[1] Alternatively, Management Innovation may be described as the invention and implementation of a management practice, process, structure, or technique that is new to the state of the art and is intended to further organisational goals.[2]

From this definition the establishment of a research team tasked with the development of a new autonomous racing vehicle concept is fundamentally considered an application of Innovation Management. There are several further techniques and methods associated with Innovation Management, based on the type and scope of the project at hand. Such techniques range from simple creativity-inducing methods such as brainstorming, through knowledge management to business creation methods including sophisticated models of operation like spinoffs.[3]

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[1] TROTT, Paul. *Innovation management and new product development*. Pearson education, 2008.
[2] BIRKINSHAW, Julian; HAMEL, Gary; MOL, Michael J. *Management innovation*. Academy of management Review, 2008, 33.4: 825-845.
[3] European Commission. *Innovation Management and the knowledge-driven economy*. Luxembourg: Directorate-general for Enterprise, 2004.

2.2. Engineering Management

As the name suggests, Engineering Management signifies the field describing the application of management methods onto engineering issues. Its main aim is to create organisational synergy between the technical problem solving offered by engineering and the operational, administrative and planning problem solving offered by efficient management.[4]

It is important to note that Engineering Management does not stand in opposition to Innovation Management and the two fields may overlap to a large extent, and such is the case of eForce Driverless, which falls under both categories.

Like the previous example, Engineering Management can also be split into smaller areas of focus, such as Systems Engineering Management, Product Engineering, or Technical Organisational Management, however these subfields tend to be less formalized and only have blurred distinctions.[5]

3. Methodology

In this chapter, the scientific methods applied in this thesis are described, with references to relevant literature. To analyse the project at hand, three distinct methods were used – theory derivation, feasibility study and case study, each with a distinct goal in mind. In the subchapters below, each method is described in its general form, as well as in relation to its specific application in this thesis.

3.1. Documentary Analysis

The most basic, but crucial method applied in this thesis extensively in the next major chapter is documentary analysis. This describes the process of gathering relevant literature on a given academic topic and then analysing the content for relevant passages to be applied and aggregated into the new text which should build upon them. If working with datasets, this process is also sometimes called secondary (in case of one source) or tertiary (in case of more sources) data analysis. [6]

In the case of this thesis, the documentary analysis conducted in the theory-focused chapters is applied as a data collection strategy to be further used in a case study about the project as a whole in the practical implementation chapters.[7]

[4] SHAH, Hiral; NOWOCIN, Walter. *Yesterday, today and future of the engineering management body of knowledge.* Frontiers of Engineering Management, 2015, 2.1: 60-63.
[5] SHAH, Hiral; NOWOCIN, Walter. *Guide to the engineering management body of knowledge*. American Society of Mechanical Engineers (4th ed.). Huntsville, 2015 AL. ISBN 9780983100584
[6] BOWEN, Glenn. *Document Analysis as a Qualitative Research Method.* Qualitative Research Journal, 2009, 9. 27-40
[7] FITZGERALD, Tanya. *Documents and documentary analysis*. Research methods in educational leadership and management, 2012, 296-308.

3.2. Case study

A case study is a fundamental method which describes the qualitative application of a chosen general theory onto one specific case and exploring in-depth the validation of the preconceived theory assumptions. Therefore, the purpose of that study is – at least in part – to shed light on a larger class of cases (a population). Theoretically, more cases may be explored, but it is important to keep the number reasonable so that they can be described in proper exhaustive detail.[8] When choosing examples for a case study, several techniques may be used as outlined in influential literature on the topic: *typical, diverse, extreme, deviant, influential, crucial, pathway, most-similar, and most-different*. Based on the technique for choosing cases, the case study may be utilized to achieve one of two goals, or methods. The first method is *hypothesis testing* and is very well known – it simply means that there is a preconceived hypothesis that the author wishes to test using the selected cases. The other method is *hypothesis generating*, where the author elaborates about the outcome or a particular interesting phenomenon about the chosen cases and then proceeds to utilize this knowledge to produce new hypotheses that could possibly help explain these outcomes and phenomena.[9]

In the case of this thesis, the intent is to apply theories and approaches onto the eForce Driverless case as described in the next major chapter, which may be considered *typical* in compliance with the first aforementioned technique. The case is considered a *typical* example of some cross-case relationship, and a *hypothesis-generating* approach is chosen in this case to explore the applicability of management theories on this innovative engineering project. The case study is further concerned with the theories' key takeaways for the project's further sustainability.

3.3. Feasibility Study

The goal of the feasibility study is clear – to help an organisation decide whether a proposed project is feasible, or otherwise worth pursuing. This is achieved through rigorous exploration of different internal and external aspects of both the parent organisation and the project being considered.[10]

Feasibility Studies can have various contents that should be adjusted based on the evaluated project and the priorities of the organisation. Still, in general, they tend to always include the information about competition, timing, resource allocation, organisation, and risks associated with the project.[11] The main methods used within the feasibility study of this thesis are briefly described in the following subchapters.

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[8] GERRING, John. *Case study research: Principles and practices*. Cambridge university press, 2006.
[9] Same as above, pages 88-91
[10] ARAIN, M., CAMPBELL, M. J., COOPER, C. L., & LANCASTER, G. A. *What is a pilot or feasibility study? A review of current practice and editorial policy*. BMC medical research methodology, 2010. 10(1), 1-7.
[11] BURKE, Rory. *Project management: planning and control techniques*. New Jersey, USA, 2013, 26.

3.3.1. Competition Analysis

The first chapter of any Feasibility Analysis usually concerns the competition, since it is crucial to understand the landscape in which the project would be undertaken. The form of this analysis may vary, but the general aim is to describe the main competitors and their capability to disrupt the planned project.[12]

3.3.2. SWOT Analysis

The SWOT abbreviation stands for "Strengths, Weaknesses, Opportunities, Threats".[13] It represents a method to evaluate both external and internal influences on an organisation in a particular situation in which the analysis is made.[14]. Using this method, a square canvas is divided into four quarters of a matrix, each signifying one of the four words in the name. A sample template of the SWOT matrix with a description of the individual fields can be seen on figure 1.

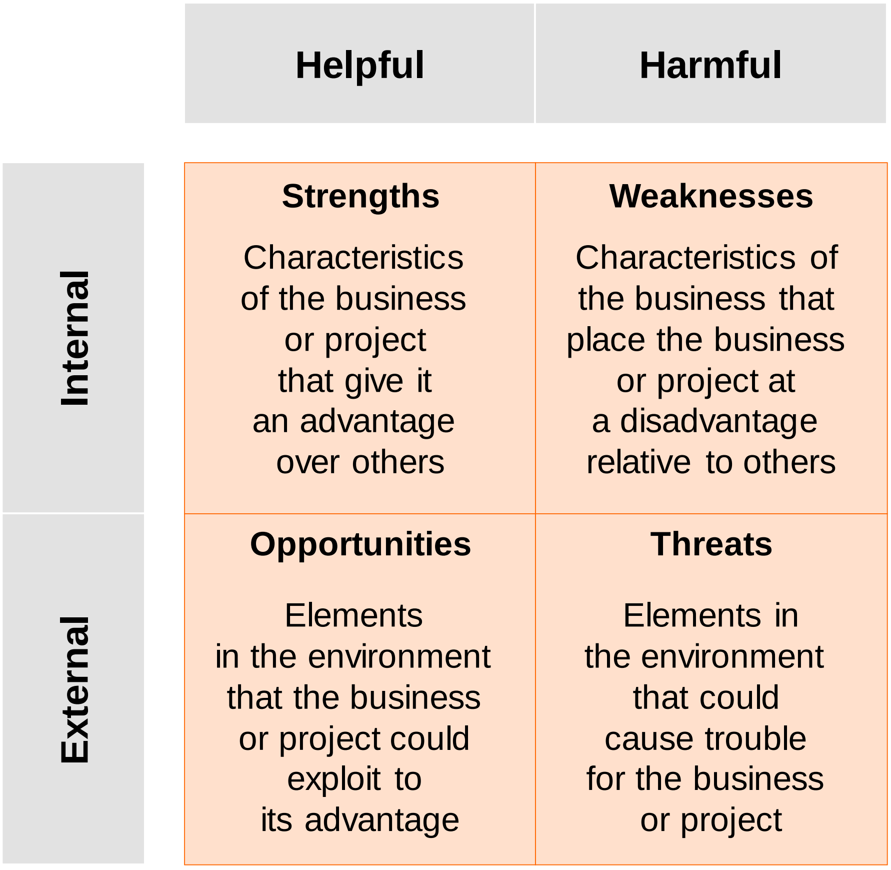

Figure 1: SWOT analysis matrix template[15]

[12] MASSEY, Patrick, et al. Market *definition and market power in competition analysis: some practical issues.* Economic and Social Review, 2000, 31.4: 309-328.
[13] GÜREL, Emet; TAT, Merba. *SWOT analysis: a theoretical review*. Journal of International Social Research, 2017, 10.51.
[14] HUMPHREY, A. *SWOT Analysis for Management Consulting*. SRI Alumni Newsletter. SRI International, Dec. 2005: 7-8
[15] SZELES, M. *Byznys plán eForce FEE Prague Formula 2018*. 2018. Bachelor's Thesis. České vysoké učení technické v Praze. Vypočetní a informační centrum.

3.3.3. Marketing Analysis

After researching the general environment, the feasibility study turns its focus onto the active design of the new project parameters. In terms of the marketing analysis, this usually means the application of the 4P methodology, meaning Product, Price, Place, Promotion.[16] This is certainly one of the methodologies that only has limited applicability onto not-for-profit project such as eForce Driverless.

3.3.4. Organisational Analysis

This analysis chapter explores the impact of the new project on the pre-existing organisation. The scope of this analysis also varies greatly, and it can range from simple organisation chart layout to a detailed analysis mapping all individual processes and workflows that could be affected.[17]

3.3.5. Resource Analysis

For each project, there are several types of resources that need to be taken into account. These cover human resources, but also raw materials and components that need to be at hand in order to successfully finish the proposed project.[18]

3.3.6. Technology Analysis

If the project is novel or technology based – which is almost always the case in Innovation Management – it usually needs specific technologies to be available during implementation. The mapping if the needed technologies and their availability is the target goal of this chapter.[19]

3.3.7. Financial Analysis

As every project has serious financial implications for an organisation a proper feasibility study contains estimates of the impact the evaluated project will have on the organisation's budget. As with other chapters, the level of detail may vary, and depends on both the organisation type and project significance.[20]

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[16] ONKVISIT, Sak; SHAW, John J. *International marketing: Analysis and strategy*. Psychology Press, 2004.
[17] SMIRCICH, Linda. *Concepts of culture and organisational analysis*. Administrative science quarterly, 1983, 339-358.
[18] BARNEY, Jay B*. Is the resource-based "view" a useful perspective for strategic management research? Yes.* Academy of management review, 2001, 26.1: 41-56.
[19] PILKINGTON, Alan; TEICHERT, Thorsten. *Management of technology: themes, concepts and relationships.* Technovation, 2006, 26.3: 288-299.
[20] HELFERT, Erich A. *Techniques of financial analysis: A practical guide to managing and measuring business performance*. Irwin, 1994.

3.3.8. Implementation Analysis

The chapter that tends to be one of the largest concerns the specific plans on the implementation of the evaluated project, namely the timing and the milestones intended. If the project is later chosen for realization, the output of this chapter usually serves as the first project plan draft.[21]

3.3.9. Risk Analysis

Finally, the project is evaluated against several "what-if" scenarios that are usually negative and would result in a setback of the project or a negative consequence to the organisation of varying magnitude. The list of risks should be as exhaustive as possible and individual risks are evaluated based on the probability and the impact of their occurrence. In some more detailed approaches, the detection difficulty is measured as well. Based on these partial values, the risks are prioritised, and the highest priority risks should be assigned specific mitigation (preventive) and contingency (minimizing negative impact) plans.[22]

4. Current approaches

In this chapter an overview of the current approaches to innovation and engineering management implementation and their related processes is presented. Three main areas were explored based on the nature of the project at hand.

First, the current academic understanding of organisational design is examined, as eForce Driverless is a new organisation founded within a pre-existing framework of a larger entity (the electric eForce team), and thus in a particular starting position.

To further understand the functioning of the organisation after establishing its foundations, the latest publications on the topic of the Management of R&D Teams and its approaches are explored in detail. This is then further supplemented by the last subchapter focusing on leadership theories to understand how complex organisations are best managed based on a top-down approach according to academic literature. [23]

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[21] PEARCE, John A.; ROBINSON, Richard Braden; SUBRAMANIAN, Ram. *Strategic management: Formulation, implementation, and control*. Columbus, OH: Irwin/McGraw-Hill, 2000.
[22] BEASLEY, Mark S.; CLUNE, Richard; HERMANSON, Dana R. *Enterprise risk management: An empirical analysis of factors associated with the extent of implementation*. Journal of accounting and public policy, 2005, 24.6: 521-531.
[23] MARION, Russ; UHL-BIEN, Mary. *Leadership in complex organisations*. The Leadership Quarterly, 2001, 12.4: 389-418.

4.1. Organisational design

As it was described in the introduction of this thesis, eForce Driverless is a new project which is however being established within a pre-existing functioning organisation, the eForce FEE Prague Formula electric Formula Student team. This puts eForce Driverless in a unique position. On the one hand, wholly new organisational structures may be established like in a greenfield project. On the other hand, high caution has to be applied as the design needs to be compatible with the parent organisation and to a large degree complementary. This is especially important since in certain areas, eForce Driverless is even inherently directly dependent upon the parent eForce electric team. This is true especially when it comes to overcoming mechanical challenges in the early years, when eForce Driverless is to have no one specifically dedicated to solving these crucial issues.

There is a significant body of academic literature on whether it is wise to design new project organisations within the existing organisational structure or whether it is better to set up a separate unit for this. In prominent business and management publications, the topic began appearing in the late 1990s, with the authors distinguishing two kinds of activities within organisations. *Exploitative* activities are those that sustain the core business and are reliant on rigid structures and processes, with only incremental innovative activities. In contrast, *Explorative* activities are much more agile-oriented, intended to try out new possibilities, such as new products, markets or ways of working.[24]

There are many academic sources arguing that exploration and exploitation activities are very different. The argumentation ranges through accentuating the differences in technological impact,[25] through the need of different management structures[26] to the opposing cultural and organisational demands by the outputs expected from such activities.[27] Even in earlier literature, it is often argued that it is not a wise idea to combine explorative and exploitative activities within one closely knit organisation, since both types of activities are very difficult to reconcile in terms of management practices, processes, culture and time scheduling. The authors go so far as to claim that "*Every company that has tried to manage mainstream and disruptive businesses within a single organisation failed.*".[28] This is argued due to the fact that clashes inevitably arise over which groups get what resources and how the priorities should be divided.

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[24] HOLMQVIST, Mikael. *Experiential learning processes of exploitation and exploration within and between organizations: An empirical study of product development*. Organization science, 2004, 15.1: 70-81.
[25] TUSHMAN, Michael L.; ANDERSON, Philip. *Technological discontinuities and organizational environments*. Administrative science quarterly, 1986, 439-465.
[26] DE VISSER, Matthias, et al. *Structural ambidexterity in NPD processes: A firm-level assessment of the impact of differentiated structures on innovation performance*. Technovation, 2010, 30.5-6: 291-299.
[27] RAISCH, Sebastian; BIRKINSHAW, Julian. *Organizational ambidexterity: Antecedents, outcomes, and moderators*. Journal of management, 2008, 34.3: 375-409.
[28] BOWER, J. L.; CHRISTENSEN, C. M. *Disruptive technologies: Catching the wave in Seeing differently: Insights on innovation* Brown JS (editor) Harvard Business School Press Boston MA USA. 1997.

The same set of influential authors advocated that a so-called “spin-out” could be the best mechanism to manage such projects, essentially putting the explorative-oriented new project into a separate unit outside of the main organisation and re-integrating it within later once it is sustainably functioning.[29]

A newer alternative approach to managing explorative activities alongside exploitative ones is the so-called “ambidextrous design”.[30] This approach describes the creation a structurally independent unit, which is however still integrated within the main organisation. According to the studies describing this approach, the balance between different activities needed by the organisation is best achieved “*not by creating separate units or projects to partition the work, but by building an organisation context that encourages individuals to make their own judgements as to how best to split their time between the conflicting demands for alignment and adaptability*”.[31] Therefore the autonomy which allows for innovation and explorative activities is delegated not to the organisation as a whole, like in the spin-out approach, but to individuals within the new unit or project.[32]

4.2. Management of research teams

Once the organisation is established, there are further challenges arising from the question of how it should be managed. There are hundreds of approaches and frameworks one could choose from; however this thesis will focus on two distinct theories that are relevant when managing a voluntary research organisation such as eForce Driverless.

The first is the theory concerning general management model design and the different paradigms that define it. This has been formalized relatively recently and the resulting framework offers interesting implications in the case explored in this thesis.

The second theory to be examined within this scope is concerning the effects of exposure to organisation “stars”, which are highly productive members that do not necessarily hold a senior position. This theory was chosen based on the experience from the existing eForce Electric organisation, where the team is mostly pushed forward by a very small group of highly active members, even though the team as a whole is relatively large. Most members are simply more passive and consider team activities as lower priority. These members also tend to manifest higher turnaround and are likely to stay in the team only for a short amount of time.

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[29] CHRISTENSEN, Clayton M.; BOWER, Joseph L. Cust*omer power, strategic investment, and the failure of leading firms*. Strategic management journal, 1996, 17.3: 197-218.
[30] RAISCH, Sebastian, et al. Organiz*ational ambidexterity: Balancing exploitation and exploration for sustained performance*. Organization science, 2009, 20.4: 685-695.
[31] BIRKINSHAW, Julian; GIBSON, Christina B. *Building an ambidextrous organisation*. Advanced Institute of Management Research Paper, 2004, 003.
[32] LUGER, Johannes; RAISCH, Sebastian; SCHIMMER, Markus. *Dynamic balancing of exploration and exploitation: The contingent benefits of ambidexterity*. Organization Science, 2018, 29.3: 449-470.

4.2.1. Traditional and alternative management models

In recent years, especially following the dotcom revolution of the early 2000s, academics in the field of innovation and business management have been increasingly interested in the architecture and typology of business models – the way companies are organized to achieve their goals. While the concept had been around before, the new tech companies, who were soon to become some of the most successful and valuable companies in the world, had a starkly different approach to organisation. This led to a collective academic effort to formalize such differences.[33]

One of the most respected and specific frameworks was developed at London Business School and it lays out four axes on which the organisation's management models may be positioned.[34] This layout may be seen on figure 2, with the left side of the figure representing traditional and the right side alternative business models. Traditional forms of management should not be understood in a negative way – it had served large and successful companies such as Walmart, Coca Cola or Exxon Mobil for decades and they remain prosperous. Still, new disruptive alternative models had proved immensely effective for more agile organisations to rise through the ranks and achieve success.[35] The framework is split between the ends, meaning managing objectives and personal motivation and the means, concerning decision making and activity coordination. Each dimension has an axis, but each company need not lie on one of the extremes – it is important to note that the models are not antagonistic and oftentimes a sensible combination of both approaches might work best.[36]

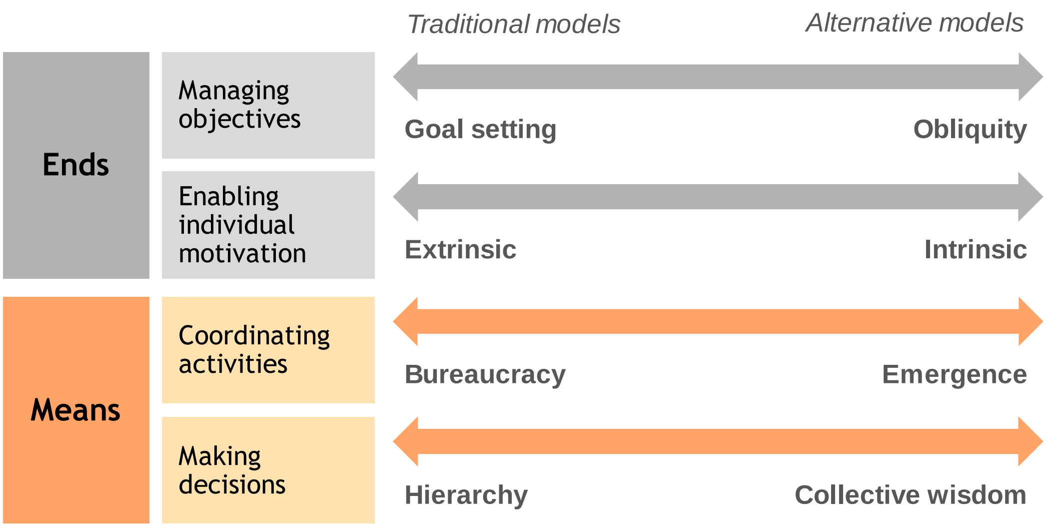

Figure 2: A framework for dimensionalising management models[37]

[33] BIRKINSHAW, Julian; HAMEL, Gary; MOL, Michael J. *Management innovation*. Academy of management Review, 2008, 33.4: 825-845.
[34] BIRKINSHAW, Julian; GIBSON, Christina B. *Building an ambidextrous organisation*. Advanced Institute of Management Research Paper, 2004, 003.
[35] MARULLO, Cristina, et al. 'Ready for Take-off': *How Open Innovation influences startup success*. Creativity and Innovation Management, 2018, 27.4: 476-488.
[36] BIRKINSHAW, Julian; GODDARD, Jules. *What is your management model?* MIT Sloan Management Review, 2009, 50.2: 81.
[37] Own graphic adapted based on original from the same source, page 84

4.2.2. Exposure to highly productive members

As discussed earlier, eForce as a whole has experience with very uneven distribution of activity and work between members, which is a phenomenon that occurs periodically every season, seemingly spontaneously. In any case, the members that are most productive form a distinct core of the team. Since they are such an integral part of the team's culture, it is worth considering their theoretical impact on the organisation overall. These talented or otherwise exceptionally hardworking individuals are sometimes referred to as "stars" in the relevant academic literature.[38]

The notion that in complex teams, work and talent is distributed unequally is nothing new. Some literature on this topic was published already in the 1960s, dealing with the patterns of productivity around Nobel laureates. It might not come as a surprise that this study argued that exposure to highly productive colleagues motivates people to maintain informal esteem.[39] This is further supported by other studies which followed, for example arguing that talented and hardworking people tend to enhance the prestige of their groups[40] and that close contact with them results in good ideas and higher productivity for the whole organisation.[41] Apart from the intangible benefits, having high status members allows organisations to also increase efficiency in specific ways. For example, studies showed that working with capable colleagues allows knowledge workers to broaden their range of skills through development, training, counselling, friendship and knowledge sharing.[42] Furthermore, since these stars have a higher productivity rate, it is often useful to funnel their work outputs to serve as the input for the work of others to inspire them and remove process bottlenecks.[43] However, not all sources agree that having more stars is always necessarily a good thing. With rising education rates and increasing workplace competition, new studies starting in the 1990s argued that even though general high group status (provided by talented individuals) increases predicted future group performance,[44] if a group becomes overly star-studded and is already highly visible to most stakeholders in its domain, adding an additional star may add only a negligible increment of visibility to the group.[45] Consequently, some recent studies have argued that too many high-status "star individuals" actually hurt the organisation and may hinder its efficiency and coherence, as members may start to lose perception of their own talents.[46]

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[38] OETTL, Alexander. *Reconceptualizing stars: Scientist helpfulness and peer performance.* Management Science, 2012, 58.6: 1122-1140.
[39] ZUCKERMAN, Harriet. *Nobel laureates in science: Patterns of productivity, collaboration, and authorship*. American Sociological Review, 1967: 391-403.
[40] GOODE, William Josiah. *The celebration of heroes: Prestige as a social control system*. Berkeley: University of California Press, 1978.
[41] ALLISON, Paul D.; LONG, J. Scott. *Departmental effects on scientific productivity*. American sociological review, 1990, 469-478.
[42] MCCALL, Morgan W. *High flyers: Developing the next generation of leaders*. Harvard Business Press, 1998.
[43] THOMPSON, Edward P. *Time, work-discipline, and industrial capitalism*. Past & present, 1967, 38: 56-97.
[44] PODOLNY, Joel M. *A status-based model of market competition*. American journal of sociology, 1993: 829-872.
[45] BENJAMIN, Beth A.; PODOLNY, Joel M. *Status, quality, and social order in the California wine industry.* Administrative science quarterly, 1999, 44.3: 563-589.
[46] GROYSBERG, Boris; NANDA, Ashish; NOHRIA, Nitin. *The risky business of hiring stars*. Harvard business review, 2004, 82.5: 92-101.

4.3. Leadership theories

Following up from the previous theory arguing about the effect of "stars" being present in the organisation, which are informally recognized as leading organisation activities, it is also crucial to inspect the formal leadership effects. Since eForce Driverless was founded by only two core members that recruited other new members almost exclusively from eForce newcomers, the effect of leadership may be assumed to be extensive in the beginning of the organisation's existence.[47] In this thesis, both traditional and more modern theories of leadership are examined.

4.3.1. Situational approach

One of the most well-known traditional approaches to leadership is the situational approach according to which leaders should adapt their styles to their subordinate's development level, or past experience and commitment in the context of a particular project or task.[48] The theory recognises four stages of worker development as seen on figure 3.

First, new workers have low competence / skills but high commitment. After some time, the worker often starts to lose their commitment as they struggle with elevating their competence. Then in the third stage, the worker still has variable commitment but has already achieved significant competence. And finally, in the last phase, the workers have both a high competence and high commitment.

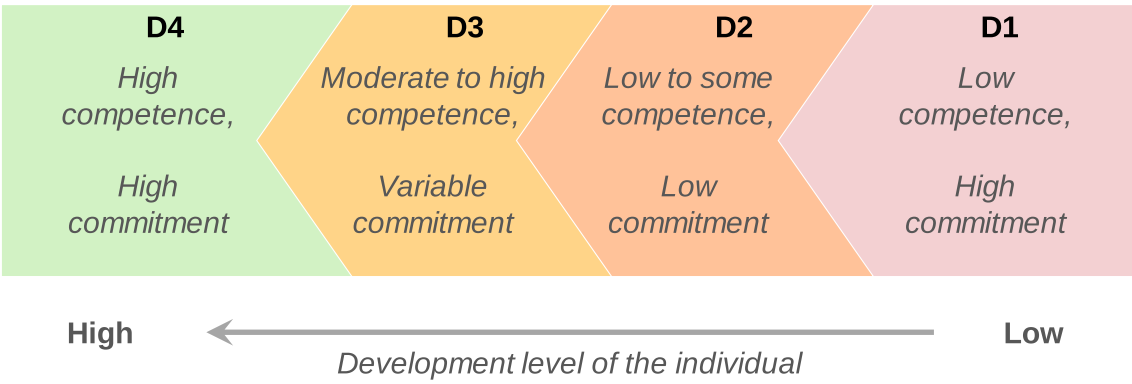

Figure 3: The four stages of development of followers in the situational leadership approach[49]

[47] DAY, David V.; GRONN, Peter; SALAS, Eduardo. *Leadership in team-based organizations: On the threshold of a new era*. The Leadership Quarterly, 2006, 17.3: 211-216.
[48] HERSEY, Paul; BLANCHARD, Kenneth H.; NATEMEYER, Walter E. *Situational leadership, perception, and the impact of power.* Group & Organization Studies, 1979, 4.4: 418-428.
[49] Own graphic adapted based on original from: HERSEY, Paul; BLANCHARD, K. H. *Situational leadership*. In: DEAN'S FORUM. 1997. p. 5.

Based on these combinations of attributes, the leader should use a combination of two types of behaviours: directive behaviours, through clarifying the details of a task and supportive behaviours, which encourage the worker's commitment. The combination of these behaviours is called a leadership style.

Behaviours used to influence others that can range from highly directive and supportive to very hands off. The four distinct leadership styles include Delegating, Supporting, Coaching, and Directing and it can be seen on figure 4 in which cases each style is to be applied.[50]

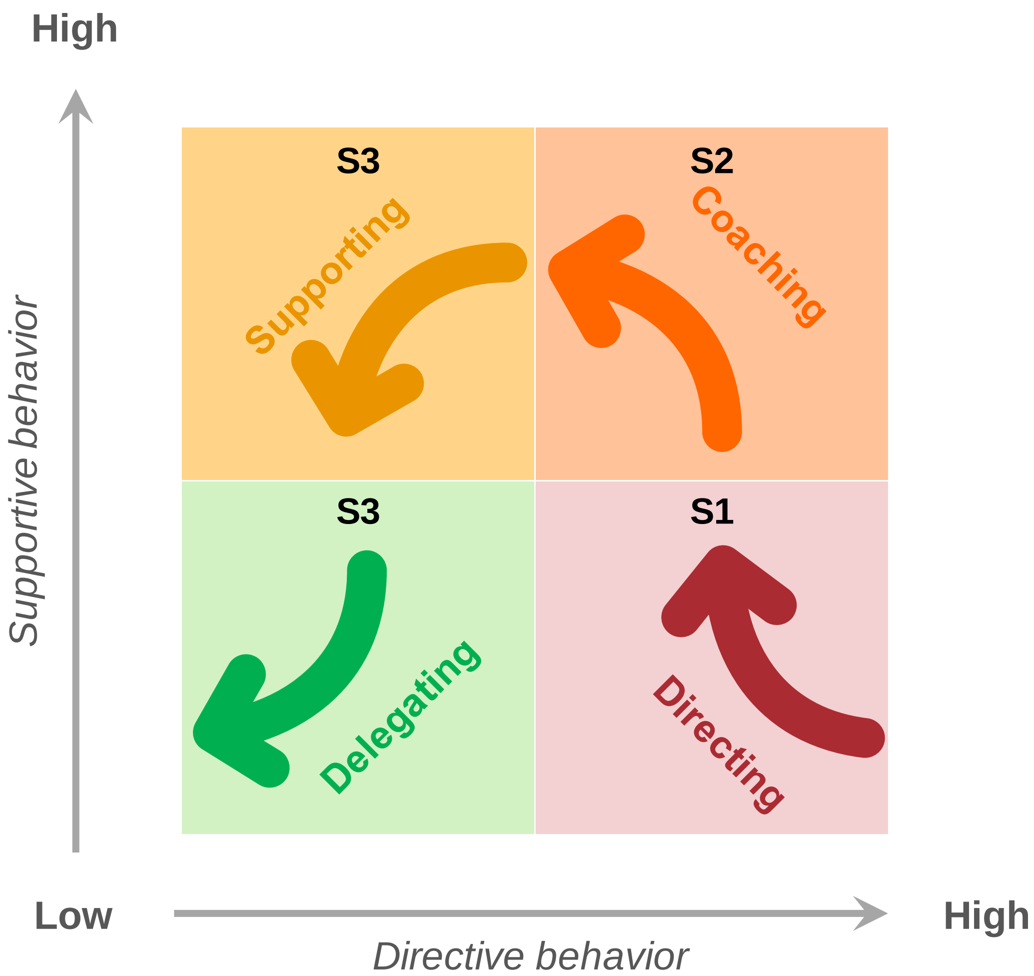

Figure 4: The four leadership styles of situational leadership[51]

[50] VECCHIO, Robert P. *Situational Leadership Theory: An examination of a prescriptive theory*. Journal of applied psychology, 1987, 72.3: 444.
[51] Own graphic adapted based on original from: HERSEY, Paul; BLANCHARD, K. H. *Situational leadership*. In: DEAN'S FORUM. 1997. p. 5.

4.3.2. Leader-Member Exchange Theory

The relatively modern Leader-Member Exchange (LMX) theory says that leaders develop a unique two-way exchange with each follower. Eventually, two distinct subgroups emerge from these relationships – the out-group and the in-group.[52]

Generally, the distinction is that in-group members are in closer contact with the leader and are more trusted. Therefore, they are often given greater responsibilities and more rewards. They could be thought of as being part of the leader's inner circle of communication.

In direct contrast, out-group members are outside of the leader's inner circle, and therefore receive less attention, fewer rewards, and are managed through formal rules, policies and bureaucratic processes.[53]

The LMX theory suggests that every leader should attempt to make all their followers feel like part of the in-group through the process of leadership making, which involves three phases[54]:

1. *Stranger phase:* People relate to each other within their prescribed roles and the follower complies with the leader.
2. *Acquaintance phase:* Leader and follower test each other's abilities to assist beyond predefined roles.
3. *Mature partnership:* Leader and follower trust each other and rely on one another for assistance beyond predefined roles to accomplish the team's goals.

Although it might not be possible to include every follower into the in-group, there are clear motivating factors enticing leaders to engage as many followers as possible. Research shows that members in the in-group show higher degrees of job satisfaction, productivity and proactivity when solving common tasks.[55]

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[52] LIDEN, Robert C.; SPARROWE, Raymond T.; WAYNE, Sandy J. *Leader-member exchange theory: The past and potential for the future*. Research in personnel and human resources management, 1997, 15: 47-120.
[53] LUNENBURG, Fred C. *Leader-member exchange theory: Another perspective on the leadership process*. International Journal of Management, Business, and Administration, 2010, 13.1: 1-5.
[54] VAN BREUKELEN, Wim; SCHYNS, Birgit; LE BLANC, Pascale. *Leader-member exchange theory and research: Accomplishments and future challenges.* Leadership, 2006, 2.3: 295-316.
[55] ILIES, Remus; NAHRGANG, Jennifer D.; MORGESON, Frederick P. *Leader-member exchange and citizenship behaviors: A meta-analysis.* Journal of applied psychology, 2007, 92.1: 269.

4.3.3. Servant Leadership

Servant Leadership is perhaps less of a theory and more of an approach to leadership, which is based on the idea that a successful and authentic leader's role is to serve others' needs. [56] Leaders may achieve this by following nine core behaviours proposed by the theory:[57]

1. *Emotional healing* – the act of showing sensitivity to others' personal concerns
2. *Creating value for the community* – a conscious, genuine concern for helping the community
3. *Conceptual skills* – possessing the knowledge of the organisation and tasks at hand so as to be in a position to effectively support and assist others, especially immediate followers
4. *Empowering* – encouraging and facilitating others, especially immediate followers, in identifying and solving problems, as well as determining when and how to complete work tasks
5. *Helping subordinates grow and succeed* – demonstrating genuine concern for others' career growth and development by providing support and mentoring
6. *Putting subordinates first* – using actions and words to make it clear to others especially immediate followers that satisfying their work needs is a priority. Leaders who practice this principle will often break from their own work to assist subordinates with problems they are facing with their assigned duties
7. *Behaving ethically* – interacting openly, fairly, and honestly with others
8. *Relationships* – the act of making a genuine effort to know, understand, and support others in the organisation, with an emphasis on building long-term relationships with immediate followers
9. *Servanthood* – a way of being marked by one's self-categorization and desire to be characterized by others as someone who serves others first, even when self-sacrifice is required

To summarize, servant leaders place the needs of their followers before their own interests and focus instead on helping them achieve their maximum potential in the task at hand and their career at large[58]. The motivation of a servant leader is not self-centred, instead they "*want theirsubordinates to improve for their own good, and view the development of followers as an end, in and of itself, notmerely a means to reach the leader's or organisation's goals*"[59]

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[56] VAN DIERENDONCK, Dirk. *Servant leadership: A review and synthesis*. Journal of management, 2011, 37.4: 1228-1261.
[57] LIDEN, Robert C., et al. *Servant leadership: Development of a multidimensional measure and multi-level assessment*. The leadership quarterly, 2008, 19.2: 161-177.
[58] GREENLEAF, Robert K. *Servant leadership: A journey into the nature of legitimate power and greatness*. Paulist Press, 2002.
[59] EHRHART, Mark G. *Leadership and procedural justice climate as antecedents of unit-level organizational citizenship behavior.* Personnel psychology, 2004, 57.1: 61-94.

5. Project background

In this section, the most relevant basic information is laid out regarding the Formula Student Competition and the eForce FEE Prague Formula Student Team in order to offer a general overview about the environment of the subject at hand.

5.1. Formula Student

The competition that eForce Driverless is part of is called Formula Student (FS), sometimes also referred to as Formula Society of Automotive Engineers (FSAE) in North America. It is one of the most recognized engineering competitions worldwide. The basic idea is for student teams from universities from all over the world to design, produce and race a prototype of a single-seat race car with various possibilities of powertrain.[60]

The competition history dates back to the year 1981[61], when it was officially founded by the Society of Automotive Engineers (SAE) in the United States. The first event outside of the United States took place in the United Kingdom in 1998 and was attended by just seven teams from both countries. Since then, the competition has attracted more and more teams each year. Gradually, the rules became formalized, and more races were staring to be organized all across the globe – and today, the only continent sleft without Formula Student races are Africa and Antartica.[62]

5.1.1. Rules

Currently, the most respected Formula Student competition is Formula Student Germany (FSG).[63] Therefore, most other European competitions use the Each Formula Student competitions use the rules published by FSG as a baseline so that student teams may attend multiple events with one car. However, it may still be the case that each event also has certain specifics that the teams need to consider. The general rules for the Formula Student Germany season 2020 can be found on its official website[64].

[60] *SAE* [online]. Society of Automotive Engineers, 2019
(Retrieved November 20th, 2019 from: http://www.sae.org/)
[61] *FSAE History* [online]. Society of Automotive Engineers, 2019
(Retrieved November 10th, 2019 from: https://www.fsaeonline.com/page.aspx?pageid=c4c5195a-60c0-46aa-acbf-958ef545b72)
[62] SZELES, Marek. *Byznys plán eForce FEE Prague Formula 2018*. 2018. Bachelor's Thesis. České vysoké učení technické v Praze. Vypočetní a informační centrum.
[63] *Formula Student World Ranking* [online]. Mazur Events, 2019
(Retrieved November 15th, 2019 from: https://mazur-events.de/fs-world/)
[64] *FSG official rules* [online]. Formula Student Germany GmbH, 2019
(Retrieved November 15th, 2019 from: https://www.formulastudent.de/fsg/rules/)

5.1.2. Racing season overview

The organisation of a racing season is fairly standard and it was already described it in detail in the author's Bachelor thesis, which is otherwise concerned with an unrelated topic however also concerning Formula Student. Therefore, the paragraphs below are curated citations of this previous work. *"Every year, the Formula Student Racing Season has a typical phased schedule, which differs slightly for every team. Overall, the timeline is mainly defined by the event dates – in Europe, most events are during the summer holidays, between July and September. During the rest of the year, it is up to the teams to divide up the time to design and manufacture their vehicle."*[65] In figure 5, a diagram shows the season stages as used by eForce, with the roman numerals on top indicating months – please note that the competition and design stages overlap by two months at eForce.

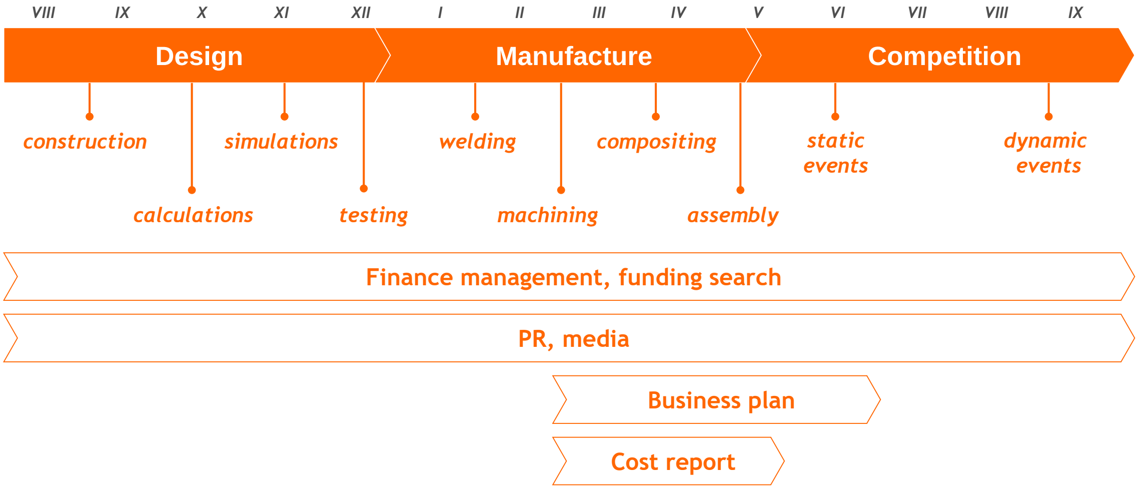

Figure 5: A typical season stages diagram for eForce[66]

In order to sign up for a race, the teams must fulfil two requirements – completing an onboarding test and paying the race fee. *"The onboarding test is essentially an online questionnaire every team wanting to participate has to fill out. It consists of questions based of the official event rules. [...] Generally, the whole team can cooperate to submit the questionnaire, but it is only accepted if there are no mistakes at all. Luckily, there are multiple re-submissions possible. Once the team manages to get all the answers right, their completion time is noted and all teams are then ranked based on their completion time, from fastest to slowest. Teams that failed to complete the questionnaire in a given time limit are not eligible to participate."*[67] Usually there are more teams interested in an event than there is capacity for and many teams are therefore put on a waiting list beyond the accepted teams. After the team is accepted as a participant, it needs to pay the event fee, which is generally in the lower thousands of Euros. Failure to do so would also result in disqualification and the spot would be offered to the next team in line.

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[65] SZELES, Marek. *Byznys plán eForce FEE Prague Formula 2018*. 2018. Bachelor's Thesis. České vysoké učení technické v Praze. Vypočetní a informační centrum. Page 9
[66] Same source as above
[67] Same source as above

5.1.3. The Driverless Formula Category

The Formula Student competition is divided into three classes: electric, combustion and driverless vehicle. The last classification, which has existed since 2017, is called Formula Student Driverless (FSD/DV), where both combustion and electric cars are permitted. Contrary to the other two classes, the driverless class rules permit the use of a team's existing race car which has already attended a previous race. Therefore, formerly manually driven race cars equipped with appropriate sensors, actors and computing hardware can be adapted to driverless cars. Nevertheless, vehicles must comply with the restrictions of their appropriate class; in particular, manual operation must still be possible. It is noteworthy that Formula Student Germany released a strategic statement in late 2019 outlining their plan to phase out FSD as a separate competition class and merge it with the other two, Electric (EV) and Combustion (CV) classes. This would mean that starting from the 2021 season, all vehicles would need to implement autonomous functionality, regardless of class, in order to be able to attain full points in the races. Furthermore, FSG announced plans to phase-out the Combustion category altogether.[68]

Regardless of the class in which a team participates, the event itself is divided into static and dynamic disciplines, and points can be scored in each discipline. In the static discipline, a cost report and a business plan must be presented by each team. Before a car is allowed to participate in a dynamic event, a technical inspection must be passed to ensure the car is mechanically and electrically safe, in accordance with the rules. Since a car's total score is comprised of both disciplines, the fastest car need not necessarily win.

The total power allowed for formula student cars with any kind of powertrain is 80kW, and for electric powertrains a maximum voltage of 600V at any time is allowed. The other major limitation is the wheelbase of at least 1525mm. Aside from those stipulations, students are free to design their cars' characteristics as they wish.

The competition requires students to design emergency systems in a detailed Failure Mode and Effects Analysis (FMEA). For instance, power or mechanical failure to the brakes or steering must be accounted for with fallback systems. When emergency braking is initiated by remote or failure detection in another subsystem, the vehicle must enter a safe state that simultaneously relies on the actuator's operation. For instance, a vehicle steering 60 degrees to the left while a full brake is initiated should first steer to the centre position to optimize friction on the wheels.

[68] Formula Student Germany, *FSG Strategic Announcement*. formulastudent.de, October 24th, 2019 [online]. (Retrieved November 11th, 2019 from: https://www.formulastudent.de/pr/news/details/article/fsg-strategic-announcement)

The track is set out with cones of different colours indicating straights, inner- and outer corners. The cones can be seen on figure 6. This is the starting point for the fast set of sensors and algorithms that need to translate this 3D workspace into a feasible trajectory for the car to follow. To follow this path a reliable model of the vehicle is essential. These models need to be heavily reliable in different conditions such as extreme temperatures, rain and different track conditions.

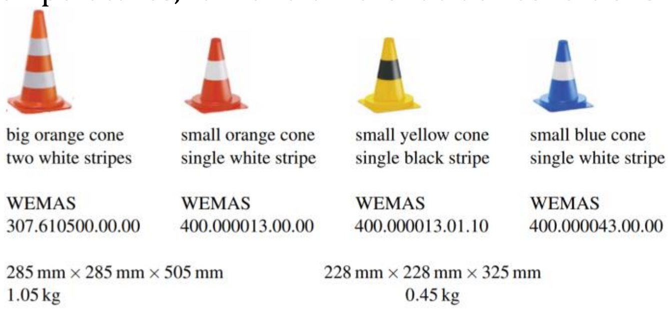

Figure 6: Cone specification

The Driverless competition, like the electrical and combustion Formula Student competitions, is divided into so called "dynamic" and "static" events, sometimes called disciplines. The dynamic events are about the car's performance, while the static events are more about the thought that went into the car's design.

The dynamic events consist of five disciplines: Acceleration, Skidpad, Autocross, Trackdrive and Efficiency, all of which are described below.

Acceleration: Drive 75m in a straight line as fast as possible, as seen on figure 7.

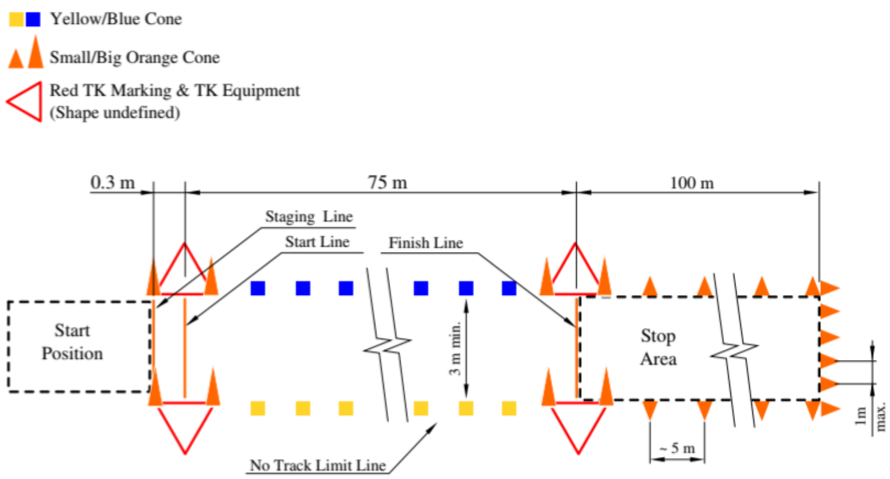

Figure 7: Track specification for the acceleration event[69]

[69] *FSG official rules* [online]. Formula Student Germany GmbH, 2019
(Retrieved November 15th, 2019 from: https://www.formulastudent.de/fsg/rules/)

Skidpad: Race through a small eight-figure track seen on figure 8 to challenge of the lateral capabilities of the race car.

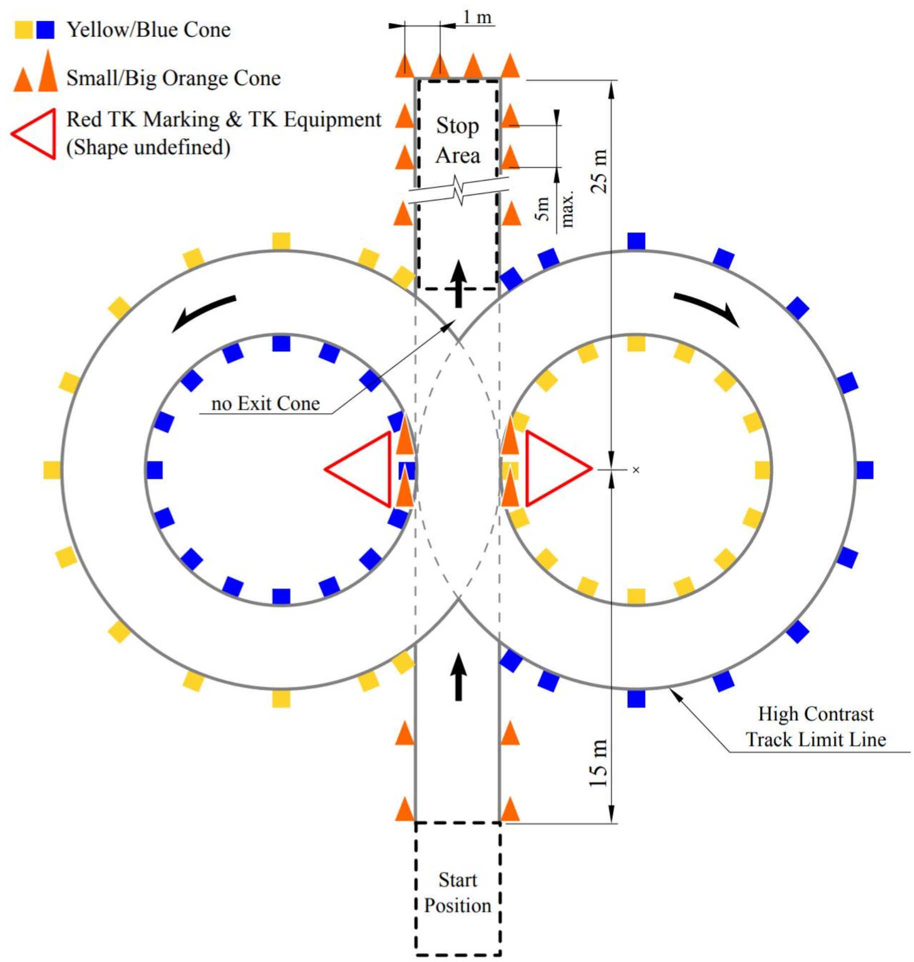

Figure 8: Track specification for the skidpad event[70]

[70] *FSG official rules* [online]. Formula Student Germany GmbH, 2019
(Retrieved November 15th, 2019 from: https://www.formulastudent.de/fsg/rules/)

Autocross: Drive a full lap on a previously unknown track, the specification of the layout can be seen on figure 9 and an example of a full lap shape on figure 10.

Trackdrive & Efficiency: Drive at least 10 laps on a track similar to the one used in the autocross discipline autonomously. Points are awarded for speed and energy efficiency.

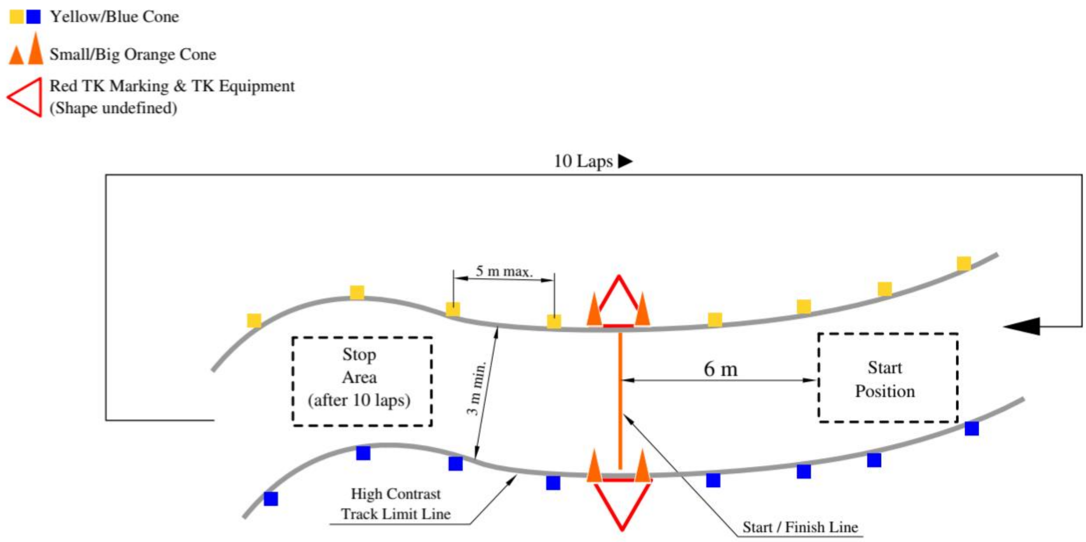

Figure 9: Track specification for the autocross and trackdrive event[71]

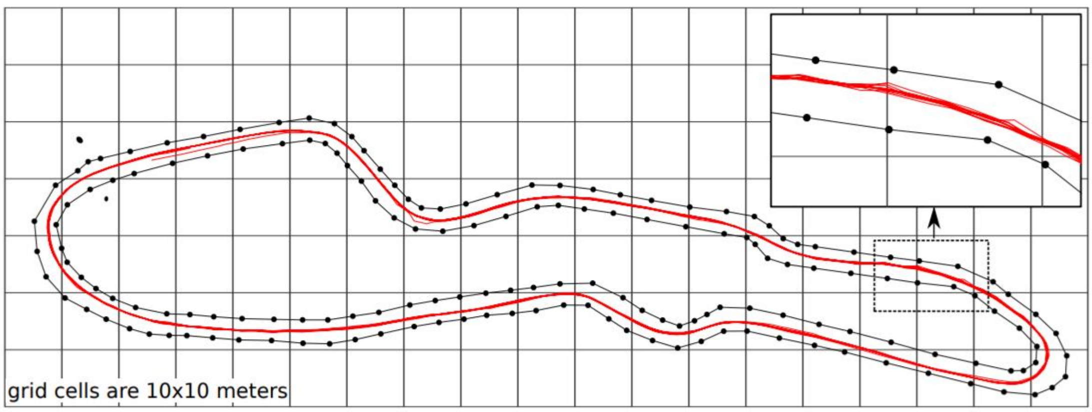

Figure 10: Example of an autocross / trackdrive event full track layout possibility[72]

[71] *FSG official rules* [online]. Formula Student Germany GmbH, 2019
(Retrieved November 15th, 2019 from: https://www.formulastudent.de/fsg/rules/)
[72] DE LA IGLESIA VALLS, Miguel, et al. *Design of an autonomous racecar: Perception, state estimation and system integration*. arXiv, 2018, arXiv: 1804.03252.

There are also four static disciplines, each of which is scored by a set of judges from commercial environments:

Engineering Design: Tests the team on their engineering and autonomous design knowledge and capabilities.

Business Plan: A business proposal for bringing the team's vehicle onto the real-world market is defended

Cost Event: The financial demands of the vehicle and the team's diligence in cost reporting is evaluated.

Overall, the disciplines are assigned point weights that usually add up to 1000 points total on each race. An example of such point distribution may be seen on figure 11.

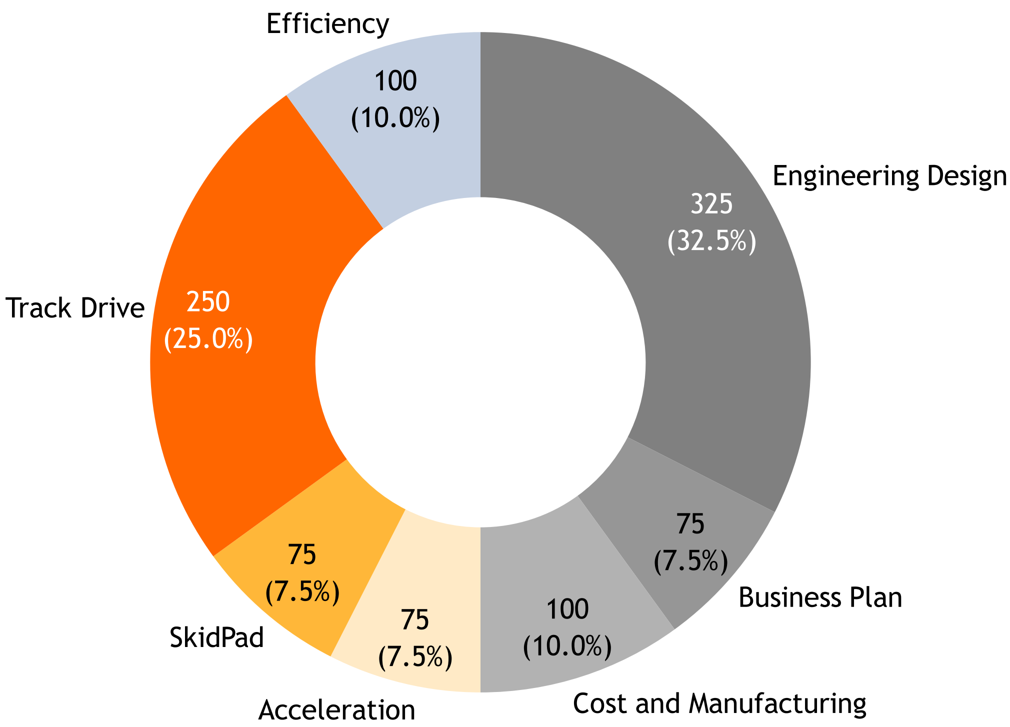

Figure 11: Point distribution between the driverless disciplines[73]

[73] Note: Autocross is sometimes excluded from races, as shown on figure. Figure adapted from: *FSG official rules* [online]. Formula Student Germany GmbH, 2019
(Retrieved November 15th, 2019 from: https://www.formulastudent.de/fsg/rules/)

5.2. The eForce FEE Prague Formula Team

The team eForce FEE Prague Formula is a unique project at the Faculty of Electrical Engineering in Prague. It allows dozens of students with diverse backgrounds ranging from mechanical engineering through cybernetics to business to interact and collaborate on a practical assignment – building a race car. The team is currently still the only Czech team participating in Formula student with an electric-powered vehicle. A picture of the team at a race can be seen on figure 12.

Figure 12: The eForce team and the FSE.07 vehicle at the Netherlands[74]

5.2.1. Team history

As stated on the project website and other official sources, the history of the team is quite complicated and eventful over the 10 years of its existence: *"The team was founded in 2010, back then as part of the older CTU CarTech Formula Team*[75]*, which was only building combustion formulas up until then. It took two years, but in 2012 the team managed to complete its first functioning electric vehicle. Two years later, the team expanded and got its own premises. With that, the electric part of the team decided to separate from the original CarTech Team in order to increase the efficiency of the organisation. Whereas the CarTech Team officially remained a team under the Faculty of Mechanical Engineering, Czech Technical University, the newly established eForce FEE Prague Formula Team moved to the Faculty of Electrical Engineering, where its new premises were located, and the team remains there to this day."*[76]

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[74] eForce FEE Prague Formula, *About us* [online]. eForce, 2019
(Retrieved November 15th, 2019 from: https://eforce.cvut.cz/o-nas/)
[75] CTU CarTech, *Formula Student Combustion Team* [online]. CarTech, 2019
(Retrieved November 15th, 2019 from: http://cartech.cvut.cz/)
[76] SZELES, Marek. *Byznys plán eForce FEE Prague Formula 2018*. 2018. Bachelor's Thesis. České vysoké učení technické v Praze. Vypočetní a informační centrum.

Since 2012, when the first eForce formula was built, the team has grown to a stable 60 or so members in total, with 30 core members that work on the formula continuously for more than one season. Every season, a new formula is built, with the general trend being that the weight of the vehicle is gradually decreased every season, and the maximum power increased. A summary of the development can be seen on figure 13. During the 2018/2019 season, the team is considering building an autonomous vehicle for the first time, thus this feasibility study is being created.

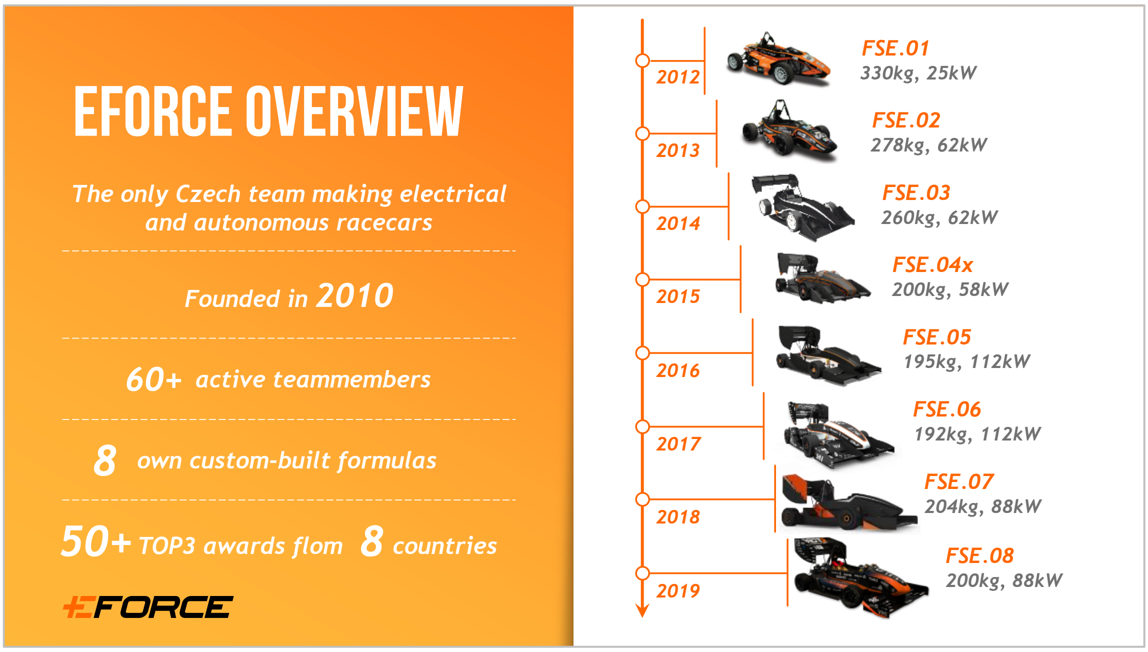

Figure 13: Brief summary of eForce history

5.2.2. Team results

Ever since eForce electric first started competing, it delivered exceptional results considering its situation. Furthermore, every season starting from 2014, it consistently manages to reach a TOP3 position in some race every season. In the following table, the results for major races since 2012 are presented, proving that eForce is remaining highly competitive consistently in the long term. The aim of eForce Driverless is therefore to replicate such success in the new competition category.

Date	Event	Competeti-veness	Teams	Place	CR	BP	EDR	ACC	SP	AX	END	EFF	Penalty	Total points
2019.08	ES	0.95	39	23.	-	6.	14.	6.	-	12.	-	-	0	259
2019.07	CZ	0.85	15	2.	5.	3.	7.	1.	2.	2.	2.	5.	0	789
2019.07	IT	0.85	25	24.	21.	23.	4.	-	-	-	-	-	-60	148
2018.08	BO	N/A	14	1.	-	-	-	2.	1.	2.	1.	-	0	905
2018.07	CZ	N/A	15	1.	2.	1.	2.	1.	3.	2.	-	-	0	789
2018.07	EA	0.88	38	12	22	11	25	-	9	7	13	5	0	528
2017.08	CZ	0.86	14	3.	6.	1.	6.	5.	5.	4.	2.	7.	0	829
2017.07	EA	0.99	38	12.	22.	11.	25.	-	9.	7.	13.	5.	0	528
2016.08	CZ	0.85	10	8.	4.	3.	3.	2.	4.	-	-	-	0	366
2015.09	IT	0.85	20	11.	8.	9.	5.	5.	4.	8.	13.	-	-75	344
2015.09	CZ	0.85	13	2.	4.	13.	3.	4.	1.	1.	2.	9.	0	839
2015.08	HU	0.90	37	28.	25.	27.	28.	14.	13.	10.	-	-	-15	352
2014.09	IT	0.85	20	2.	10.	6.	5.	9.	3.	4.	2.	8.	-90	728
2014.08	HU	0.90	38	33.	33.	24.	23.	-	-	-	-	-	0	180
2013.09	IT	0.95	24	11.	11.	19.	7.	12.	14.	12.	9.	-	0	495
2013.08	AT	0.97	39	33.	37.	38.	16.	30.	-	35.	19.	-	-10	205
2013.08	HU	0.92	37	26.	27.	34.	19.	28.	16.	27.	-	-	0	309
2012.09	IT	0.85	17	8.	13.	16.	11.	10.	9.	9.	8.	8.	0	555
2012.08	HU	0.91	39	19.	37.	38.	24.	31.	18.	25.	14.	6.	0	472

Table 1: eForce race result history overview[77]

[77] Selected races, expanded based on original from: SZELES, Marek. *Byznys plán eForce FEE Prague Formula 2018*. 2018. Bachelor's Thesis. České vysoké učení technické v Praze. Vypočetní a informační centrum.

6. Feasibility Analysis

This section of the thesis is dedicated to an analysis of the situation which the eForce electric team had to face when considering the founding of a new driverless division during the end of the year 2018 and then at the beginning of 2019. In order to better assess the situation, it was decided to conduct an all-encompassing feasibility analysis of the project, to be better prepared to assess the possibility of completing the project successfully, the challenges to be faced and to make an informed decision whether to go forward with it.

A Feasibility Analysis study is mostly concerned about the external and internal factors. The external factors are usually concerning the market environment of a company. In the world of Formula Student this means two things – firstly the environment of the formula student teams, and secondly the sponsors that are granting funding to the teams and thus allowing for the teams' existence. The internal factors on the other hand are more straightforward and are similar to what could be found in standard feasibility studies – they are concerning the organisational, financial and personal capabilities of the organisation.

6.1. Competition analysis

The first type of analysis focuses on the current situation within the Formula Student community in early 2019, both as a whole and in the driverless category. It is analysed from two aspects – wider international and local Czech perspective.

6.1.1. Global competition

As seen on figure 14, the Formula Student Driverless largely remains a European-dominated competition, as 42 out of 53 total teams are based there, including all the teams that already competed or that have at least completed a prototype.

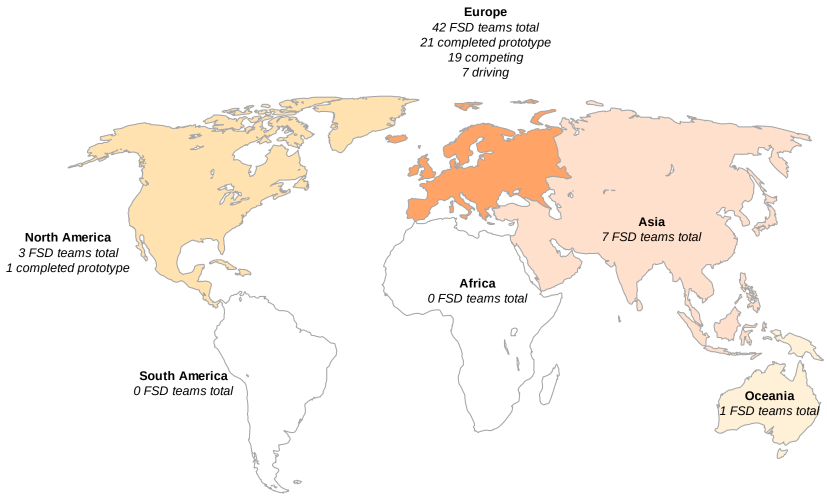

Figure 14: Overview of driverless teams per continent with their highest achievements as of the 2018 season[78]

[78] Based on own analysis of team websites done in January 2019

As seen on a close-up on Europe, depicted on figure 15, the current status is that the driverless competition is dominated by the German speaking world. The only formulas driving on the competitions are either from Switzerland (most notably the AMZ team from ETH Zürich) or from Germany (most notably the Ka-Racing from the Karlsruhe Institute of Technology). Interestingly, other university teams that have already participated at competitions (albeit not driven) come from Scandinavia and, interestingly, from Hungary.

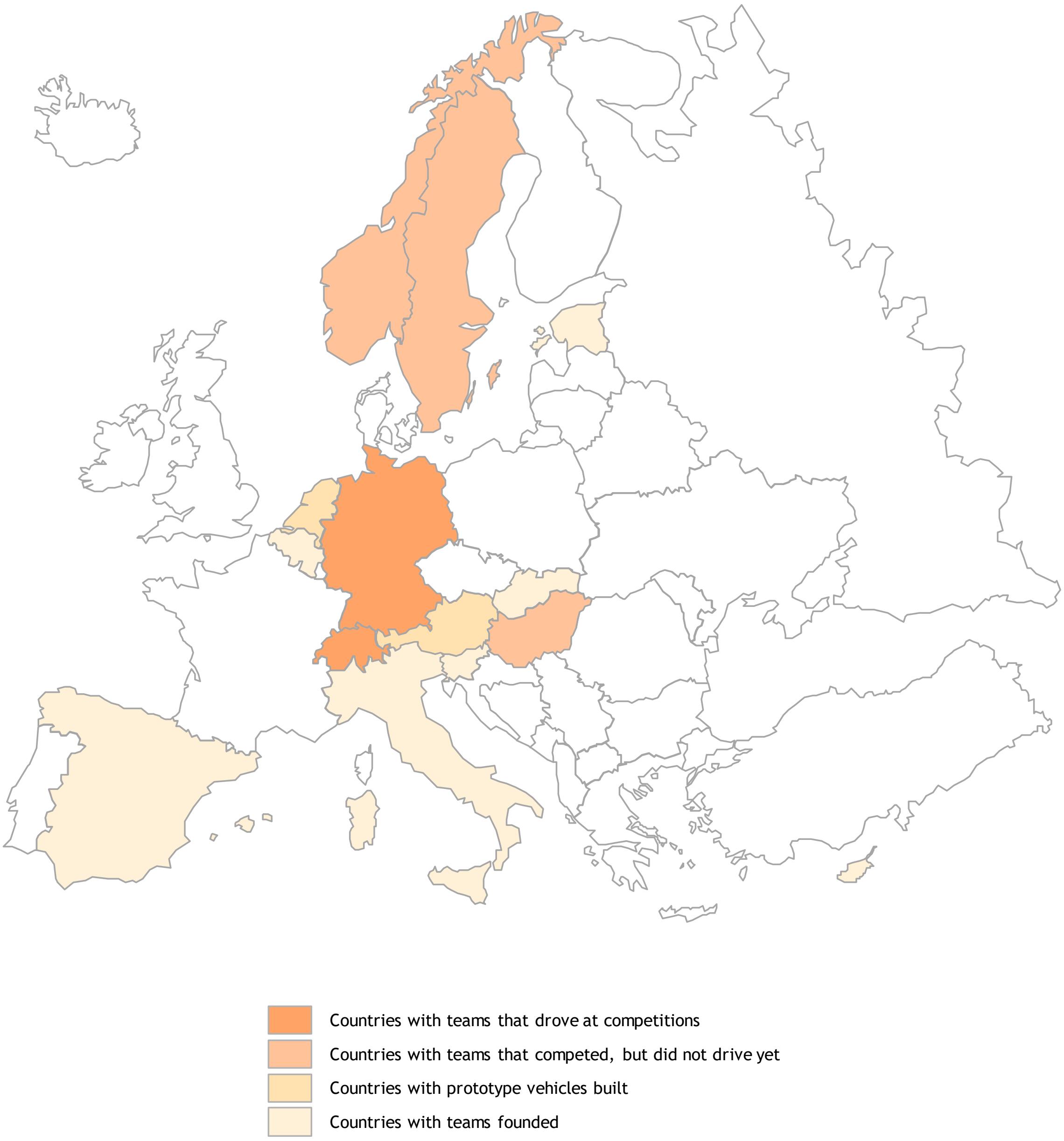

Figure 15: Driverless Formula Student teams landscape in Europe[79]

[79] Note: The only prototype completed in the Netherlands at the Delft University of Technology was co-created with the USA-based Massachusetts Institute of Technology (MIT). Graphic is based on own analysis of team websites done in January 2019

6.1.2. Local competition

As indicated previously, there are no driverless teams in the Czech Republic in early 2019. Still, it is worthwhile to look at the Formula Student landscape as a whole, which can be seen on figure 16. As shown, there are 6 combustion teams scattered all over the country, however the Prague-based eForce FEE Formula Student team is the only electric one. Generally, building a driverless machine out of an electric model is considered much more viable, since electric teams already have extensive experience with software development and because the electric powertrain can be controlled much more precisely than its combustion alternative. Thus, one can expect the barrier of entry to be too high for any other teams to attempt also trying to start an autonomous division.

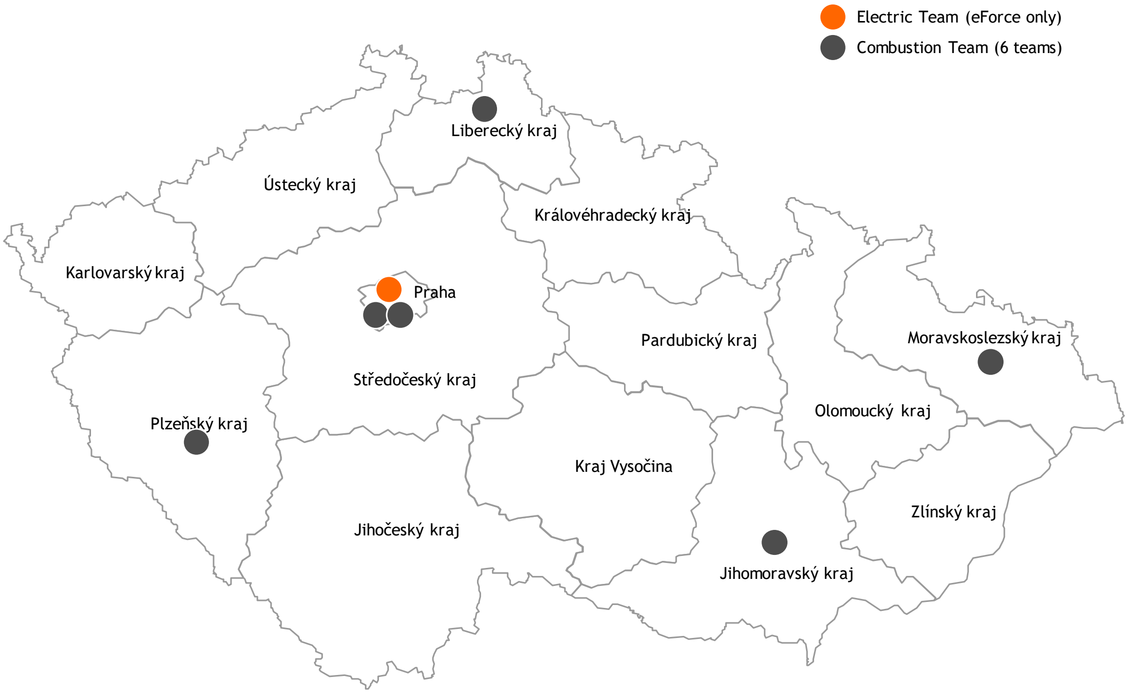

Figure 16: Formula Student teams in the Czech Republic in the 2018 season[80]

For comparison – in Slovakia there are no combustion teams and only one electric team (STUBA Green Team), which is coincidentally also trying to construct an autonomous vehicle at this time. In Hungary, there are currently 4 combustion teams, one electric team and one driverless team and in Poland there are 8 combustion teams, two electric teams, but no attempts to construct an autonomous vehicle at this time. The number of teams in each category might hint at some interesting observations regarding each country's support of technical education, push for new technologies (in case of electric/autonomous teams) and industrial capacity. The testing of such hypotheses is out of scope of this analysis, however.

[80] Note: Since this analysis, TU Brno Racing had announced their intent to build their first electric vehicle for the 2020 season and started recruiting for a potential driverless vehicle as well. Graphic based on own analysis of team websites done in January 2019

6.2. SWOT Analysis

The basic SWOT analysis of the project can be seen on figure 17. The analysis makes it clear that the main benefit of the project would be the current momentum – there are no other teams in the region that would be positioned in a similar way to start an autonomous team and the team is in a good and agile organisational shape. The biggest threat is the continuous advances of the competitor teams especially from Western Europe – this would, however, only potentially influence results at competitions and not the functioning of the team itself, nor system development.

	Helpful	Harmful
Internal	**Strengths** Quick and effective communication between team members	**Weaknesses** Knowledge not yet stored digitally may be lost
External	**Opportunities** A successful project would mean a first autonomous formula in Czechia	**Threats** (International) Competition is advancing fast

Figure 17: SWOT analysis of the eForce Formula Team situation in early 2019

6.3. Project strategy

Due to the current state of competition within the Czech Republic, the strategy of the project is to be the first and only student testbed for applied Artificial Intelligence (AI) powered autonomous driving. This is also the main selling point when approaching potential sponsors.

6.4. Manufacturing plan

There will be only one scale model RC prototype manufactured in 2019 and one autonomous formula vehicle prototype manufactured in 2020 as part of this project, which is further elaborated in the timeline chapter 6.8.1.

6.5. Marketing Mix

For the marketing mix strategy, only the reduced 4Ps methodology is used:

- **Product**
  - The product would be the first autonomous formula team in the Czech Republic and also the centre of Academic excellence of students interested in AI and autonomous driving.
- **Price**
  - The price for sponsors to take part in is not strictly set, however the sponsors are split into categories according to the value of their contribution: General sponsors (300K CZK+), Main sponsors (150K CZK+), Important sponsor (40K CZK +), etc.
- **Place**
  - The eForce team is based in Prague, but it is aiming at sponsors from all around the country and often participates in their events outside of the Czech capital.
- **Promotion**
  - The promotion of the project will be done mostly by guerrilla marketing to reduce costs, but also using the already established eForce presence on social media, as seen on figure 18.

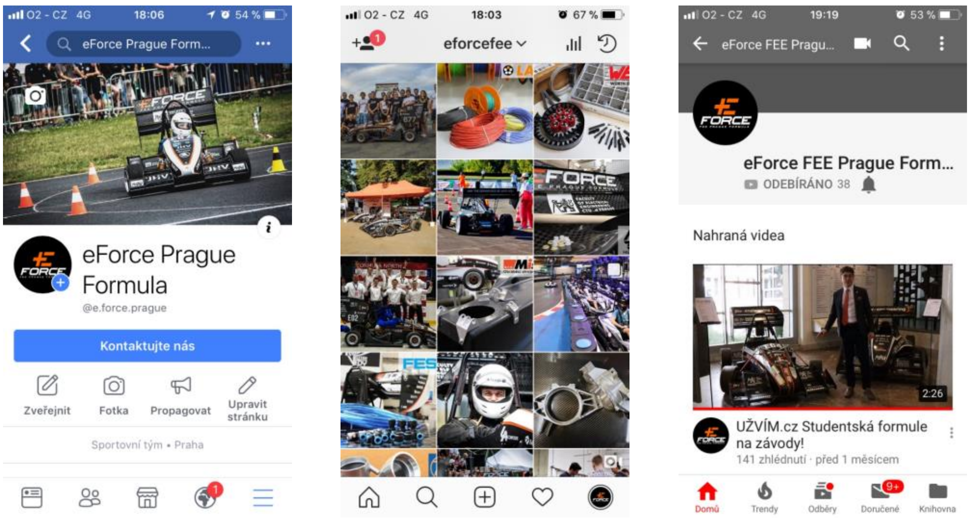

Figure 18: Some of the online channels at eForce's disposal

6.6. Customers

There are two customer (sponsor) segments eForce driverless will be aiming for. Firstly, it will be the large sponsors such as Škoda Auto or ZF that the electrical eForce team already secured and that sponsor multiple teams (and would presumably be interested in funding an additional new innovative project). Secondly, it would be companies that are not involved in Formula Student yet because they are focused on the fields more relating to Computer Science and Artificial Intelligence – which was much less prevalent in Czech Formula Student Teams before eForce driverless. Examples would include Valeo, Porsche Engineering, and other similar companies.

6.7. Organisation

The organisational structure is one of the things that ought to be most visibly immediately affected by a potential creation of an autonomous division. This chapter explores the implications such a development would have and visualizes the changes that would follow.

6.7.1. Traditional state (Legacy)

Although it is not presently used, it is important to mention the organisational structure used by eForce before the 2018 season. It included four divisions – Mechanical, Electrical, IT and Project groups, as seen on figure 19. This legacy structure proves that eForce was already able to work with a more complex structure in the past and can manage four divisions. Furthermore, it shows that in case of failure of the driverless project, eForce already has experience in consolidating itself, redistributing the work and resources and moving on without extensive damage caused to regular operations in the other divisions and the team as a whole.

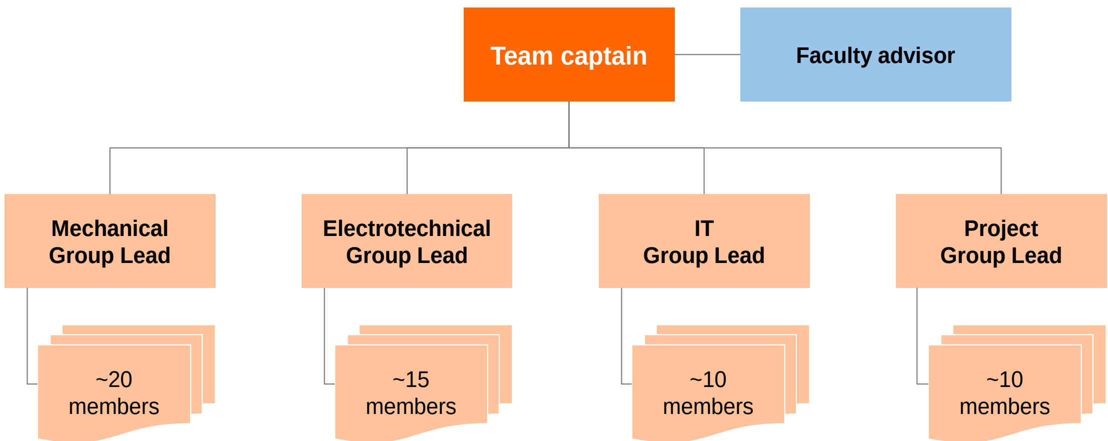

Figure 19: Legacy high-level team organisation chart

6.7.2. Current state (AS-IS)

The current state only includes three groups – the Electrical group consumed the IT group after the last IT Group Leader left the team, as seen on figure 20. This led to a simpler management structure; however the output of software was limited to vehicle-related fields and thus internal software systems (such as web development) suffered.

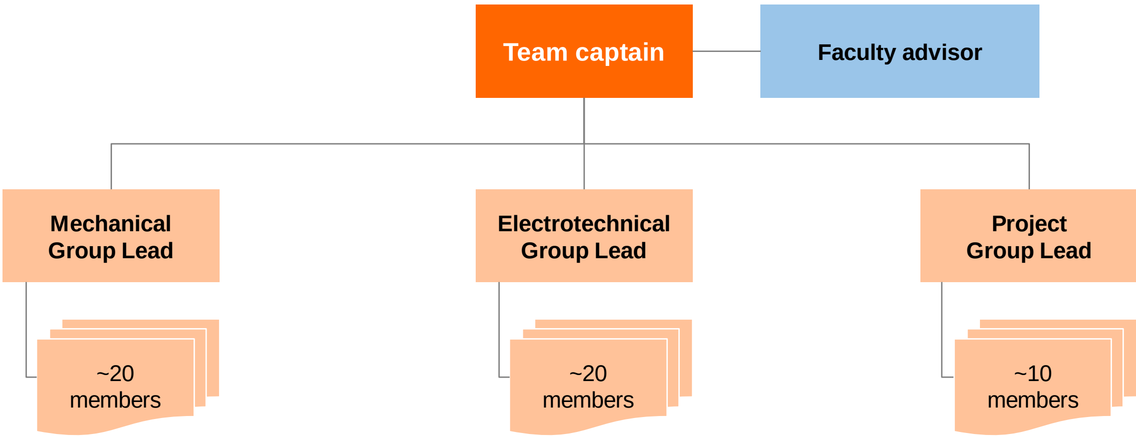

Figure 20: Current high-level team organisation chart

6.7.3. Future state (TO-BE)

The future intended state, as shown on figure 21, adds an additional group/division focusing on autonomous vehicle development, consisting of around 10 members solely dedicated to the development of the first Czech autonomous formula.

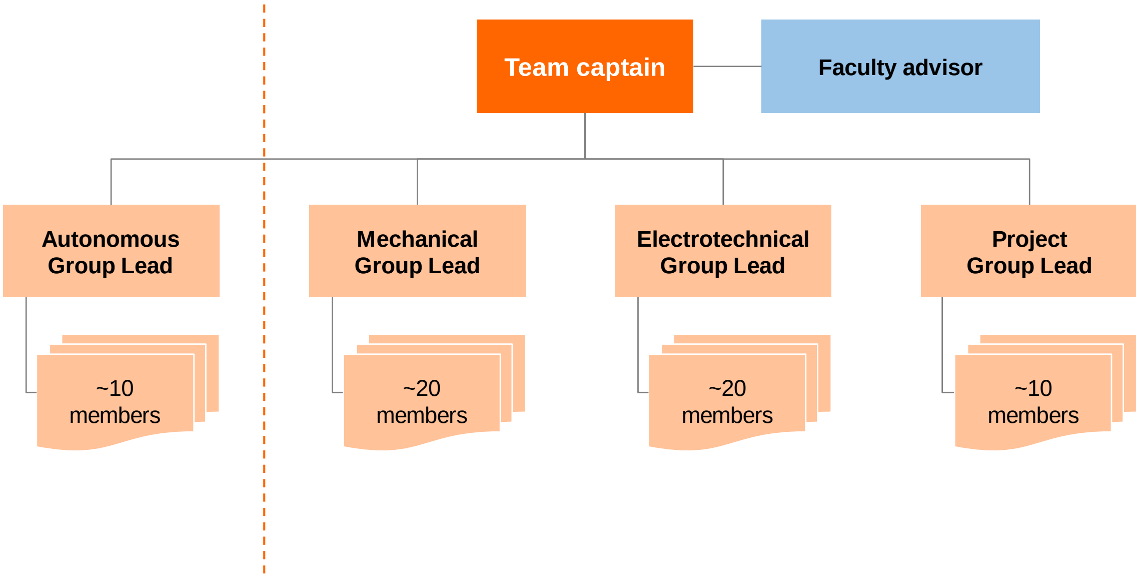

Figure 21: New high-level team organisation chart

6.8. Implementation

This chapter is concerned with the actual process of creating the autonomous branch of the eForce Team. The current state (AS-IS) is the purely electric Formula Student team and the desired future state (TO-BE) is an electric Formula Student team including an autonomous vehicle division.

6.8.1. Work breakdown structure

For simplicity and the possibility of making agile changes of scope, the whole venture is split into four phases:

Phase 0: Team building

The phase before the official start of the project is split into three main activities:

- Team recruitment
- Team building
- Knowledge sharing workshops

Phase 1: RC model prototype

The first phase is split into six main activities:

- Strategy definition
- Funding security
- RC car design
- Software development
- Hardware assembly
- Testing

Phase 2: First Driverless Formula manufacture

The second phase is split into four main activities:

- Second round of funding security
- Second round of recruitment
- Hardware transfer to the formula vehicle
- Software adjustment
- Races registration
- Vehicle testing

Phase 3: Racing season and handoff

The third phase consists of only the racing season and later on the handing over of project responsibilities to senior team members continuing the project.

6.8.2. Timeline

Based on the work breakdown structure, a rough timeline was drafted, as seen on figure 22. A more detailed expected schedule of the 2019 racing season can be found in Appendix [A]

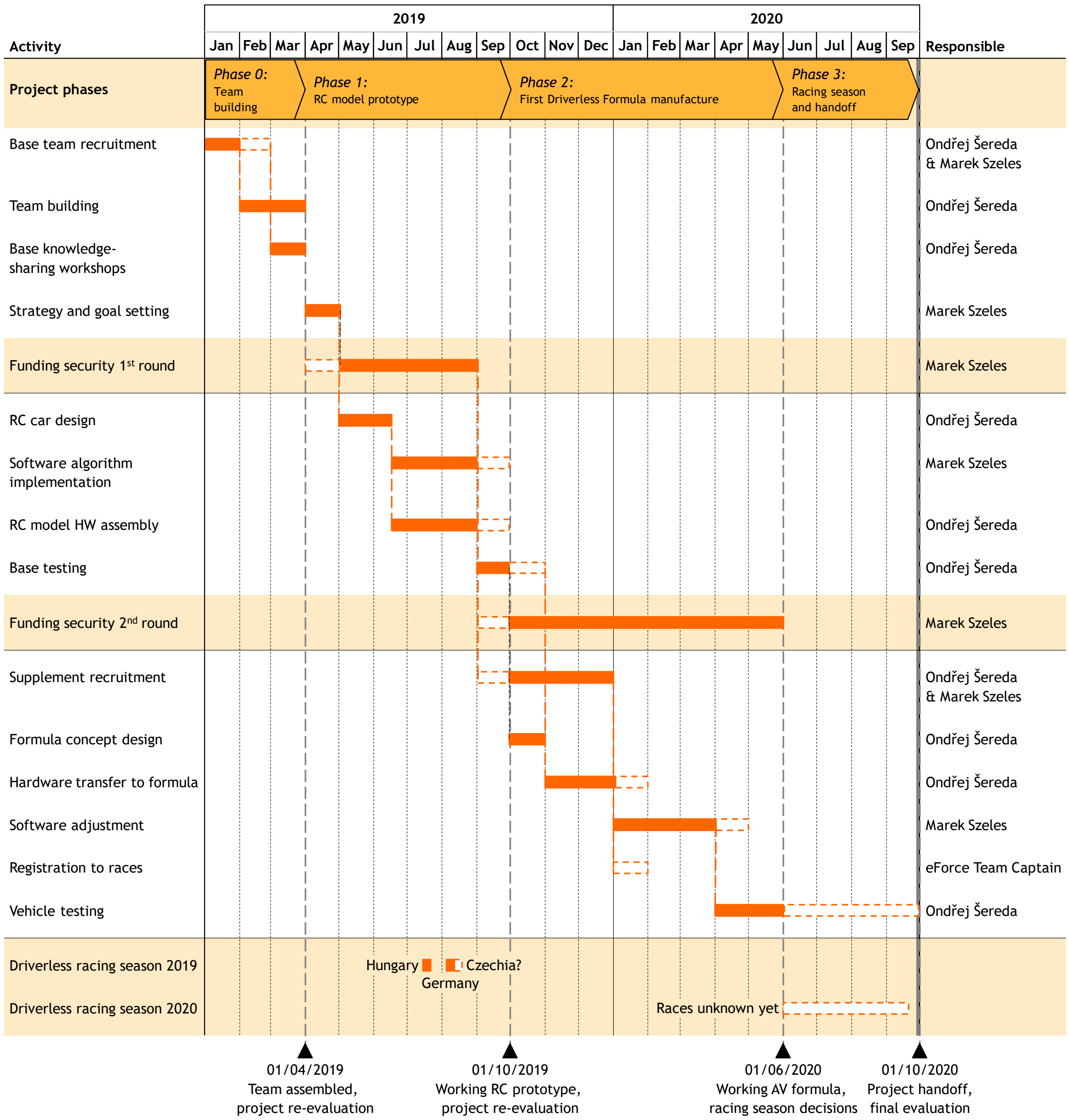

Figure 22: Gannt chart of the implementation[81]

[81]Note: The race registration in 2020 will be facilitated by the team captain. Graphic based on own analysis

6.9. Human Resources

The project development will require significant amounts of dedicated work. It is difficult to predict the time allocations of different activities, but a high-level holistic estimation can be seen on table 2. The plan is to create an approximately 10 man-unit strong team with a good combination of more experienced students that will carry the technological side of the project while expecting to graduate soon, and some more junior, but dedicated students that will serve as a "second generation", gathering experience during the first season so that they could take over the project as experts at its end.

Work type	Cost per hour	Man units	Average hours per week	Weeks	Total cost
Manual	100.00 Kč	3	5	47	70,500.00 Kč
Junior engineering	150.00 Kč	3	5	47	105,750.00 Kč
Senior engineering	250.00 Kč	5	13	47	763,750.00 Kč
Organizational / management	200.00 Kč	2	7	47	131,600.00 Kč
Total					1,071,600.00 Kč

Table 2: Human Resources value and volume estimation[82]

6.9.1. Know-how management

Since the aim is to create a sustainable autonomous team, knowledge management is one of the most crucial aspects that will ensure the long-term sustainability of the team. It shall be done using three pillars: tutorials, mentoring and shared data storage, as seen on figure 23.

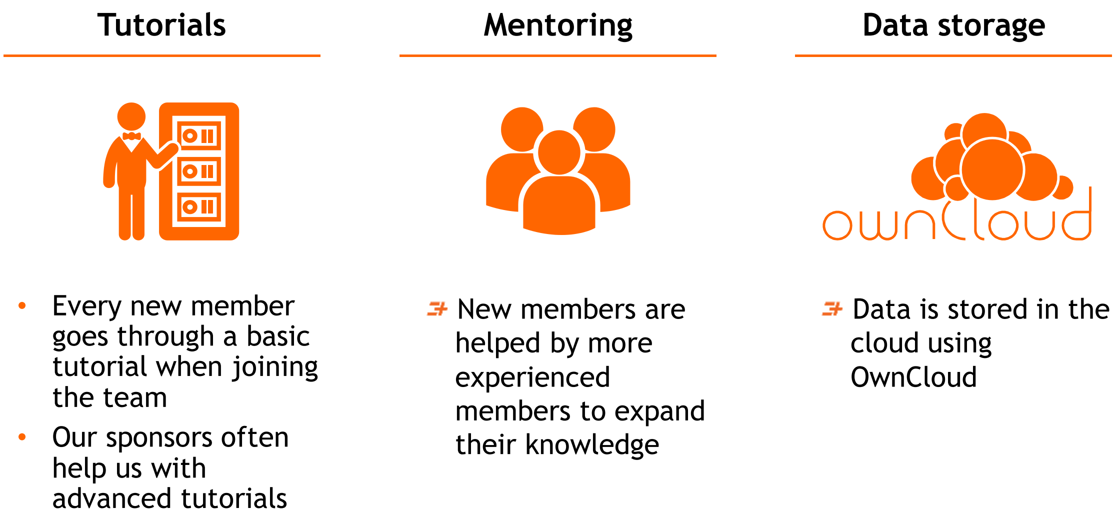

Figure 23: Know-how management plan

[82] Note: Individual "real" team members could be performing more types of work defined in this table and thus the total "Man units" exceeds the planned cca. 10 members.

6.10. Location

All of the activities of the newly formed autonomous driving team will be held at either a remote location, or at the current workshop and headquarters of the eForce team. The workshop is located within the Faculty of Electrical Engineering at the Czech Technical University (CTU) campus, the address being "*1902/, Technická 1902/2, 160 00 Praha*". The exact location of the workshop within the CTU premises can be seen on figure 24. A view of the workshop itself can be seen on figure 25.

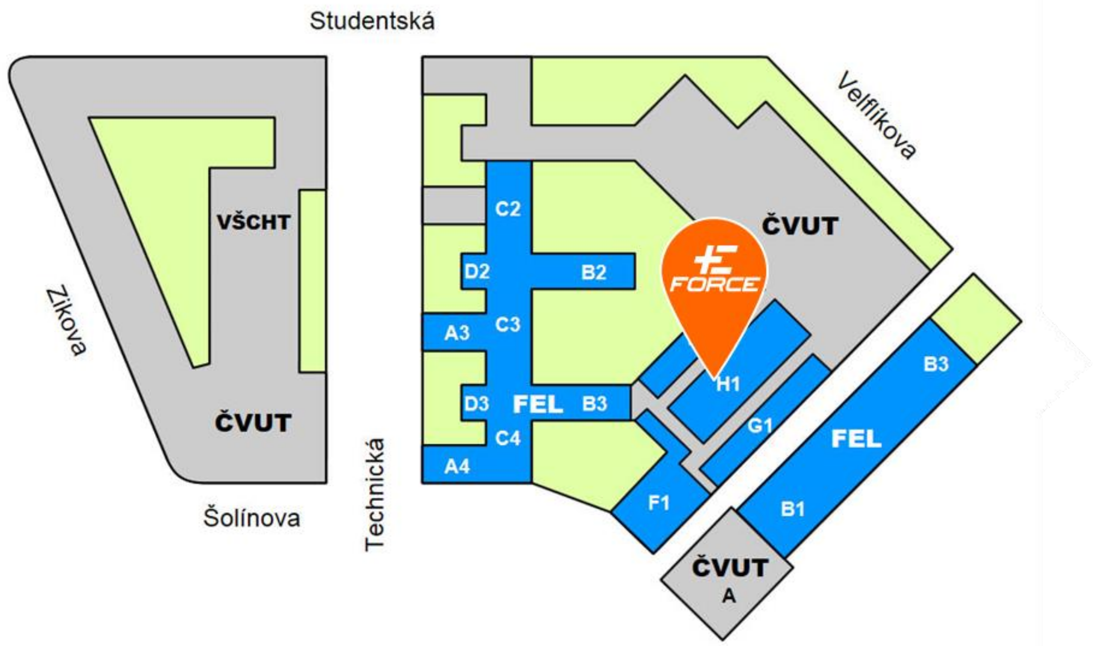

Figure 24: CTU campus in Dejvice with the highlighted location of the eForce workshop[83]

Figure 25: View of the workshop while the FSE.07 vehicle was being built

[83] Custom adaptation. Original source: ČVUT FEL, *Kde najdete učebny?* [online] 2020. (Retrieved November 20th, 2018 from: https://www.fel.cvut.cz/cz/glance/rooms.html)

6.10.1. Construction works

No construction works are needed to expand the current eForce workshop premises, the only needed feature that is currently missing would be some sort of proving grounds for the testing of the developed system. However, this requires a large, flat (ideally outdoor) surface, which was not identified within the CTU premises. Nevertheless, it can be easily constructed on the go on any outdoor premises fulfilling the requirements, like car parks, airports, automotive proving grounds etc. and thus this mobile solution is preferable, and no planned construction is needed.

6.11. Technology and equipment

This chapter describes in detail the expected technological and material needs that the eForce Driverless will face during its first year.

6.11.1. Technology

While the development of the autonomous prototype will require implementation of many different technologies, it is estimated that for at least the first season, the technologies currently used by eForce can be replicated in many cases and thus no further investment is needed. Examples of such technologies already in use can be seen on figure 26.

Organizational support systems | **Technical support systems**

Figure 26: Main technological systems used at eForce

6.11.2. Equipment

The current equipment in the eForce workshop is fully satisfactory for the side-by-side development of an additional autonomous concept and thus no new manufacturing equipment is needed.

6.12. Inputs and deliveries

This section describes some of the basic resources needed to transform one of the past Formula Student vehicles constructed by eForce into a driverless machine which would be able to create an abstract version of reality and navigate it, as seen for example on figure 27.

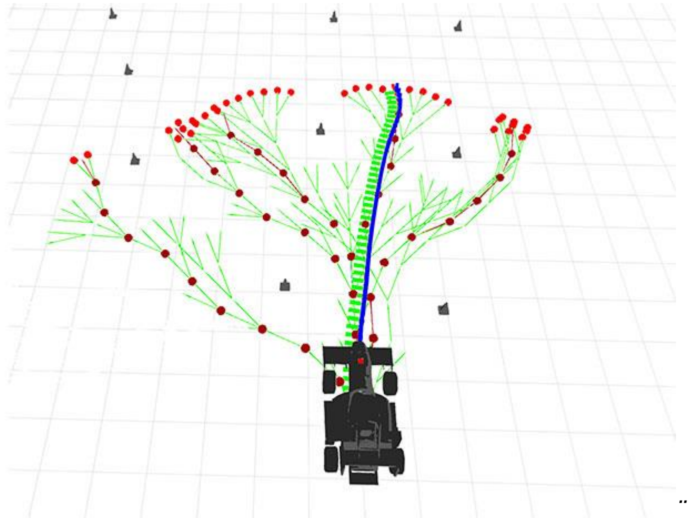

Figure 27: Path searching example of an autonomous formula[84]

6.12.1. Autonomous driving tools

The most important aspect would be the various sensors that gather the necessary data. A possible layout of the sensor setup can be seen on figure 28.

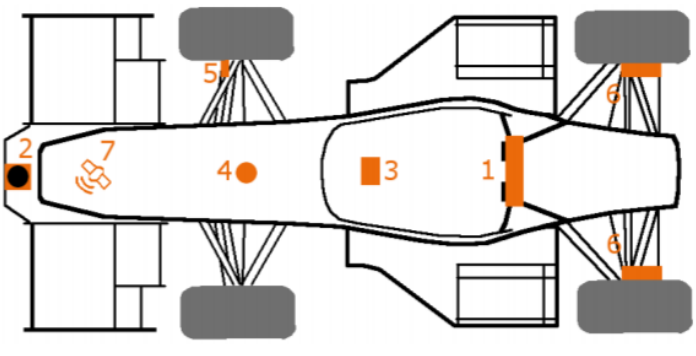

Figure 28: Sensor placement on the vehicle: 1 stereo camera, 2 laser scanner, 3 IMU, 4 steering angle encoder, 5 wheel speed encoder, 6 rotor position encoder, 7 GPS[85]

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[84] ETH Zürich. *AMZ Formula Student Driverless Team,* 2018
(Retrieved January 10th, 2018 from: http://driverless.amzracing.ch/en/about)
[85] ZEILINGER Marcel, HAUK Raphael, BADER Markus and HOFMANN Alexander. *Design of an Autonomous Race Car for the Formula Student Driverless (FSD),* 2017
(Retrieved January 4th, 2018 from: https://diglib.tugraz.at/download.php?id=5aaa45931188a&location=browse)

6.12.2. RC model prototype

The model that is assumed to be used for the RC model prototype phase is a small RC vehicle developed by the Department of Control Engineering, CTU as seen on figure 29. This vehicle has the IMU and dual GPS sensors prepared, but a limitation is its size. It seems that in its current configuration it is too small to fit all the required perception sensors such as cameras and LiDAR. Therefore, in order to utilize this vehicle for the prototype, a new, larger model wheelbase would have to be bought or a different vehicle altogether would have to be used.

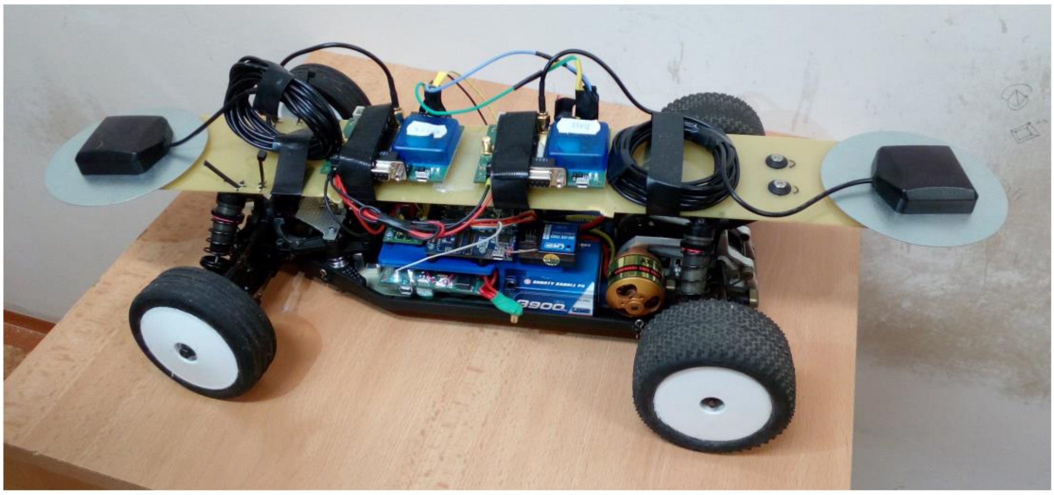

Figure 29: RC model considered for implementation

6.12.3. Formula vehicle

For the full-size competition-ready vehicle the Driverless team may consider two options: FSE.07 and FSE.08, both of which are visualized on figure 30. The first mentioned vehicle is a racing formula developed by eForce Electric in 2018. This vehicle is fully operational as of early 2019, but it is still being used by the team to test new systems for the FSE.08. This latter vehicle is only being finalized in manufacture by the time this feasibility study is being written and is expected to be finished by Summer 2019. The state of both vehicles at the end of Summer will determine which will be used for the first autonomous formula.

FSE 07 FSE 08

Figure 30: Two considered vehicles for the driverless formula

6.12.4. Generic resources

The generic resources needed for the autonomous formula are twofold – one type is generic components that make up the formula, such as bolts, wires or battery cells (as shown on figure 31). The second type would be miscellaneous other items, such as traffic cones imitating those used for setting out a racing track when testing the vehicle. As seen on figure 32, these tend to be blue and yellow (determining the inside/outside of the track).

Figure 31: Example of generic resources (battery cells)

Figure 32: Coloured cones used at the competition to mark the intended track

6.12.5. Manufactured components

The components that will need to be manufactured (and possibly also redesigned) would be mostly mechanical components such as the suspension (as seen on figure 33), chassis or the aero packet.

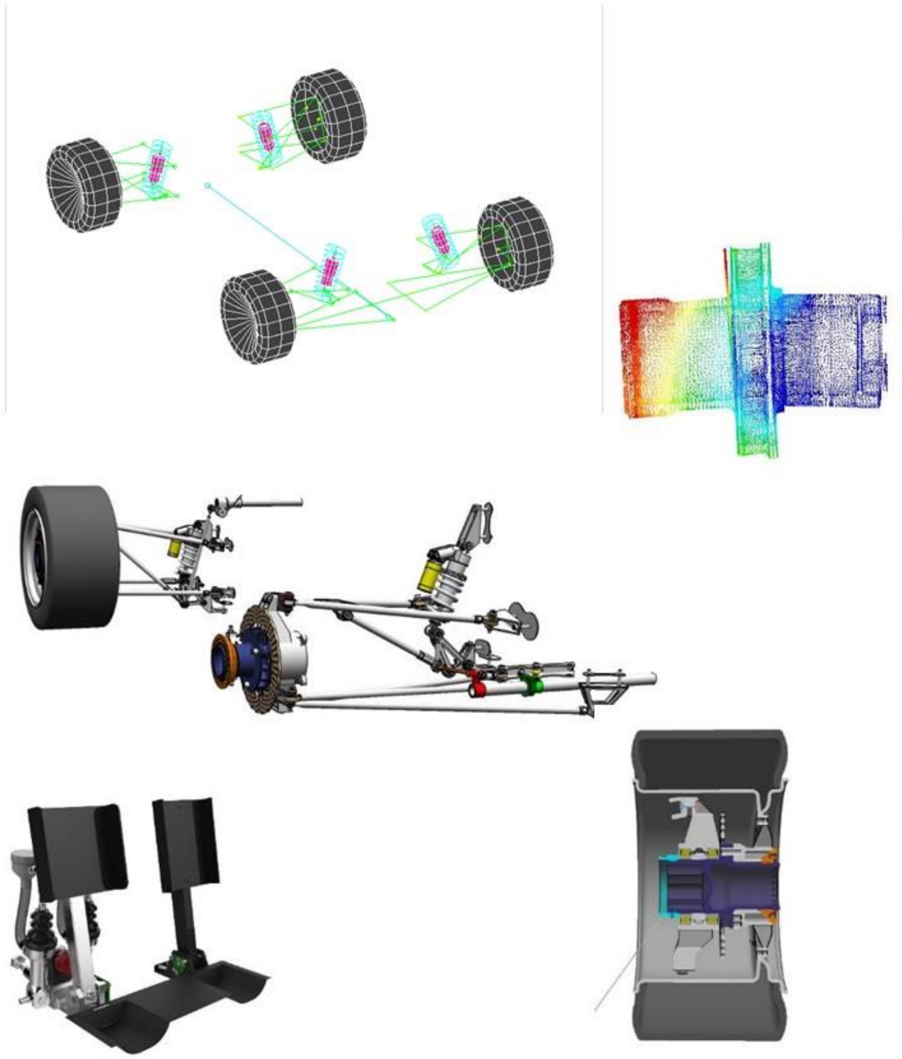

Figure 33: Example of designed and manufactured components (suspension)

6.12.6. Replacement parts

The key replacement components would be those damaged in case of a crash, i.e. those that are fragile and exposed to crashing, for example the aerodynamic package as seen on figure 34. However, it is not common practice for eForce to keep spare components, as this would require high additional costs. Replacements are usually only manufactured ad hoc after a crash happens for the specific critical features which are damaged. For this reason, the proposed autonomous budget does not assume any replacement parts costs.

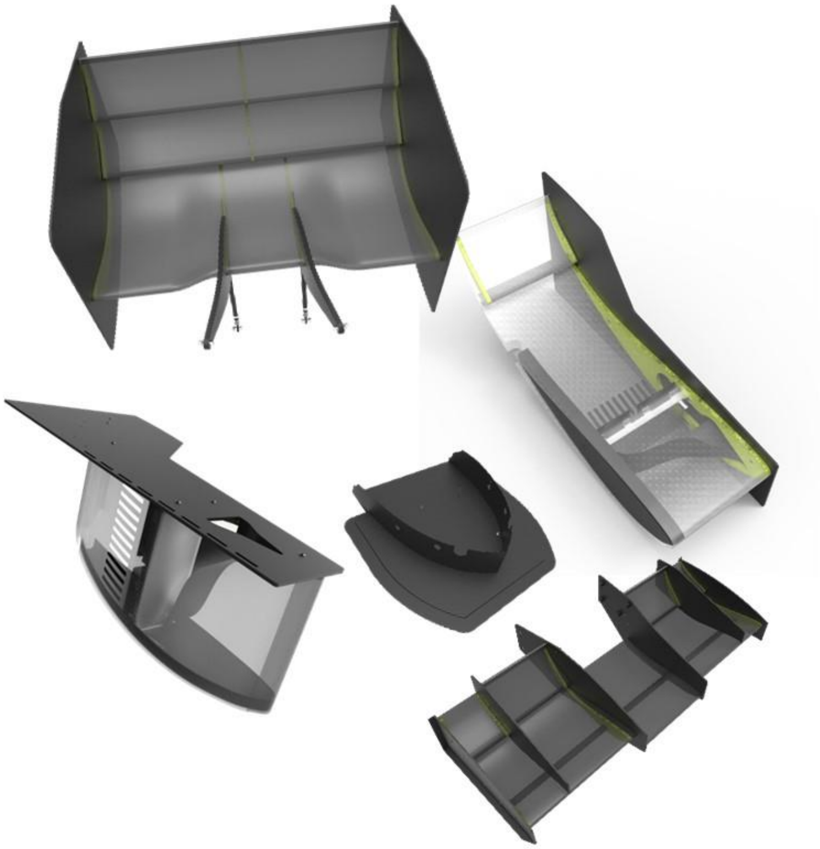

Figure 34: Example of possible replacement parts (aerodynamic package)

Please also note that in case of an autonomous vehicle, some parts – for example the measuring equipment, especially the LiDAR – are exposed, fragile and especially expensive. The risk of crashing should therefore be maximally mitigated so that no spare parts are needed because of an abrupt crash.

6.13. Budget

Since the eForce team struggles to fulfil all its plans on the budget it sets out even as it is, the autonomous team has to have a separate budget in order to keep the original team financially secure and stable. This chapter explores the structure of the current budget and how it compares to the planned budget of the autonomous division.

6.13.1. Current eForce budget

The official budget of the current eForce team is around 3.5-4 million Czech Crowns per year. This however excludes the non-financial contribution by the university (for example, free usage of the workshop premises inside the campus) and the time contribution by the students. If both are taken into account, the budget reaches over 6 million crowns and the share of investment is split into close to even thirds between the university, the commercial sponsors and the students themselves, as seen on figure 35.

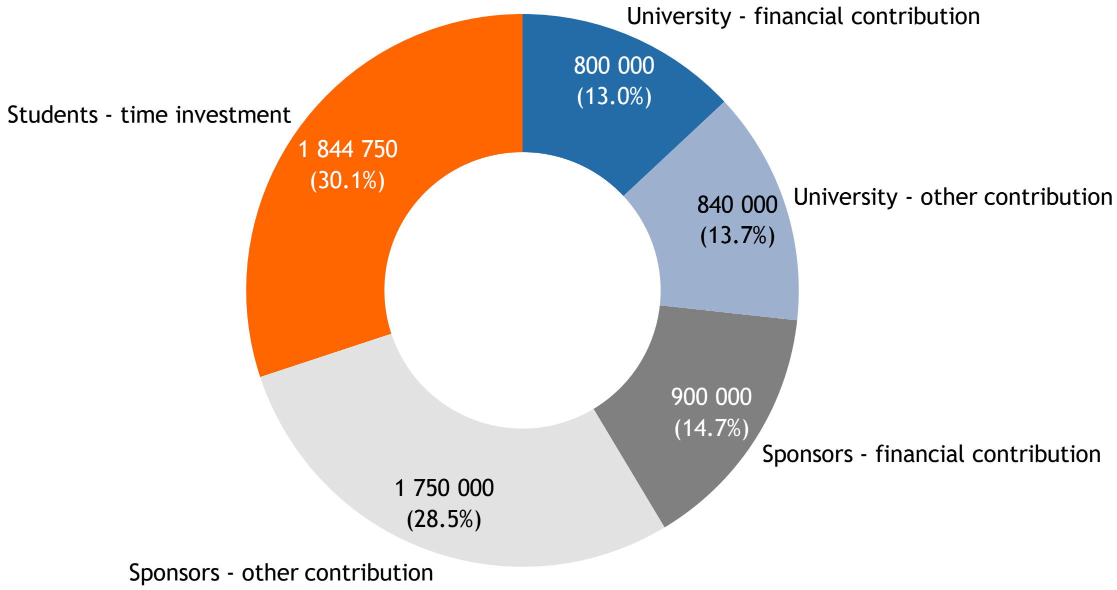

Figure 35: Current approximate eForce budget[86]

[86]*Note: See appendix [B] for details on the cost estimates of individual formula parts and manufacturing costs and appendix [C] for details on the valuation of current eForce team's student work investment*

6.13.2. Planned autonomous team budget

Expenses

As seen on figure 36, about three quarters of the budget are already taken care of by either eForce (when it comes to software, which is pre-existing in the team) or the students (who invest their time into the project). The remaining costs add up to approximately half a million crowns and are split between new hardware costs and organisational costs (logistics, registration fees, etc.).

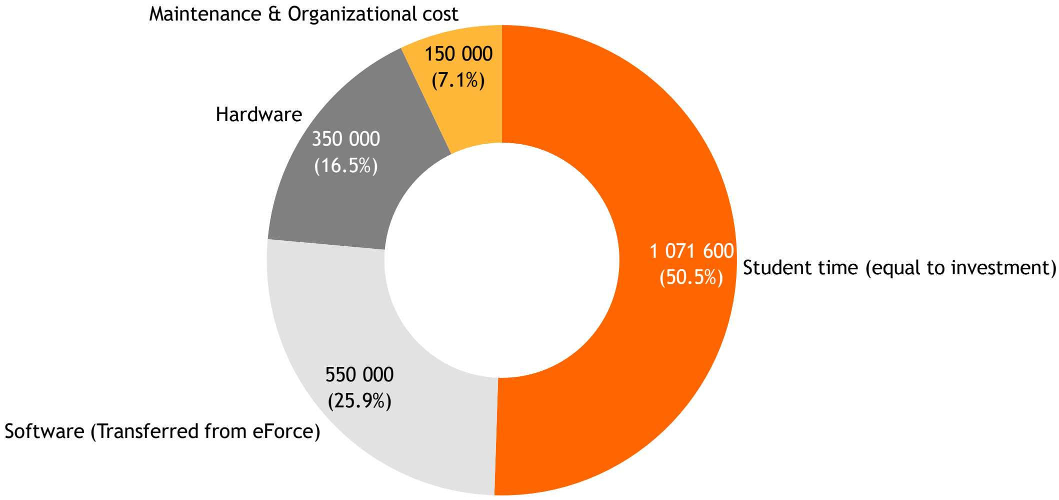

Figure 36: Planned expenses of the autonomous division

Income

As mentioned above, only one quarter of the needed investment needs to be taken care of, totalling 500 thousand crowns. Based on eForce's past experience, it would expect to raise two fifths from the university and the rest from commercial sponsors, as seen on figure 37.

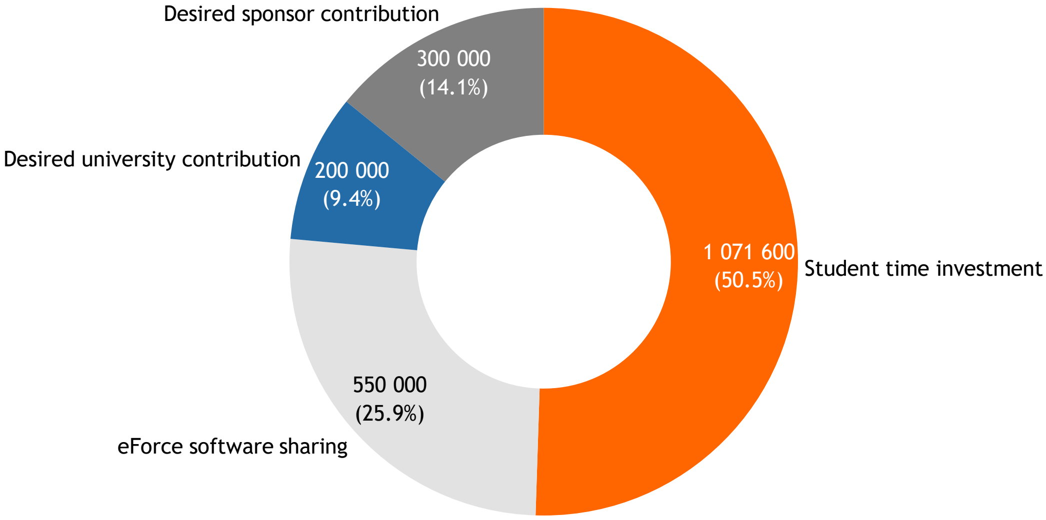

Figure 37: Planned income of the autonomous division

6.14. Risk analysis

The basic risk analysis can be seen on table 3. The main risks identified fall into three categories. Firstly, not being able to correctly start the team due to either personnel or financial shortage, which is mitigated by an intense member and sponsor recruitment campaign diversified across the CTU campuses. Secondly, the concerns about knowledge management are mitigated through setting up knowledge sharing systems and processes. And thirdly, the major concern over the negative effect on the original eForce team is mitigated by a strict separation of concerns in the critical areas of the organisation.

Risk	Probability	Impact	Mitigation
Team not assembled	Medium	High	Focus on recruiting as many people as possible during both recruitment stages, and use a second personal interview round to filter out candidates with good potential for the project
Funds not secured	Medium	High	Target both current sponsors of eForce for additional funding, as well as new players interested in AI-focused research, stressing the uniqueness of the project and access to expert student talents
Experts leaving	Medium	High	Based on recruitment, assemble a versatile team of experts that can sustain the project; create a friendly and attractive atmosphere for them to stay
Knowledge forgotten	Medium	Medium	Prepare and use a cloud-based data and knowledge management platform from day 1 of the project
Data stored lost	Low	High	Prepare and use a cloud-based data and knowledge management platform from day 1 of the project
Team closing down	Low	High	Create a stage-by-stage implementation plan with exit points that would not affect the original electric team, separate the teams‘ finances

Table 3: Project risk assessment

A major risk outside of the scope of only eForce Driverless is the consequences for eForce electric in case of the project's possible failure. These consequences would get more negative through increasing time and financial investments sunk into the project by that point. As a mitigation, the eForce Driverless project is to be evaluated at the end of each phase, by which point the current state and risks are to be re-evaluated and a decision taken on whether to continue with the project or whether to terminate it.

6.15. Other issues to consider

One more issue has been identified for consideration when implementing the driverless vehicle in addition to the chapters above – since it is highly likely that a pre-built electric vehicle from one of the previous seasons will be used, but new sponsors will be onboarded, it needs to be decided on a specific manner in which the sponsors' logos will be shown. Specifically, if the old logos of sponsors only contributing to the electric vehicle should be removed and replaced by the new driverless sponsors, or if both logos will be displayed at the same time.

This is especially important to take into consideration when signing agreements with the sponsors, so that no clause in the agreement would force the team to break the policy to be decided regarding the logos.

6.16. Summary and recommendations of the analysis

In the feasibility analysis chapter, a rigid analysis of the current autonomous Formula Student vehicles landscape is presented, as well as a thorough look on the current state of the eForce FEE Prague Formula team. Based on both, a preliminary plan of implementation for the creation of a new autonomous vehicle division is set out. During this analysis, four key resource elements were identified to be key to the functioning of the new team: human resources, finance, technology and premises. As seen on figure 38, at the end of this analysis which corresponds to end of phase 0, eForce Driverless has a reasonably good position for the past phase and also resources which make it possible to advance to phase 1 – although these resources may and will need to be expanded in every dimension.

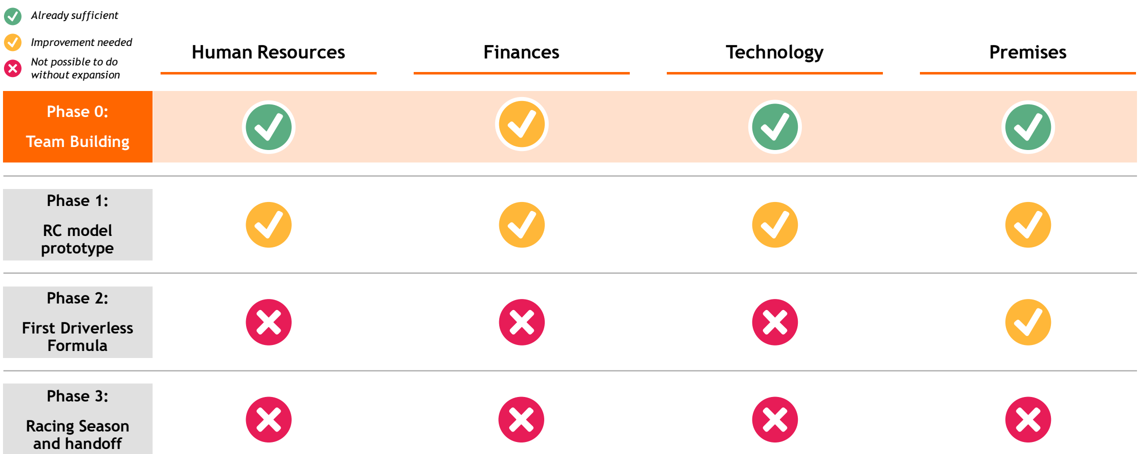

Figure 38: The state of the four key resource elements at the end of phase 0

Based on this analysis, it is recommended to go forward with the autonomous formula project, given that the proposed plan allows for three re-evaluation checkpoints where the project can be either cancelled or rescheduled and the project has a reasonably good starting position when considering the four required resource elements.

7. Implementation of the project

In this part of the thesis, the actual project of eForce Driverless is described as it was implemented in the past year. The first chapters hold a similar structure to the last chapters of the feasibility study. This is to make it easier for the reader to directly compare the intended plan with the resulting reality.

The difference in chapters is that while the beginning of the feasibility study needed to cover external factors through competition analysis and put increased focus onto high-level marketing and strategy planning, this is much less relevant for the implementation of a project that is already set up.

On the other hand, the following subchapter go into much greater detail in areas covering organisation, the actual vehicle development and competition strategy, which in turn would be hard to define in the feasibility study. Overall, the two analyses are meant to not only contrast, but also complement each other in this thesis.

The description of the implementation is structured and intended as a case study, as defined in the early chapters of this thesis. As for which technique was used to choose eForce Driverless for this case study, apart from the context stated in previous chapters, it could also be considered an example of *deviant case selection,*[87] since eForce Driverless is deviating from a general trend of rising likelihood of project failure with increasing engineering complexity.[88]

Since this thesis does not work with a pre-existing hypothesis, this case study analysis will be used in a *hypothesis-generating* manner, meaning that after the project implementation and its evaluation will be described in detail. Then, these findings will be discussed and used to generate potential hypotheses that could explain the project's success, particularly in the context of the previously presented theories of management, organisational design and leadership.[89]

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[87] GERRING, John. *Case study research: Principles and practices*. Cambridge university press, 2006, pages 105-108
[88] LAWRENCE, Philip; SCANLAN, Jim. *Planning in the dark: why major engineering projects fail to achieve key goals.* Technology Analysis & Strategic Management, 2007, 19.4: 509-525.
[89] GERRING, John. *Case study research: Principles and practices*. Cambridge university press, 2006, page 72

7.1. Timeline

Before focusing on the specific technical and organisational aspects of the implementation, it is useful to revisit the schedule proposed at the end of the feasibility analysis and contrast it with how the real implementation steps unravelled from a high-level perspective. This schedule was outlining four phases: "Team Building" (Phase 0), "RC model prototype" (Phase 1), "First Driverless Formula" (Phase 2) and "Racing Season and Handover" (Phase 3). Perhaps as a testament to the volatility of complex research projects, only the phase 0, which was already described in the feasibility study, was executed as expected.

Phase 1, focused on the implementation of the RC model prototype, was started shortly after the completion of the feasibility study. As per the proposed plan, a recruitment of the planned core team was conducted, and 10 talented students were selected to become part of the founding team in spring 2019. Furthermore in summer 2019 the team managed to establish a close cooperation with the Toyota Research on Automated Cars in Europe (TRACE) lab and the Centre for Machine Perception at the Department of Cybernetics FEE CTU through prof. Matas. Through this partnership, the team got a much-needed boost in know-how and establishment in the academic environment at the university since it gained an official faculty advisor, Dr. Jan Čech who has since played a pivotal role in advising the team and has attended almost all meetings. At the same time, this partnership provided the team with the first financial capabilities, since TRACE was willing to invest into the project if needed. Another sponsor that was already onboarded at this time was Valeo, providing a modest financial contribution and the driverless-specific traffic cones for testing. Some hardware was also offered but deemed unsuitable.

This is however where reality diverged from the plan. After exploring options with the RC models at the team's disposal, it soon became obvious that none of the models available could be reasonably converted for the expected needs. The one that was proposed in the feasibility study turned out to be too small to hold all needed sensors and also had Therefore, the work during this time was limited in the end to implementing initial software draft solutions for the autonomous system, as well as gathering knowhow from other teams on the Formula Student races in the 2019 season. The final state of the resource elements at the end of the first full phase can be seen on figure 39. Although all factors were satisfyingly complete for the previous phase, the team still faced challenges in terms of technology (where sensors for testing were needed), premises (the team was using the eForce electric workshop which was starting to be crowded and sometimes led to conflict with the electric team) and human resources (with requirements getting more specific came more demands on actual skilled work). The latter issue was deemed to be a serious hinderance preventing the team to further develop and thus a recruitment initiative was conducted as described in the next chapter.

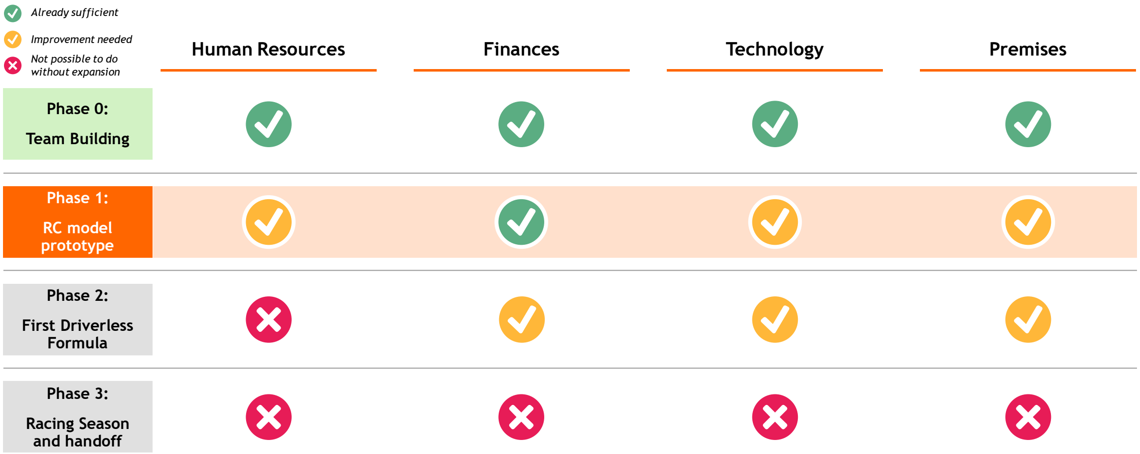

Figure 39: The state of the four key resource elements at the end of phase 1

After the great challenges of Phase 1 described above, the fortunes of the eForce Driverless began changing. The recruitment between the phases was successful and greatly expanded the personal capabilities of the team, as described in the next chapter. At the same time, further major sponsors like Skoda and Porsche Engineering were confirmed and supported the financial capabilities of the team. The team also secured key technology partners and acquired crucial components and sensors including a LiDAR and inverters. Furthermore, the team also finally managed to secure its own premises through an extension of the eForce workshop. Thus, the satisfactory state of the four key resource elements at the end of phase 2 can be seen on figure 40. However, not all was well – as it is well known, the later period of phase 2, Spring 2020, was also the time when the global Coronavirus pandemic started. Due to this fact, the team got locked out of its newly acquired workshop and almost all races and plans were cancelled or postponed to next year. Nevertheless, the team still kept the goal to build the first Czech driverless formula by the end of Summer 2020.

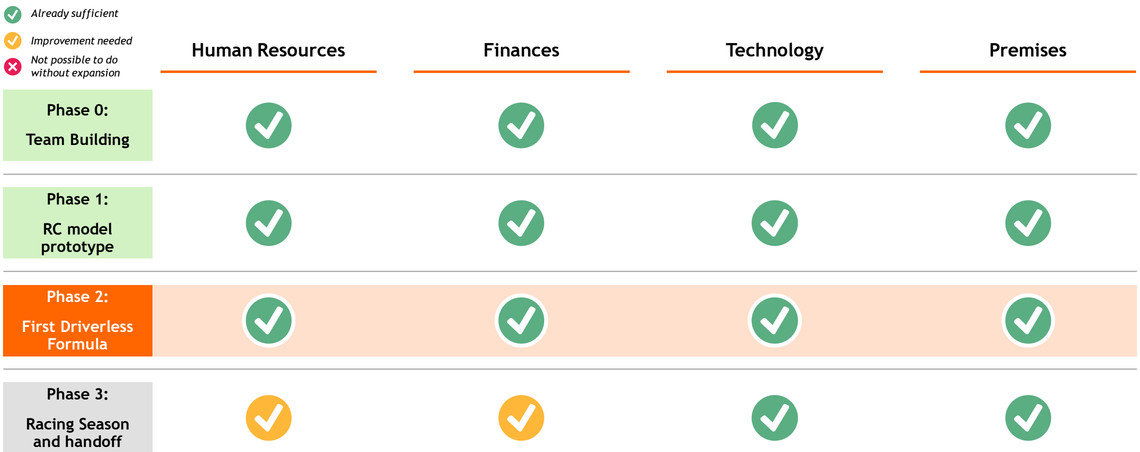

Figure 40: The state of the four key resource elements at the end of phase 2

The last phase 3 concerning the racing season and project handover is still ongoing and will be further elaborated upon in the larger chapter concerning future sustainability.

7.2. Human Resources

As it was already hinted at in the previous chapter human resources were one of the key challenging issues for the eForce Driverless project, especially at the end of phase 1. This is perhaps not surprising when looking at a schematic of how work was divided between the individual members of eForce Driverless as promoted to potential sponsors during phase 1, seen on figure 41. A wide array of activities was divided between just 9 students, many of them with overlapping interests. In order to develop further, the team clearly needed to recruit new members and further refine their individual focus.

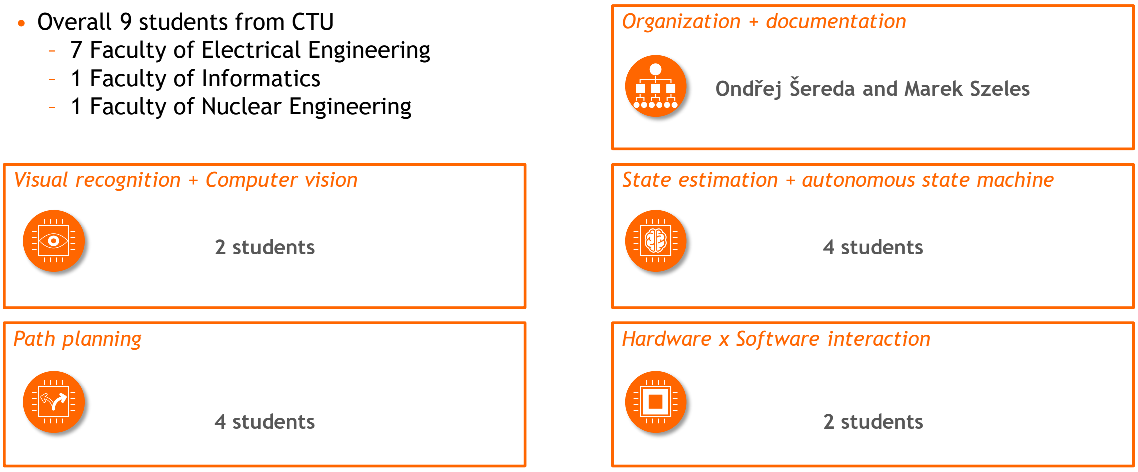

Figure 41: The initial personal state of eForce Driverless as pitched to sponsors in early 2019

This need was met by a big recruitment push at the end of phase 1, which more than doubled the number of members who took part in eForce Driverless. However, this large increase was not to last, as will be discussed further. The numbers of members have been steadily decreasing as could be expected under the circumstances, however it does accent the need for another recruitment push in the present – at the end of the phase 3. A new generation of members will be needed to create a new generation vehicle.

During the existence of eForce Driverless thus far, the engagement of its members could be split into four different categories:

- ***Core members*** – Basis of the team, dedicating a significant chunk of their time to the team every week, also have key know-how
- ***Core away*** – Similar to core members in activity and skill-wise but physically remote and thus unable to attend in-person tasks and meetings
- ***Regulars*** – Members that fulfil their asks and regularily communicate and participate in the team activities
- ***Infrequents*** – Team members who do participate every now and then, but not in a stable way; they may also not communicate as well

Apart from those, the team also got steady support from the academic advisor, Dr. Čech and several alumni and members of the electrical team (ELS) who decided to help the team in their free time.

If the change of activity of individual members throughout the history of eForce Driverless is tracked and laid out, the graph as seen on figure 42 is produced. There, the big recruitment influxes between phases 1 / 2 and the phases 2 / 3 can be clearly seen. It is also noteworthy that the less active members, most notably irregulars, are much more volatile and likely to either change category or leave the team altogether.

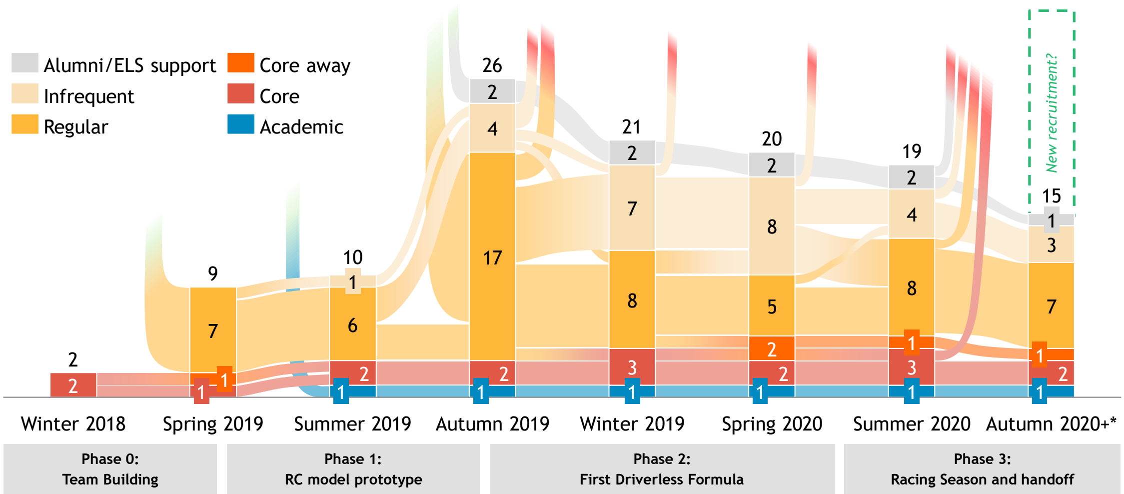

Figure 42: The flow of members across activity categories throughout the existence of eForce Driverless

However, another interesting notable phenomenon emerged – members are not necessarily only moving down towards more engagement but may recede into previous stages. This is seemingly contradicting the situational approach to leadership theory, which assumes a linear path of development for each member.

7.3. Work organisation

In any complex and agile organisation such as eForce Driverless, it becomes increasingly difficult and thus important to organize actual work that needs to be done between members and respect the time constraints imposed by the outside environment. In the following subchapters, three aspects of this phenomenon are examined – work division, work tracking, and risk management.

7.3.1. Work division

After being joined by the academic advisor Dr. Jan Čech, eForce Driverless abolished the simplistic work division based on areas of interest as described in the previous chapter. Instead, it switched to a system based on "work packages", as proposed by Dr. Čech. From the start, the project was split into 10 work packages, on which the work could be done in parallel. Once the work packages were laid out, the need for recruitment specifically for individual work packages was assessed, as seen on figure 43.

Legend:
●Very high - Current capabilities not sufficient to complete all tasks
◕High - Current capacity not sufficient to complete all tasks on time
◑Medium - Some areas can use more support
◔Low - Some additional capacity is a nice-to-have
○None - No benefit of additional members

WP1 Electronic Hardware Actuators
Person responsible: Ondřej Šereda
Other team members: Marek Szeles,
Radek Štěpánek (Mechanical)?,
Marek Laszlo (Control)?

Need of further recruitment: ●Very high
Personal demands: Competence in mechanical engineering, electronics

WP4 Calibration and Vehicle identification
Person responsible: Jan Svoboda (BP)
Other team members: n/a

Need of further recruitment: ◕High
Personal Demands: Experience in robotics, multi-sensor fusion, control theory

WP7 Control algorithm
Person responsible: Marek Boháč (BP)
Other team members: n/a

Need of further recruitment: ◕High
Personal demands: Control theory

WP2 Sensors
Person responsible: Marek Szeles (DP)
Other team members: n/a

Need of further recruitment: ◕High
Personal demands: Basic familiarity with digital photography, experience with elementary embedded electronics

WP5 Perception
Person responsible: Šimon Mandlík
Other team members: Matěj Zorek, Bronislav Doubek,
Marek Boháč, Marek Mařík, Tomáš Roun (DP)

Need of further recruitment: ◔Low
Personal demands: Experience with convolutional neural networks, computer vision, (SLAM)

WP8 Simulations
Person responsible: Michal Lukeš
Other team members: Branislav Doubek?, Marek Mařík

Need of further recruitment: ◑Medium
Personal demands: Willingness to get acquainted with one of the selected simulation systems

WP3 Computational system and software integration
Person responsible: Tomáš Roun (DP -> perception)
Other team members: n/a

Need of further recruitment: ◕High
Personal demands: Experience with computer systems, familiarity with ROS, software engineering tools

WP6 Planning
Person responsible: Matěj Zorek
Other team members: Branislav Doubek, Šimon Mandlík

Need of further recruitment: ◑Medium
Personal demands: Experience with discrete (and continuous) optimization welcome

WP9 Experiments and ride tests
Person responsible: Ondřej Šereda
Other team members: n/a

Need of further recruitment: ○None
Personal demands: Everybody will participate, a person responsible for ride tests should maintain the formula in a well working condition

WP10 Static Events
Person responsible: Marek Szeles
Other team members: n/a

Need of further recruitment: ○None
Personal demands: Everybody will participate to an extent, a person responsible for each of the three static events is needed with strong communication and at least basic economical skills

Figure 43: Work packages at eForce Driverlessas of end of phase 1

7.3.2. Work tracking and quality control

For overall quality control, eForce Driverless used a mix of two approaches. First is functional crowdsourcing, where members working on connected tasks (for example software developers) in a work package shared knowhow and feedback. The second is expert reviews, where critical outputs ready to be implemented always had to be signed off by a leader or senior member of the team.

While this system on its own worked in a flexible and agile way, it was very hard to self -organize in a way that would also be transparent. Furthermore, once the lockdown came into place in phase 2 and members could not be meeting in person anymore, the motivation and discipline quickly diminished. In order to combat this development, so-called "work reports" were introduced, which was inspired by a practice seen in eForce's sister combustion Formula Student team, CTU Cartech. These are personal pages for each member that are on the shared internal eForce Wikipedia page. It is the responsibility of each member of eForce Driverless to fill in the following details before each and every team meeting:

- Date of update
- A list of tasks this member is responsible for including:
    - Current state
    - Initial expected date of finish
    - Current expected date of finish
    - Real date of finish

An example of such work report can be seen on figure 44.

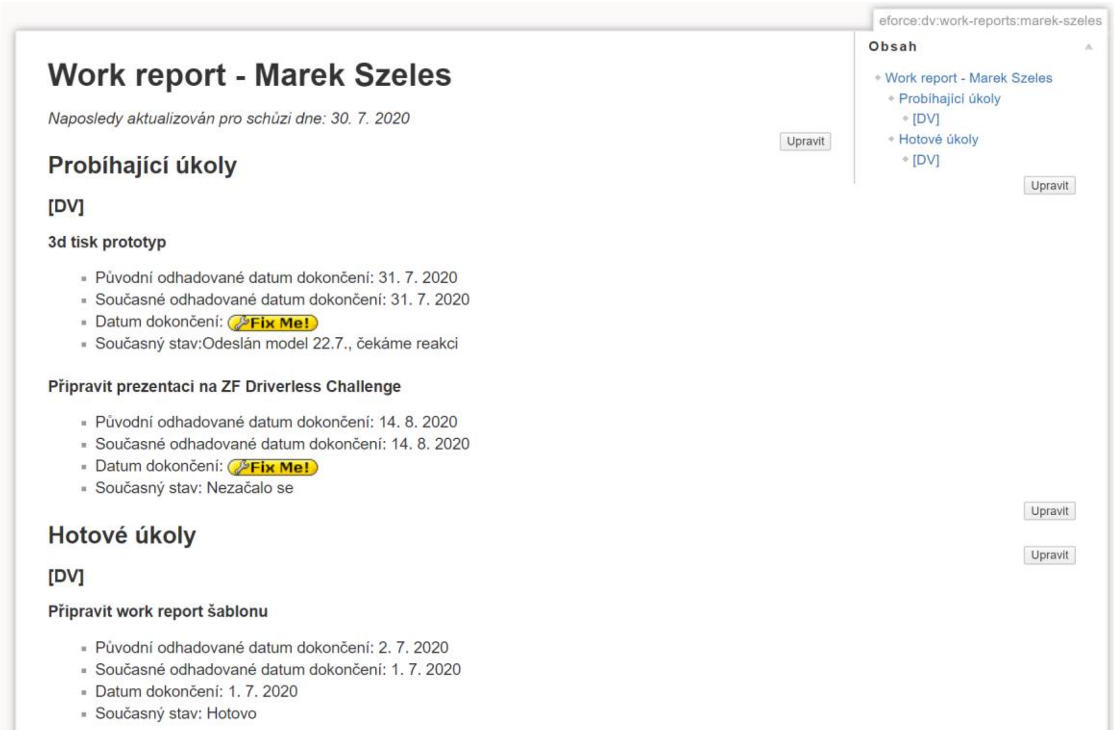

Figure 44: Example of a work report

The work reports have proved useful in several ways. Firstly, they make each member do at least one small activity each week (update their work report), which in turn helps the leaders keep an up-to-date idea about member activity. Secondly, by asking members to estimate the finish dates, it teaches them scheduling (though penalties for inaccuracy are not enforced). Thirdly, it is a useful tool for self-evaluation since members can easily see how many and which tasks they completed and how they compare to others. Finally, it also helps with keeping minutes of the in-person meetings, since the leader can just copy-paste the current state of the work reports into the minutes and only focus on the productive discussion.

7.3.3. Risk Management

With the COVID-19 pandemic, risk management became a very important aspect of team management. The team had used a risk matrix approach, quantifying the probability and severity impacts of the identified risk factors. The risks were evaluated on a 0-10 scale using the following evaluation matrix as seen on figure 45.

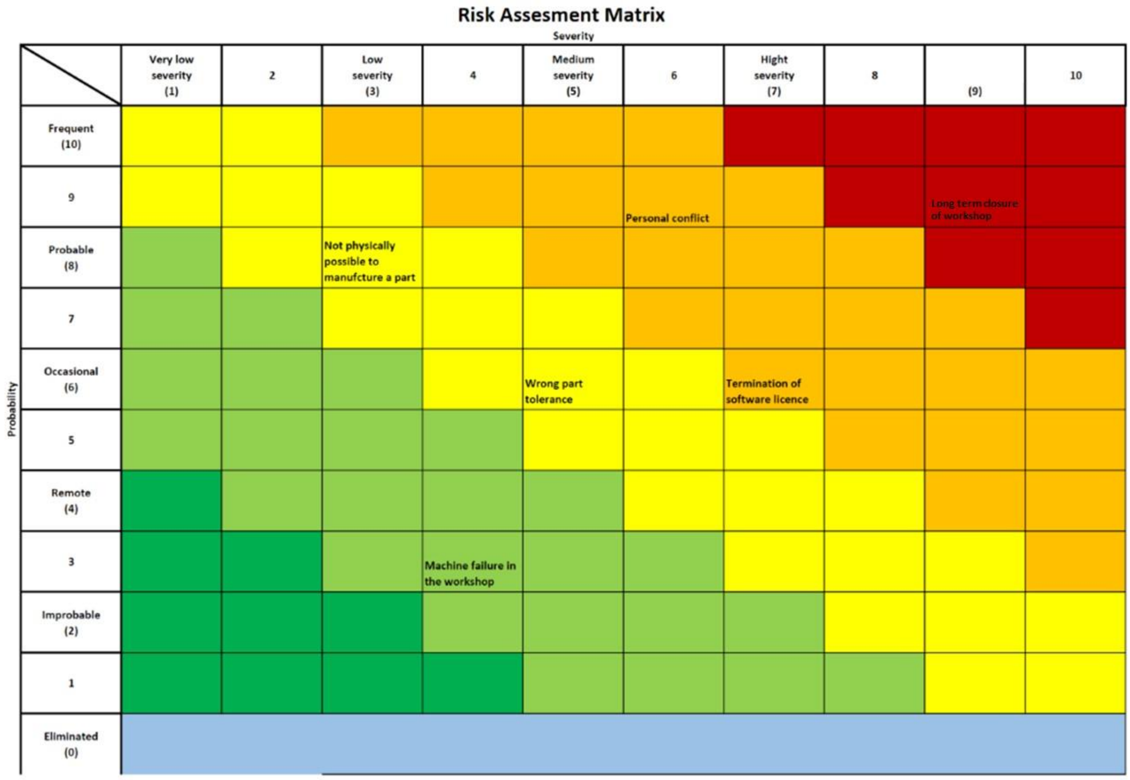

Figure 45: Partially filled in template of the used risk matrix

As seen in the matrix, the most significant risk defined as part of the COVID-19 pandemic was being locked out of the workshop, which did happen between February and June and stalled progress in a significant way. The team nevertheless intends to keep its original goal of finishing the vehicle in Summer 2020 even though some components are still yet to arrive due to delivery delays.

7.4. Physical premises

As the team was growing in size after the end of phase 1, it became increasingly apparent that the current arrangement in which the eForce driverless team shared premises with the eForce electric team was not sustainable. The personal meetings were often clashing between the groups and not enough space was available for neither these meetings nor hands-on work when members of both groups were present in the workshop. And thus, the eForce Driverless team set out to acquire its own premises.

Two particular spaces came into mind when considering expansion, both very near the original workshop of eForce Driverless. This attribute of being close was absolutely a key priority as the new team sensed the need to stay in close contact with the old since many projects needed to be completed in cooperation. The two considered spaces may be seen on a map layout on figure 46 and as seen from the workshop entrance in figure 47.

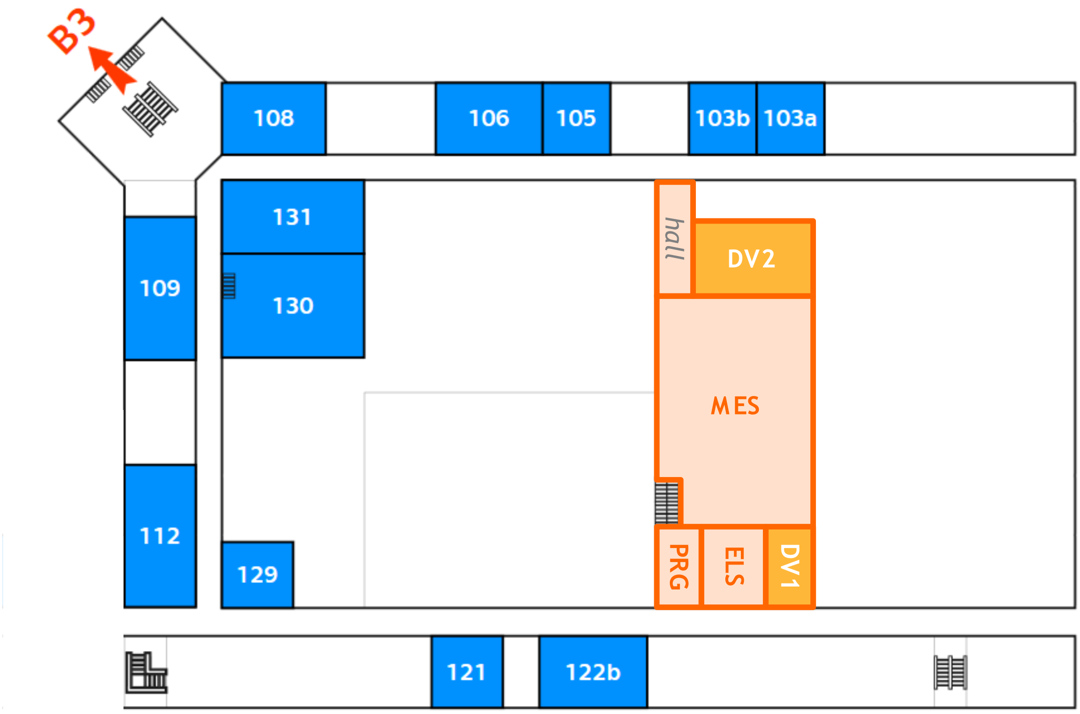

Figure 46: Layout of the eForce workshop withinin the FEE CTU laboratories, two possibilities for the Driverless Workshop highlighted in orange

The first variant was a disused warehouse directly neighbouring the office of the electrical group in the upper floor of the workshop. This space was occupied by the Department of Electrotechnology FEE CTU for storage, but not used actively. The second variant was a larger room in front of the workshop entrance, which is used by the building management for the storage and maintenance of vending machines and other amenities.

Figure 47: The two workshop options highlighted in red as seen from the present eForce workshop entrance

The pros and cons were evaluated for both rooms, such as size, lack of roof, connectivity to the rest of the workshop and so on, however in the end the decision came down to the simple fact that only one space was really available – unlike the building management in charge of variant 2, the director of the department using variant 1 was willing to hand the room over, with support and words of encouragement from the dean of the faculty.

The room was handed over in mid-March as a room that had been used clearly only for storage and technical purposes and was therefore in a rougher state. The first weekend was therefore dedicated to cleaning the room and the second weekend to setting up new furniture, painting the walls and isolating the roof to prevent the settling of dust from the rest of the workshop. From that point on, electrical circuits were installed, and the room has been used as a proper workplace with a capacity of up to 8 student researchers at any one moment. The images of this transition can be seen on figure 48 and more pictures of the current state can be found in appendix [D].

Figure 48: Images of the new workshop after the initial cleaning and after basic furnishing

7.5. Technology

One of the key resource elements needed to keep going forward with the project are technologies. These come in many forms, both digital and physical. Digital ones include software licences and access to relevant knowledge bases. Most of these were already possible through resource sharing with the electric team. However, the hardware needed to transform an electric formula into a driverless vehicle was not readily available and needed to be acquired.

This included perception sensors such as depth cameras and LiDAR, autonomous system components for assemblies such as the emergency braking, electrical components, the most notable of which are new industry standard inverters and computing units, all of which can be seen on figure 49.

Figure 49: Some of the needed physical technology resources. From bottom clockwise: stereo cameras (Intel Realsense and Stereolabs ZED), LiDAR, Remote Emergency Shutdown, Emergency Brake air reservoir, inverter with electronics, computational units (Nvidia Jetson)

By the end of phase 3 of the plan, only one crucial sensor is missing – the planned dual-antenna inertial navigation system. However, a partnership with the manufacturer is established and the sensor should be delivered in September.

Furthermore, one of the races which ended up being organized online required a running instance of a custom autonomous vehicle simulation software. Unfortunately, this software was based on the Unreal Engine videogame engine which is quite resource demanding and only very few eForce members were able to run it at home – and there was no machine to run it in the workshop. But thanks to the quick action taken by team captain Josef Med, the team managed to procure the required computer to be placed in the driverless workshop, as seen on figure 50. The specification of the computer is quite high end and can be seen in table 4. The computer is intended to be also used as a basis for the planned project of a stationary simulator which is ought to be built from a disused formula chassis.

Figure 50: The new eForce computer workstation used for competing in the Formula Student Online 2020, simulations of the autonomous systems and training of neural networks

Parameter	Name	Price
Processor	AMD Ryzen 5 3600x	5 790,00 Kč
Graphics card	Nvidia 2070Super	14 999,00 Kč
Memory	32 GB, DDR4, 3600MHz	5 349,00 Kč
Motherboard	MSI B450 Tomahawk Max	2 988,00 Kč
Hard drive	NVME M.2 512gb	2 199,00 Kč
Case	Fractal Design Define R5 Black	3 279,00 Kč
Fans	Fans for cooling	296,00 Kč
Power supply	Corsair RM650	2 691,00 Kč
Screen	35" AOC AG352QCX	13 790,00 Kč

Table 4: eForce workstation parameters

7.6. Technical implementation

The actual technical implementation is a group effort and is out of scope of the core of this thesis. Presenting the technical output of any one member of the team, including the author of this text, would provide only a very narrow, albeit deep view into what the whole project had to overcome. Instead, it was decided to describe only a high-level concept in the main text here and include the more detailed description of the systems, which was a collective effort, in attachment. In appendix [E], the autonomous system is described, in appendix [F], the engineering concept from electrical and mechanical points of view are described and finally in appendix [G] the main technical specifications are summarized.

Overall, the technical goal for the first eForce Driverless season was clear – build a drivable autonomous race car according to the published regulations. While this goal was affected and postponed by the COVID-19 epidemic and its consequences, it is still planned to implement this concept and introduce it at the rollout on September 4th, 2020. In order to simplify the task at hand, the team used a pre-existing vehicle, the FSE.07 built for the 2018 racing season and winner of FS Czech and Baltic Open that year. A rendition of how the finished vehicle should look like during a race may be seen in figure 51.

Figure 51: A visualization of the end goal – a functioning autonomous formula race car, the first of its kind in the Czech Republic

The vehicle was improved by new inverters, a higher main hoop and new high voltage and electronics. It was further enhanced through needed sensors, namely depth cameras – two on the front wing and one on the main hoop and a LiDAR also on the front wing. Emergency systems for braking were also added and rigorously tested. Software manipulating the vehicle was developed fully in-house and should depend on the fusion of the depth cameras and LiDAR inputs, although this will be done in the future and currently only relies on the camera input. More detailed information may be found in the corresponding appendices.

7.7. Finances

As it was described in the implementation timeline chapter, finances became much less of an issue in phase 2 after onboarding new major sponsors like Skoda and Porsche Engineering. If the final approximate budget with the planned budget from the feasibility study are compared, it can be seen that the real budget is larger in the end, as seen in figure 52. However, it is interesting to note that this is entirely due to contributions by commercial sponsors, as the university did not make any contribution directly to the newly established driverless team, on neither the university nor faculty level. This might be partially due to the strong insistence of CTU Cartech, the combustion Formula Student team at the same university, that eForce Driverless should be treated as just a part of eForce electric and not a new team. Still, the fact remains that the team was thus far very self-sufficient and apart from sponsorship agreements which it arranged for itself, it only received the new premises from the Department of Electrotechnology.

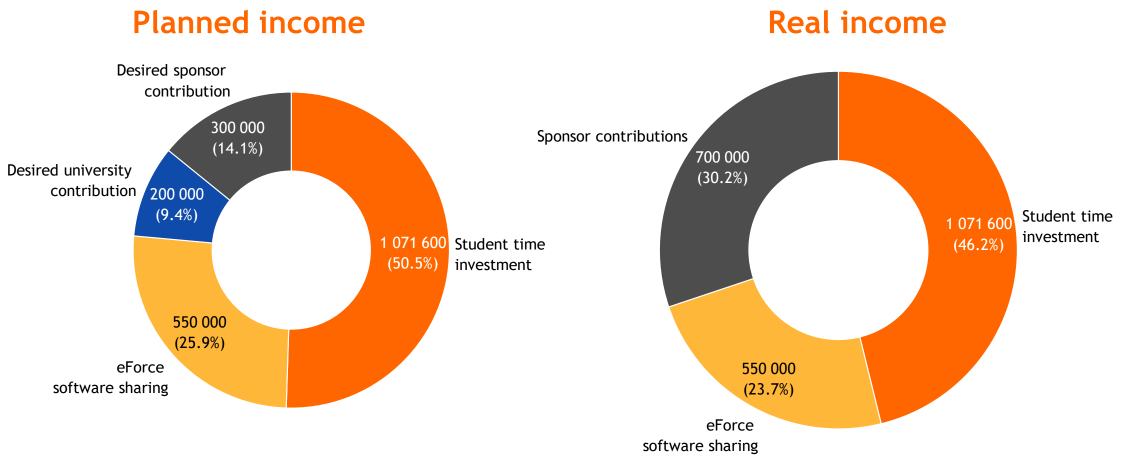

Figure 52: Comparison of the planned and real income of eForce Driverless in its first season

7.8. Competitions

The races are the pinnacle of every season and most team members are naturally looking forward to participating in them every summer. This is perhaps even more pronounced for new teams, who expect to get their very first chance to prove themselves in direct competition against other teams. However, with the COVID-19 pandemic, the 2020 race season turned out very differently than it was expected. Thus, the chapter is split into pre- and post-pandemic view on the season.

7.8.1. Before the COVID-19 pandemic

As seen on figure 53, Formula Student expected to have another lively season in 2020 with more than 10 official races in announced in Europe alone. Each race had its own registration process that teams needed to go through if they wanted to participate as there are generally limited slots available for teams. The plan of eForce Driverless was to coordinate with eForce electric and only sign up to races that the teams could visit both together – namely those in Italy, Spain, Czechia and Germany.

Figure 53: Plans for the 2020 Formula Student Racing season before the pandemic

The registration to Czechia was the most straightforward. The electric team was pre-registered thanks to their 2nd place last year and eForce Driverless had a preferential opportunity to register early as a Czech team – the only team in this category. The registration to Italy seemed easy as well, as it was only through filling in contact details at a given time, however the driverless team was not successful this time for an unexplained reason. Still, both teams managed to register successfully to the prestigious FS Spain, to which eForce electric would only go for the second time in history.

The biggest shock came when registering to FS Germany though, which is considered to be the most prestigious Formula Student race worldwide. While eForce did not reach a registration slot in the electric category, eForce Driverless managed to grab the last slot in the Driverless category[90] and it was therefore decided that both teams would crowdsource the best people to represent at this race under the new Driverless banner.

Overall, this first race registration outcome for the new team can be evaluated as largely successful, especially since eForce was unsuccessfully trying to register to FSG for several years in the electric category.

[90] *FSG 2020 Registered teams* [online]. Formula Student Germany GmbH, 2020
(Retrieved May 12th, 2020 from: https://www.formulastudent.de/teams/registered/2020/)

7.8.2. After the COVID-19 pandemic

Unfortunately, the plans of the 2020 racing season quickly dissipated after it became obvious in February that the COVID-19 outbreak will truly be a global issue. Soon thereafter, almost all events were cancelled one after another, offering the registered teams partial money refunds or reserved spots for the next year's event. Even traditionally alternative unofficial races such as Baltic Open in Finland were cancelled. The only controversial exception turned out to be FS Alpe Adria, an unofficial event in Croatia.[91] After due deliberation, eForce decided not to participate there out of safety concerns and prioritizing the driverless formula development.

In late March, a new kind of event was announced – the Hungarian and Dutch races joined forces to create FS Online, the first online-only Formula Student race. Since this provided a safe opportunity to compete for both teams, eForce decided to register for both the electric and driverless categories and dedicate the Summer to work on static disciplines and preparation for the virtual dynamic events. The Driverless category got its own custom simulator where the autonomous systems of the teams will be compared, which is seen in figure 54. The development is still ongoing and eForce also took part in its active development.

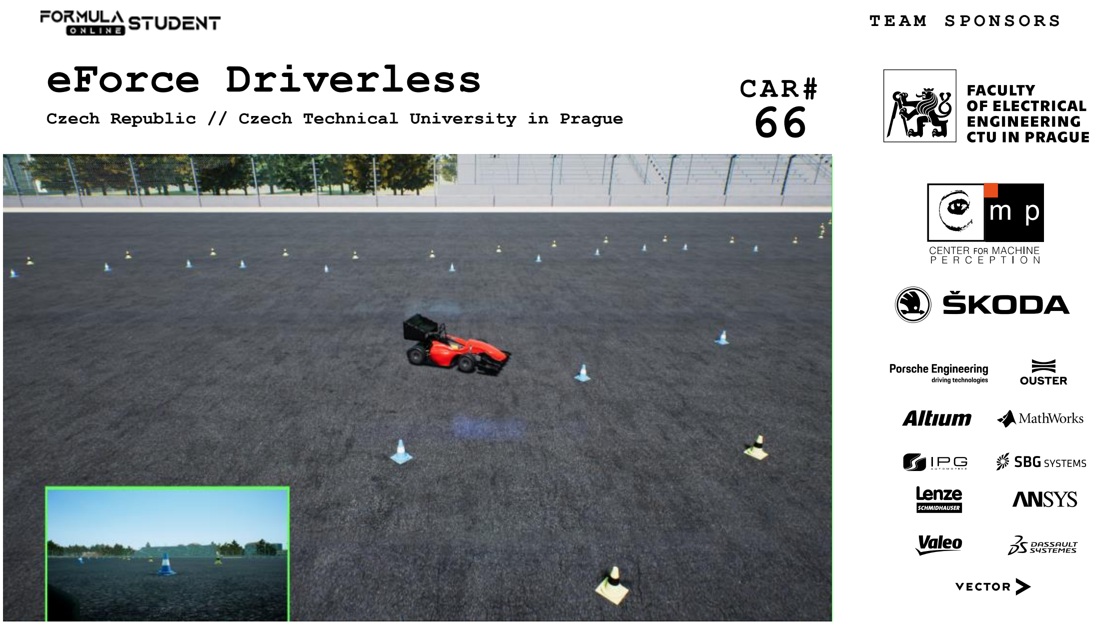

Figure 54: Screenshot from the simulator used for the FS Online Driverless event, including eForce Driverless sponsor frame

[91] *Alpe Adria 2020* [online]. Alpe Adria, 2020
(Retrieved June 26th, 2020 from: https://fs-alpeadria.com/)

At the time this thesis is being finished, eForce Driverless is only one of three driverless teams that managed to drive dynamic events at FS Online and it is therefore battling for podium finishes with a team from Karlsruhe Institut für Technologie (KIT) and a combined team of Technical University Delft and Massachusetts Institute of Technology (MIT), both already quite advanced teams. This in itself is a significant success for the team, as it turned out to be comparable to some of the best teams in the world and it proved that it can implement a functional autonomous system at least virtually. Furthermore, it managed to beat some other high-ranking teams such as the one from Technische Universität München (TUM), which did not manage to develop the autonomous system and therefore could not participate in the dynamic events. [92] The outputs produced by eForce Driverless for the static disciplines can be found in appendix. Engineering Design Report is covered in appendix [E], [F] and [G]. The FS Online-specific discipline of the Concept Design Challenge is covered by output in appendix [H]. The Business Plan Executive Summary for the Business Plan discipline can be found in appendix [I]

Another event taking place in the 2020 season is the ZF Driverless Challenge, which was expected to be only a supplementary activity but has since become one of the main events due to the circumstances. It challenges teams to show their early driverless system concepts. At the time of writing, eForce Driverless is one of only 8 finalist teams battling for 5 winning positions with sponsorship and mentoring prizes. Should eForce Driverless succeed in the August finals, it would be a great success in the first year of the new team's existence.

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[92] *FSO 2020 results* [online]. Formula Student Online, 2020
(Retrieved August 6th, 2020 from: https://formulastudentonline.com/?page_id=712)

8. Theory application

As it was shown in the previous chapter in the case study, the eForce Driverless project has gone a long way from its inception and it can already be deemed successful by many measures, since it has gathered sufficient personal, financial and institutional support. Due to the nature of research defined at the beginning of the case study chapter, it is now clearly needed to generate hypotheses as to why the outcome of this case turned out the way it did. For this process, the thesis will be relying on the theoretical frameworks defined at the very beginning of this thesis.

8.1. Organisational design

The first major variable that is sure to inherently heavily influence any organisation is the way it is structurally set up. When creating a significant new initiative, a clear challenge arises – how to combine the exploitative activities of the legacy organisation with the explorative activities expected of the new one? From literature referenced above it was shown that combining these activities within one organisation is not best practice.

One possible approach is to use a spin-out model, creating a new separate organisation for the project, which can be later re-absorbed. While this approached was heavily considered and partially attempted with eForce Driverless, ultimately it failed on a very basic caveat – all functions that the new project needed could not be provided by the new members and some activities (especially mechanical engineering) had to be insourced from the legacy eForce Electric team. This would be very hard to do if the organisations were truly separate, so the idea was abandoned.

On the other hand, once the approach shifted to ambidextrous design, the team encountered no further issues, This approach combined the advantages of having one organisation with interconnected communication channels and a separate workstream structure and resources so the new project could have its autonomy to work on the disruptive exploratory activities separately.

8.2. Management of research teams

When it comes to management styles, it was no surprise that eForce Driverless emerged with a strong tendency towards the alternative typology of management models. This is partly caused by the outside environment – for example, the extrinsic rewards offering will always be weak as the organisation is non-profit in nature and therefore the majority of motivation will come from intrinsic rewards. Equally, bureaucracy is also inherently weak since the organisation will deem it low priority and it is in perpetual need of more active members. On the other hand, many factors come from the culture eForce had built, such as a low hierarchical structure resulting in a culture of collective wisdom. The only dimension in which eForce Driverless is leaning towards the traditional models is managing objectives, as seen on figure 55. Since the project is relatively structured and with clear hard deadlines, goal setting plays an important role in its regular functioning. Overall, this setup seems to work well as it had emerged naturally in the new collective.

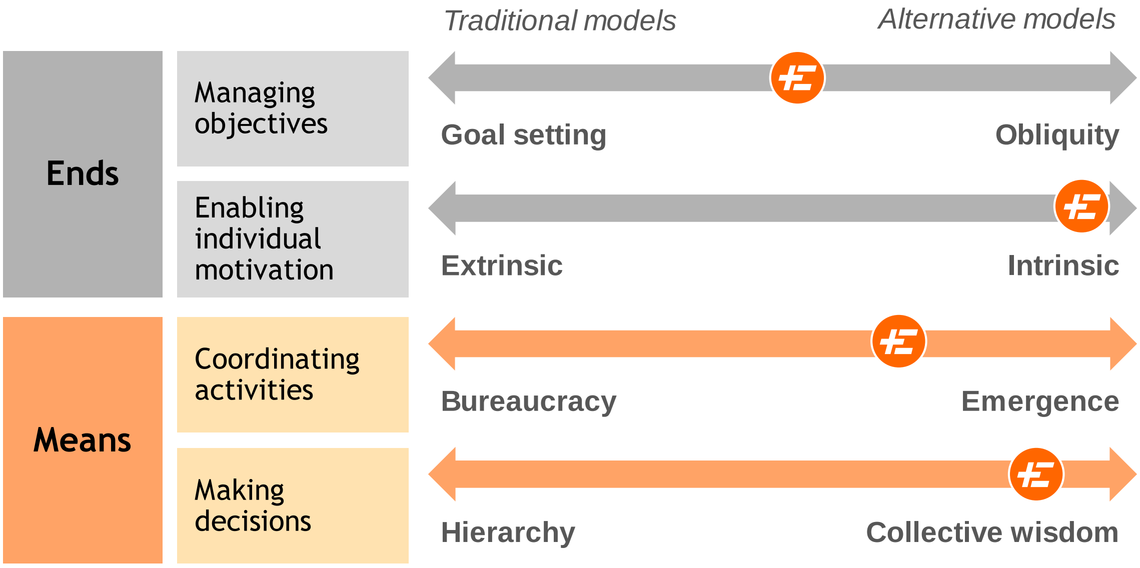

Figure 55: Approximate position of eForce management models as determined by the author

The second theoretical aspect of research team management that was worked with is the exposure to highly productive individuals, also called "stars". During the implementation of eForce Driverless thus far, it could be seen that the output of stars is motivating to the team overall, however, this phenomenon was much stronger when the team was still having meetings in person. Once the pandemic lockdown was put into place in March, the effect was much less profound. On the other hand, the opposite effect lasting even throughout the lockdown could be perceived as well – if the stars deemed the rest of the team to be unproductive, they sometimes became demotivated as well. It is notable that this phenomenon is less explored in academic literature and may be suitable for further research.[93]

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[93] ALIPOUR, K. K., MOHAMMED, S., & RAGHURAM, S. *Differences in the valuing of power among team members: A contingency approach toward examining the effects of power values diversity and relationship conflict.* Journal of Business and Psychology, 2018, 33(2), 231-247.

8.3. Leadership theories

When reflecting the effect of the three leadership approaches explored in the theoretical preface of this thesis, one has to note that they are not mutually exclusive. When keeping in mind this particular combination of classical and modern leadership theories, one can see that it is possible to achieve very satisfactory results even in challenging environments. There have however been members of the organisation not reaching their full potential, sometimes leaving the organisation, which could be considered a failure of leadership. In these cases, the reason was always assessed, and the cause of leaving was always external, most conflicting time pressures from regular curriculum of these members. These external factors therefore also need to be duly considered when evaluating a technique's success.

According to the situational approach to leadership, each member onboarded into eForce Driverless goes through four stages of development defined by motivation and skills. Based on the stages, the leadership representatives should approach the member with a different technique. This approach was generally confirmed to be useful, as the new members required considerably more guidance and attention. However, as they developed, it some members seem to be relapsing into previous stages of the development, which is not predicted by the theory. This is sometimes included in critiques of the situational leadership approach.[94] However, in the case described in this thesis, it seemed to be simple to adapt to this development by also choosing the corresponding previous technique once noticing the member's behavioural change.

Similarly, the Leader-Member Exchange Theory recommends creating bonds with every member in order to make them feel that they are a part of the "in-group" which can boost their productivity. Through various informal gatherings, it was attempted to introduce every new member to the in-group, however with varying success, as different people had different motivations, commitments and expectations. Furthermore, as noted in some academic literature, there might be a limit to how large the in-group may become. [95]

Servant leadership defines the attributes leaders should adhere to in order to motivate their subordinates successfully. In general, this approach was also beneficial, however with the eForce flat and collective wisdom management model and thus several informal leaders being active at the same time, it proved difficult to coordinate all leaders to adhere to all attributes. This approach therefore proved to be the least scalable of the three theories.

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[94] THOMPSON, G., & VECCHIO, R. P. *Situational leadership theory: A test of three versions*. The leadership quarterly, 2009, 20(5): 837-848.
[95] VIDYARTHY, P. R., LIDEN, R. C., ANAND, S., ERDOGAN, B., & GHOSH, S. (2010). *Where do I stand? Examining the effects of leader–member exchange social comparison on employee work behaviors*. Journal of Applied Psychology, *95*(5), 849.

8.4. Takeaways from theories

As stated in the methodology of this thesis, the purpose of applying abovementioned theories is not to test a preconceived hypothesis, but rather to generate new insights and hypotheses that might help explain the perceived outcome. Although they are not conclusively proven, these hypotheses can still offer clear takeaways to be learnt from this analysis.

Firstly, as it was demonstrated at the very beginning of the project, when designing a new innovative engineering organisation, it is important to consider which organisational layout is best. Academic literature proposes two models – a spin-out model and ambidextrous organisational design. As it was shown on a practical example of the eForce Driverless case, the spin-out model cannot be used if all activities of the new project cannot be guaranteed to be reasonably insourced into the project. In cases where the new project cannot function well while separate from the new organisation, ambidextrous design is a clearly better approach that allows the new project autonomy in decision making while still being connected to the communication channels and resources of the parent organisation.

Secondly, in the same scenario it worked best not to force a specific management model onto the new project but rather respect the natural emergence of a particular modification adapted from the parent organisation. This observation could be explained by the fact that a new organisational culture takes time to develop and it might clash and be incompatible with the culture of the parent organisation.[96] The cultures of new projects tend to be closer to the alternative models of management within the framework outlined in this thesis. As far as working with high-value members is concerned, it proved as a motivating factor, which was unfortunately diminished due to the lockdown preventing interpersonal meetings. On the other hand, the opposite phenomenon was strongly present – the "stars" became demotivated if others were not as productive at times.

Finally, the leadership theories explored here seem to have had a very positive effect on member retention, if external factors that might be affecting the students are considered as well. The organisation members were kept engaged and individual approaches have shown success; however, this approach is time-consuming and requires experience in leadership and it may be difficult to sustain.

Based on these observations, it may be concluded that the presented techniques and theories have proved useful in creating a successful venture in this particular case study. However, it would be beneficial to conduct further research to confirm these hypotheses on a larger sample of cases and to further narrow down the findings – for example to determine which leadership theory was most beneficial.

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[96] SCHOLZ, Christian*. Corporate culture and strategy—The problem of strategic fit*. Long Range Planning, 1987, 20.4: 78-87.

9. Long-term sustainability

As this thesis is nearing its end, so is the planned roadmap of the eForce Driverless project as outlined in the feasibility study. It is therefore worth revisiting the matrix of resource elements needed for individual stages, this time from the perspective of the slowly finishing phase 3 – Racing Season and Handoff. As it is shown in figure 56, the project is currently in a very good situation overall. It has comfortable premises in the form of an own workroom directly connected to the older eForce workshop, it has all the technology needed for the implementation of a working autonomous vehicle and finances to spare even for the upcoming 2021 season.

The only slightly unsatisfying factor is human resources. While the current team is talented and able, it would definitely be beneficial to onboard new recruits. On the other hand, this is not a high-risk deficiency, since in just two months the *Day with Formulas* will be happening at Czech Technical University, traditionally the biggest recruitment event for eForce to gain new student members.

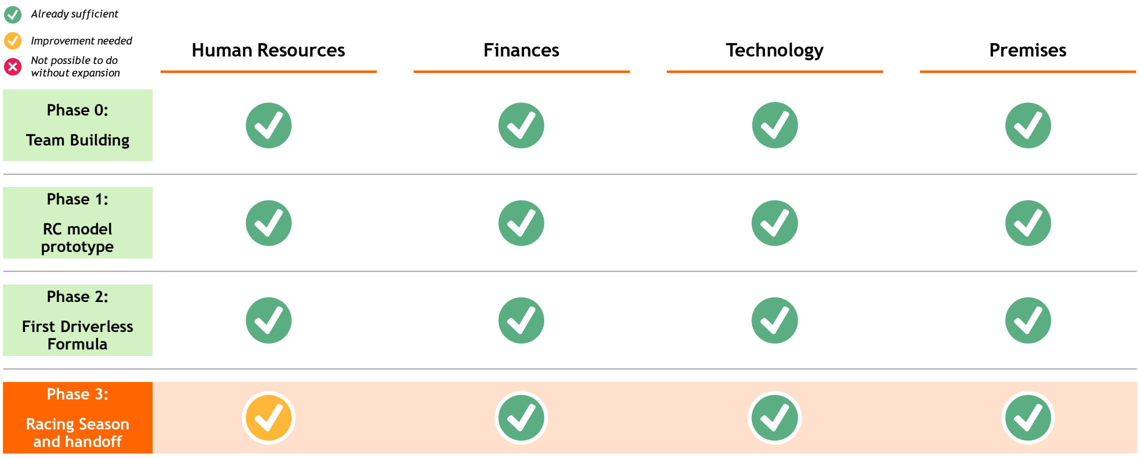

Figure 56: The state of the four key resource elements when nearing the end of phase 3

In fact, the four-phase timeline was less of a roadmap for eForce Driverless, which will hopefully have a much longer story and more of a roadmap for the personal journey of the author's own activities there and thus also for this thesis. It is therefore a joyful fact to be able to finish both this thesis and activities in the team at a moment when eForce Driverless seems to be in a suitable position for the future. Still, it is beneficial to reflect what can be done to encourage further development, sustainability and success for the project.

Firstly, the most obvious and easy to do next steps are clear – finish the development of the working prototype this summer and present it at the rollout in September to the wider audience of Czech Technical University. Based on discussions with the faculty dean, it might be useful to also prepare a more science-oriented interactive exposition for the colleagues from the faculty to try and establish more research partnerships. In order to promote stability and lower turnaround of members, it could be beneficial to transform eForce Driverless from a primarily voluntary activity to a primarily research activity.

When reflecting the theories discussed in this thesis, it is good to note that all of them seem to have been useful when creating a successful project environment. However, they were also quite work-intensive, and it would therefore be wise to choose one approach to focus on. In terms of leadership theories, the situational approach might be easiest to grasp and apply, although it needs to be understood in the context that members may move forward and backward between the states in contradiction to the traditional assumptions of this theory, as shown in the chapter concerning human resources.

The organisational design frameworks will probably become less and less relevant for the future, as it is much harder to affect an organisational management structure of an already functioning organisation. It can be expected for eForce Driverless to further integrate with the original eForce team or to eventually split as a spin-out, although this is not deemed very likely at this point. In terms of management models, it will still make more sense to stick to alternative models of management as they come naturally to such informal organisations. As the team keeps growing, it might be inevitable to keep moving towards the more traditional ends of the spectrum, as informal ties and communication channels could become unmanageable and processes will need to be established.

10. Summary

It is always a gamble to establish a new project and dedicate resources to it without knowing whether it will become successful and the risk increases with its complexity. With a similar anxiousness, eForce Driverless was kicked off in late 2018 with the goal of establishing the first Czech research team building life sized autonomous racing vehicles. As it is described in this thesis, the gamble was worth it and a stable organisation full of talented individuals got established.

This thesis itself had four distinct goals to be achieved. Firstly, it mapped out and described the current academic understanding of innovation and engineering management, including relevant theories in the field. These theories were then practically applied during the description of the implementation and it was evaluated how applicable they were in this case. Secondly, a feasibility study in the earlier chapters of this thesis described the decision process preceding the foundation of eForce Driverless – how and why it was decided by eForce to go forward with this project. Thirdly, the thesis contains both an organisational and a technical description of the project outcomes as of now Summer 2020. And finally, in the theory reflection and sustainability chapters at the end of this thesis, academically supported recommendations for the newly founded team are provided to remain sustainable and ultimately successful in the future of the competition.

Similarly, all research questions outlined at the beginning of this thesis were answered. The first question asked to what degree could the eForce Driverless project be considered successful. During several chapters in this thesis, the success of the project was measured using a direct comparison to the expected outputs as defined in the feasibility study. While the initial expectations in the prototyping phase were not met, the team quickly caught up and overcame both this difficulty and the critical challenge posed by the COVID-19 epidemic. At the present, time, the team has a stable group of members, is finishing its first vehicle and is in the final round of an international Formula Student Driverless event, which means it may certainly be described as successful.

Then, using a hypothesis-generating case study design approach, I answered the second research question of whether the success of eForce Driverless could be explained or supported by some of the contemporary theories of innovation management. The theories were systematically applied onto this case and it was evaluated that they could indeed be a part of the deciding factor of the eForce Driverless success, but a further more quantitative research approach would be beneficial to support this argument or even conclusively prove it. Lastly, assuming that these theories indeed are applicable, specific recommendations were made for the future eForce Driverless leadership in order for the team to remain sustainable and successful in the long run.

Overall, I would like to end this thesis on a personal note. It has been a great honour to be one of the founders of eForce Driverless and a privilege to work on its inception and implementation for the past two years with some of the most talented people our university has to offer. I am strongly convinced that the team is capable of achieving great success in research and on competitions worldwide and it will become one of the prominent student research teams at the university.

The Czech Technical University is rightfully known to be challenging to its students. A minority of those who enrol manage to complete all requirements necessary for graduation and fewer still manage to participate in extracurricular activities. At graduation itself, it is not often that a student can look back at an achievement done for the university as a whole in parallel to their regular studies. I am therefore extremely happy to have been part of eForce for the past five years and the founder of eForce Driverless for the past two. It provided me with a wide range of practical experience and a large network of invaluable personal contacts. The team also provided the University with one of the best PR materials that can be presented by such institutions – successful students fulfilling their dreams. I am proud to have made my contribution, but also grateful for the environment that had to be already in place in order to make all this possible. And thus, I would like to dedicate the last words here to thank the Czech Technical University and its staff, I wish it to remain open to new ideas and I wish it keeps welcoming an ever-growing pool of talented students that will found many more inspiring projects in the future.

11. Registry

11.1. Abbreviations

Abbreviation	Expanded	Meaning
ACC	Acceleration	A dynamic discipline in the Formula Student competition, see chapter 5.1.3
AI	Artificial Intelligence	Field of Computer Science focusing on intelligent behavior demonstrated by machines
AX	Autocross	A dynamic discipline in the Formula Student competition, see chapter 5.1.3
BLC	Business Logic Case	A preliminary BP overview document submitted to some races
BP	Business Plan	A static discipline in the Formula Student competition, see chapter 5.1.3
BPES	Business Plan Executive Summary	A preliminary BP overview document submitted to some races
CR	Cost Report	A static discipline in the Formula Student competition, see chapter 5.1.3
CTU	Czech Technical University	A technical university in Prague, Czech Republic, where this thesis was written.
EDR	Engineering Design Report	A static discipline in the Formula Student competition, see chapter 5.1.3
EFF	Fuel Efficiency	A dynamic discipline in the Formula Student competition, see chapter 5.1.3
FEE	Faculty of Electrical Engineering	An electrical faculty of CTU, where this thesis was written.
FS/FSAE	Formula Student	Student engineering competition for students, see chapter 5.1
FSC/CV	Combustion Vehicle	Formula Student competition category
FSD/DV	Driverless Vehicle	Formula Student competition category
FSE/EV	Electric Vehicle	Formula Student competition category

Abbreviation	Expanded	Meaning
FSG	Formula Student Germany	Formula Student race in Germany
FSO	Formula Student Online	Formula Student race done entirely online in the 2020 season, see chapter 7.8.2
GPS	Global Positioning System	System measuring the precise position on Earth of the vehicle
IMU	Inertial Measurement Unit	Sensor measuring the vehicle's specific force, angular rate, and sometimes also orientation
KIT	Karlsruhe Institut für Technologie	A university in Germany competing in Formula Student
LiDAR	Light Detection and Ranging	Sensor very precisely measuring distance using light ray refraction and detection
MIT	Massachusetts Institute of Technology	A university in the United States competing in Formula Student with TU Delft
SP	Skid Pad	A dynamic discipline in the Formula Student competition, see chapter 5.1.3
TD	Trackdrive	A dynamic discipline in the Formula Student competition, see chapter 5.1.3
TUD	Technische Universiteit Delft	A university in the Netherlands competing in Formula Student with MIT
TUM	Technische Universität München	A university in Germany competing in Formula Student
WRL	World Ranking List	Official ranking for Formula Student teams

11.2. Figures

11.3. Tables

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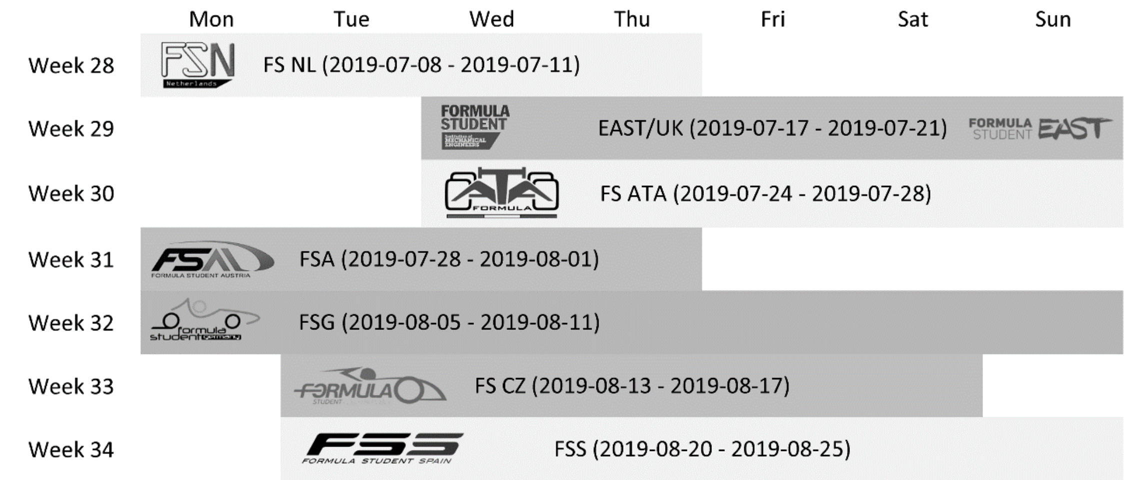
13. Appendix

Appendix [A] - Expected schedule of the 2019 Formula Student racing season as of January 2019



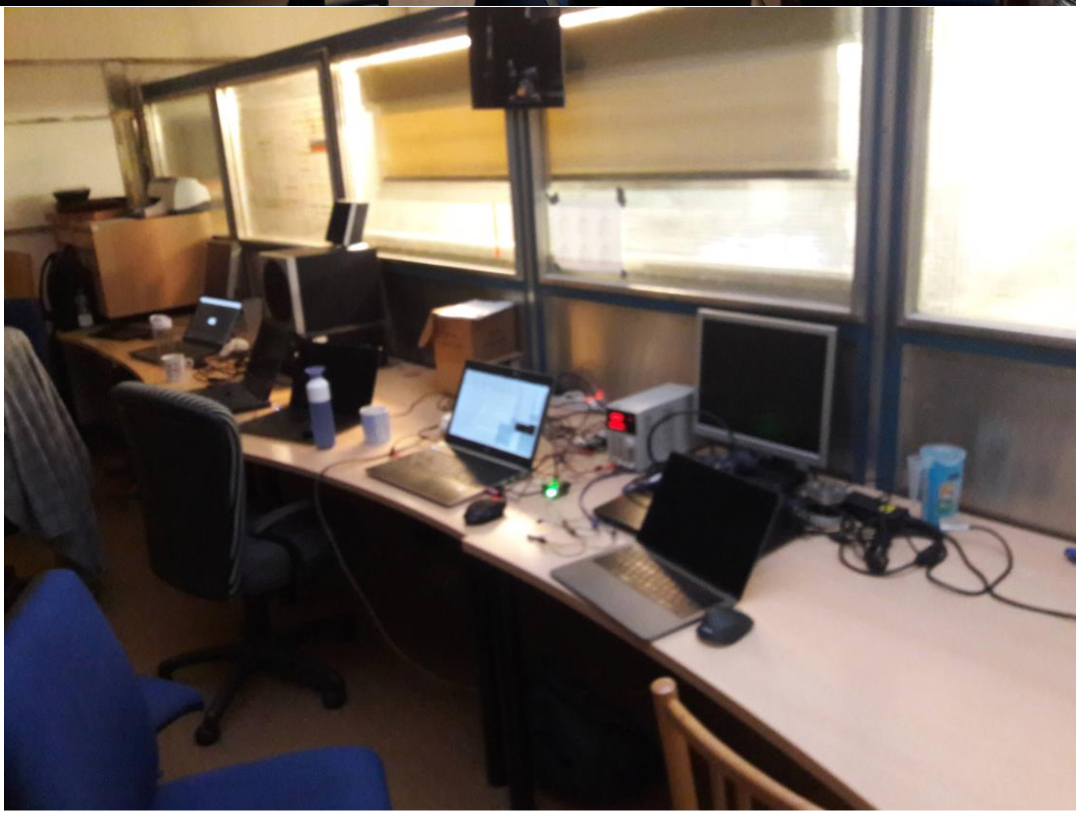
Appendix [B] - Billed cost of materials of the current vehicle

	Materials	Processes	Fasteners	Tooling	Total
Brake System	$780	$205	$5	-	$989
Engine & Drivetrain	$5 055	$499	$31	$6	$5 591
Frame & Body	$3 087	$6 229	$15	$41	$9 372
Instruments & Wiring	$8 504	$509	$2	$0	$9 015
Miscellaneous, Fit & Finish	$559	$270	$2	$4	$835
Steering System	$116	$353	$3	$0	$472
Suspension & Shocks	$1 452	$555	$8	$23	$2 036
Wheels & Tires	$2 103	$488	$6	-	$2 597
Total Vehicle	**$21 655**	**$9 108**	**$70**	**$74**	**$30 908**

Appendix [C] - eForce time investment valuation calculation

Work type	Cost per hour	Man units	Average hours per week	Weeks	Total cost
Manual	100.00 Kč	10	5	47	235,000.00 Kč
Junior engineering	150.00 Kč	15	7	47	740,250.00 Kč
Senior engineering	250.00 Kč	5	10	47	587,500.00 Kč
Organizational / management	200.00 Kč	6	5	47	282,000.00 Kč
Total					1,844,750.00 Kč

Appendix [D] – eForce Driverless workshop photos



Appendix [E] – Autonomous Design Report eForce Driverless 2020

Autonomous Design Report

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EForce Driverless (66) FS Online 2020

This paper describes the design of the f rst Czech autonomous electric formula developed by eForce Driverless at CTU Prague for season 2020. We present the complete design focused on simplicity, safety and reliablity covering both hardware and software. In this paper, we describe all the key components that allow the car to drive autonomously. We start at the lowest level with automatic steering and braking systems, the perception sensors that allow the car to see its surroundings, the computing unit that processes the data and f nish with the algorithms necessary for safe operation of the car, namely cone detection, localization and mapping, path planning and motion control.

1. INTRODUCTION

Team eForce Driverless was founded in 2019 as a branch of the successful eForce FEE Prague Formula with the goal to attend multiple races in season 2020. Our team successfully designed the f rst autonomous car by repurposing an existing electric car named FSE07 built for season 2018.

During the past year and a half of development, we designed a complete system for autonomous racing. We trained cone detection algorithms, SLAM algorithm for localization and mapping, path planning and motion control. As a f rst-year design, we have deliberately chosen to use simpler algorithms over more sophisiticated algorithms which allowed us to keep the overall complexity of the system at minimum. Since safety is our main priority, all algorithms were thoroughly tested and validated.

Despite the COVID-19 pandemic, which made development and especially testing much more complicated, our team continued working on the design and algorithms using virtual environments and simulations. A detailed description of the chosen algorithms and results of experiments are shown further in the paper.

As mentioned earlier, the main design goal of our f rst ever driverless car was to use simpler and more straightforward algorithms. As such, we see signif cant opportunities to improve the performance and sophistication of our algorithms. We will use the data and experience gained during our f rst season to make our next car faster, safer and even more reliable.

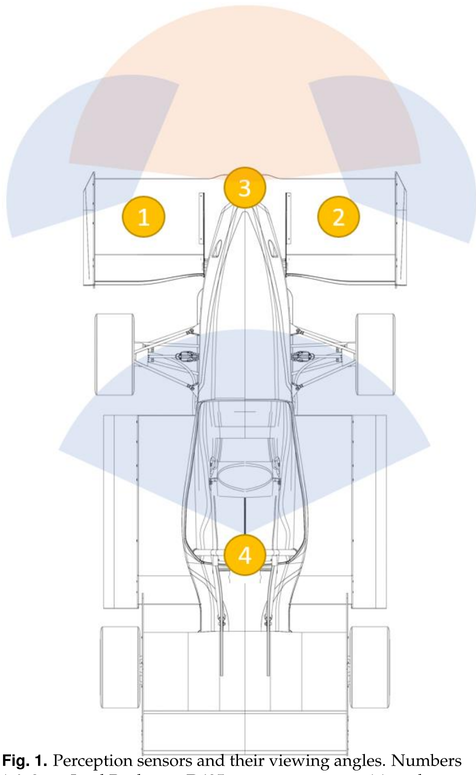


Fig. 1. Perception sensors and their viewing angles. Numbers 1 & 2 are Intel Realsense D435 stereo cameras positioned at an angle. Number 3 is Ouster OS1 LiDAR and number 4 is a Stereolabs ZED stereo camera placed at the top of the main hoop.

This paper is structured as follows. In section 2, we describe the hardware architecture of car including steering, service brake and emergency brake system. In section 3, the software architecture based on ROS presented. In section 4, describe the way the formula senses its surroundings. We discuss image cone detection using neural networks and show methods of cone localization. In section 5, we introduce our SLAM algorithm based on FastSLAM 1.0. Section 6 describes a high-level path planning algorithm used in conjuction with SLAM. In section 7, we present our motion control algorithm. Section 8 brief y discusses autonomous safety and f nally, section 9 concludes the paper.

2. HARDWARE ARCHITECTURE

A. Steering

To control the steering wheel, a Kartek power steering kit is used. This kit is connected to the steering column and its steering angle is determined with using a negative feedback control and a PI regulator implemented in MCU, which then controls an H-bridge and power steering kit current.

B. Service brake

As a service brake, we are using two high voltage SAVOX SB-2230SG servos. Both of these two are connected to the brake pedal through a pulley.

C. Emergency Brake System

The emergency brake system (EBS) consists of three main parts. These parts are air reservoir and actuators.

C.1. Air reservoir

As a reservoir, we use a Festo 5 liter 18 bar tank whith plans to replace it with a carbon 1 liter 300 bar tank for the following season. The only problem with this approach is the need for a regulator capable of reducing pressure from 300 bar to 6-8 bar which is the pressure under which our system operates.

C.2. Actuators

The actuator is directly connected to the brake pedal. The travel distance of the actuator is 80mm and it is capable of providing 753N of force with 6 bar at the inlet.

D. Sensors

The car is equipped with three stereo cameras and one LiDAR. A Stereolabs ZED stereo camera is positioned at the top of the main hoop looking directly ahead. Two Intel Realsense D435 stereo cameras are mounted on the front wing looking to the side under a slight angle. Ouster OS1 LiDAR is positioned in the middle of the front wing.

E. Computing unit

The computing responsible for running the autonomous system is Nvidia Jetson AGX Xavier. Compared to its predecessor, Nvidia Jetson TX2, this computing includes a more powerful CPU, more RAM, and a much more powerful GPU. In addition to the main computing unit, the autonomous system has access to Nvidia Jetson Nano decreasing the load on the main load by preprocessing images from cameras.

3. SOFTWARE ARCHITECTURE

Our autonomous system runs on Robot Operating System (ROS) [1] as it has proven to be one of the best options for robotic programming applications. Moreover, it has a large number of packages and libraries for use in robotics and a very active community.

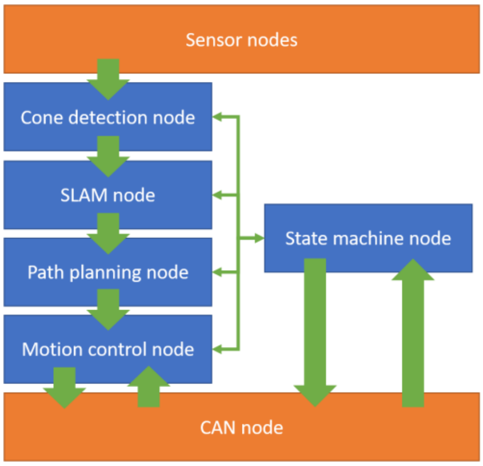


Fig. 2. ROS architecture

We are currently using ROS version 1, but plans are underway to migrate to ROS 2. It has become much more stable in the last year and it offers native integration with Python 3 and much more comprehensive support for Python in general.

A. Project structure

The project is divided into several nodes, each responsible for a different part of the autonomous system.

Sensor nodes interface with the actual sensors e.g. the LiDAR and provide data to be processed by the system. The cone detection node is responsible for taking sensor data from stereo cameras and LiDAR and producing 3D positions of cones in the scene. The SLAM node receives data about positions of cones and movement of the vehicle and gradually builds a map of the track while localizing the car inside the track. The path planning node receives the potentially incomplete map of the environment and plans a high-level path through the map which the motion control node translates into lower-level commands for engines and steering which are sent by CAN. The safe operation of the system is controlled by the state machine node which runs the autonomous state machine def ned in the rulebook.

As is typical with ROS, the project is structured into several self-contained packages roughly corresponding to the described nodes, each responsible for one part of the system e.g. the image cone detection package is responsible for taking in camera inputs and producing 3D positions of the cones.

This decoupling of the individual parts of the system allows the package developers to focus only on their work without having to worry about changes made in other parts of the system, making it easier to coordinate the work being done.

Moreover, the decoupling into nodes and packages allows for easily swapping out nodes if the need arises. For example, we could have two different implementations of a path planning node, and this design makes it easier to change between them seamlessly.

B. Testing

We employ standard CI/CD techniques to ensure the integrity of the system. Every new change to the project is f rst tested in an isolated system on our Gitlab server. It verif es that the project builds successfully and runs a test suite to ensure no regressions were introduced in the commit. Only then are the changes merged.

In addition, every merge request to the main repository must be reviewed by another team member before it can be merged. This allows for a high code quality and reduces the number of bugs signif cantly, making for a codebase that is easy to maintain and change.

4. CONE DETECTION

Arguably the most important of a successful DV car is a reliable cone detection algorithm. Typically there are two approaches and it is possible to choose either or both of them. One approach is to use RGB(D) cameras and run some kind of object detection algorithm. Another option is to use LiDAR and obtain cones from the provided point cloud data [2].

Since we have obtained our Ouster LiDAR relatively recently, we have not fully integrated it into our autonomous system. For now, we rely only on object detection from color images provided by three cameras - a single Stereolabs ZED mounted on the main hoop looks directly ahead and two Intel Relsense D435 mounted on the front wing under an angle looking to the side.

A. Object detection

To safely navigate the track, we need to locate the cones in the images provided by our cameras. This is a typical object detection problem. Object detection as a whole is a very popular topic in machine learning literature nowadays and there are many approaches to object detection problems such as detecting cones.

Arguably the best methods take advantage of Convolutional neural networks (CNNs) as these networks have proven to work very well with image data.

A.1. Sliding window

Prior to the introduction of YOLO and other single-shot detectors, sliding window techniques were used to detect objects in an image. Using this technique a sliding window of varying size would be used to scan the image. For every window position, a trained classif er would decide whether or not there is an object of interest fully contained in the window.

This approach allows for relatively simple classif ers but the computational overhead of having to scan the image many times is too prohibitive for our use case. In a standard race track, there could be cones dozens of meters away which will appear much smaller in the image than cones that are very close. This would require many different window sizes making this approach even slower.

A.2. YOLO

In contrast, YOLO only needs one pass through the network to generate a set of bounding boxes. The disadvantage is that the network is much larger and thus even a single forward pass can take hundreds of milliseconds for larger resolutions.

There are currently three versions of YOLO, v1 - the original YOLO - version 2 and version 3. YOLOv2 improves on the original version with increased speed and accuracy while v3

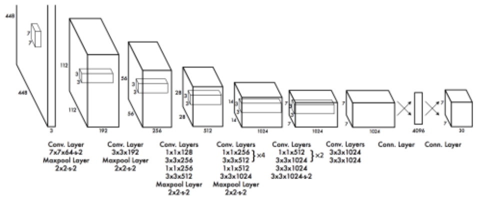


Fig. 3. The YOLOv2 architecture (image taken from here)

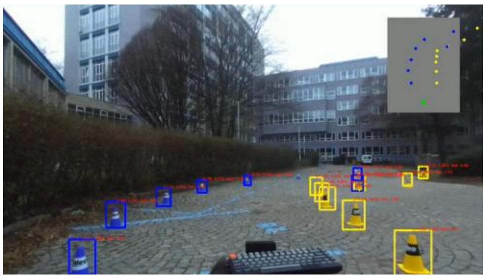


Fig. 4. Cone detection using our trained YOLO-based detector

offers only marginal improvements over version 2 while being slightly slower overall [3].

Consequently, we decided to use YOLOv2 in our autonomous system as it offers the best combination of speed and accuracy for our needs.

B. Training

For training, we use the well-known Formula Student Objects In Context (FSOCO) database of a large number of labeled images. The network is trained in a standard train/validation/test setup where the dataset is split into three parts, one for training, one for validation and the f nal one for testing [4].

We used 12000 images to train and 3000 to test. The detector is able to detect is able with a frequency of 10 frames per second. The resulting mAP (mean average precision) achieved by the network is ≈ 0.49. Below is the average precision for different types of cones:

Class name	Average precision (AP)
Blue cone	0.51527
Yellow cone	0.45529
Orange cone	0.45423
Big orange cone	0.51627

C. Recovering 3D position

Both Stereolabs ZED and Intel Realsense D435 are capable of providing depth information. Once we can locate a cone in the image, we are able to use this information to recover the 3D position as well.

We have verif ed empirically that the accuracy of both of the cameras decreases drastically with increasing distance. For

Stereolabs ZED, the accuracy for objects located further than 15 meters tends to be too low and unreliable to be usable. We have observed the same for Intel Realsense with distances above approximately 7 meters.

If this localization technique proves inadequate, we have developed another solution that can give us more precise depth information at larger distances. We take advantage of the fact that the track can be largely thought of as a 2D plane. Consequently, the cones can be thought of as points on this 2D plane. Since the camera is essentially mapping points from this 2D plane, there exists a homography H between this world plane and the image plane. It holds that:

$$\underline{Y} = H\underline{X}, \quad (1)$$

where $\underline{Y}$ and $\underline{X}$ are homogenous coordinates of the image and world point respectively. H is the desired homography.

Once we have estimated the homography H, we can establish a bijection mapping between the world and image planes allowing us to freely convert between those two and recover 3D positions of the cones.

C.1. Homography estimation

To estimate the homography, we need at least 4 points in the scene whose precise location is known. We then f nd the coordinates of their projections in the image. Using SVD or posing the problem as a set of linear equations, it is possible to compute the f nal homography such that

$$\underline{Y}_i = H\underline{X}_i \quad \forall i \quad (2)$$

$$|H| = 1. \quad (3)$$

Using more than 4 points will give us larger accuracy and make the estimation less sensitive to measurement errors.

Once we have the homography, we can recover the 3D position of any point lying on the plane. In theory, this computation should be independent of the distance, allowing us to accurately estimate the depth of distant objects with a high degree of accuracy.

It should be noted that in order to f nd the homography, it is not necessary to construct the image-to-world correspondences manually. Assuming the relative rotation and translation between the camera frame and the car frame is known, we can use one of the many RANSAC[5] variants to f nd the 3D plane automatically. Once the coeff cients of the plane are known, we can choose any 4 points lying on the plane and project them into the image plane using the camera matrix P. This gives us the 4 correspondences we need to compute the homography. We can convert the homography results into the car coordinate frame since the relative position of the camera and the car is known.

5. SLAM

To simplify the overall design, we initially considered controlling the formula in a purely reactive manner. This means the formula would neither build nor remember the map and would drive solely based on the current sensor input e.g. the currently visible cones. Opting for this approach would allow us to simplify the design signif cantly - it would only require robust detection of cones and a simple reactive algorithm such as following the centerline.

The drawback is that a purely reactive approach severely limits the maximum speed of the formula. Since we have no

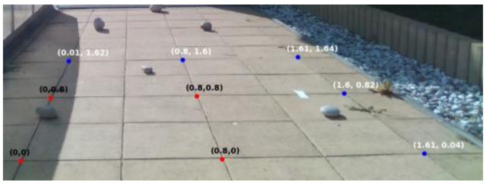


Fig. 5. Using homography to estimate points the location of 3D poitns. Red points were used for calibration, blue points were estimated by the homography. The error stays within 5 cm.

knowledge of what may lie ahead of the car, we can never be certain if it is safe to go fast.

Eventually, we decided to incorporate SLAM [6] into our design however we retained the reactive approach for the f rst lap. Regardless of utilized mapping techniques, the map is not known during the f rst lap and therefore a reactive control mechanism is needed. During the f rst lap we use SLAM to create an accurate map of the track so that we can accelerate to higher speeds and use a better path planning in future laps.

A. Choosing a SLAM algorithm

Since the map only contains several dozen cones (referred to as landmarks), we can use one of the sparse SLAM techniques. Both EKF-SLAM and a particle-based SLAM were considered. EKF-SLAM models the state of the car as a single Gaussian distribution together with the landmarks. Particle-based SLAM on the other hand, typically approximates the state distribution with discrete particles where each particle has its own copy of the map attached to it.

Even though EKF-based SLAM may be arguably conceptually simpler and easier to implement, particle-based SLAM offers several advantages. The most important characteristic is that compared to EKF-SLAM, particle SLAM is an any-time algorithm, meaning that the more time (or particles) it is provided, the better results it is able to provide. In contrast, EKF has a f xed loop time which is a problem in systems requiring real-time operation.

Particle SLAM can also deal with the problem of data association more robustly. Data association is needed since there is no way to identify measurements as belonging to a certain landmark uniquely. Moreover, data association can be incorrect for a multitude of reasons such as a faulty sensor or sensor noise. Since EKF-SLAM only considers a single hypothesis, it is diff cult to recover from incorrect data association. On the other hand, particle-based SLAM, provided it has enough particles, will very likely retain at least a few particles that have the correct association, allowing it to recover from such errors and making it more robust overall.

B. FastSLAM 1.0

For our autonomous system, we chose to use FastSLAM 1.0 [7]. FastSLAM 1.0 is a particle-based SLAM method where the map is further decomposed into individual independent landmarks each having its own Extended Kalman Filter (EKF).

B.1. State representation

The state of the car is modeled simply as a 3-vector s given as

$$s = [x, y, \theta], \tag{4}$$

where x, y is the vehicle position and θ is its heading. To make the design simpler, we make the simplifying assumption that the track is close to 2D.

Each particle p is then defined as a tuple containing the state s together with n landmark means and covariance matrices:

$$p = \langle s, \mu_1, \Sigma_1, ..., \mu_n, \Sigma_n \rangle. \tag{5}$$

Here, $\mu_i = [x, y]$ is the position of the landmark and Σ_i is the associated covariance matrix. The position of a landmark is assumed to be modeled as a Gaussian distribution so that we can take full advantage of EKF to track its position.

B.2. Initialization

Each particle p_i also has an associated weight w_i which is proportional to the posterior probability of the particle describing the true state. At the beginning, the particles are initialized with random positions, possibly drawn from Normal distribution centered on the car position. The particles are initialized with a uniform weight of $1/N$, where N is the number of particles, since at the beginning the particles are equally likely to model the true state so there is no reason to prefer one particle over another.

B.3. Sampling new poses

Given a control input u, new particle poses are sampled based on the control noise. The control input is applied to each particle together with the control noise. In this step, the landmark positions and weights remain unchanged and only the poses change. The sensor measurements are incorporated in the following step.

B.4. Landmark update

In the update step, the algorithm computes new landmark positions and covariance matrices based on the measurements provided by the sensors. Before the landmarks can be updated, new measurements need to be associated with existing landmarks and potentially new landmarks have to be created. This step, often called data association, is discussed in more detail in the next section.

The update step only considers landmarks that were reobserved by the sensors. The position and covariance matrix of landmarks that were not seen in the current step remains the same. New landmarks are initialized with the position provided by the sensor and their covarience matrix is initialized as the noise of the sensor.

Landmarks that were reobserved are updated using the standard EKF update rule. The perception model is first linearized using Taylor expansion from which we compute the Kalman gain K and update the landmark mean μ and covariance Σ based on the formula:

$$\mu^{t+1} = \mu^t + K(z_t - \hat{z}_t)^T \tag{6}$$

$$\Sigma^{t+1} = (I - KG^T)\Sigma^t, \tag{7}$$

where G is the Jacobian of the perception model, z and $\hat{z}$ is the real and predicted measurement respectively.

B.5. Particle resampling

The last but nevertheless important part of FastSLAM 1.0 is particle resampling. New particles are drawn with replacements from the old set proportional to their weights. This is needed because the particle state changes only as a result of the control input u without the sensor measurements taken into account.

We use systematic resampling to create a new set of particles. This method samples more uniformly and guarantees that no samples are too far apart from each other.

Apart from it being computationally expensive, it is not necessary to resample particles in every iteration. We will use a metric called effective N (N_{eff}) which measures the number of particles meaningfully contributing to the probability distribution. It is given as

$$N_{eff} = \frac{1}{\sum \omega^2}. \tag{8}$$

With N_{eff}, we only resample when it is lower than some chosen threshold which needs to be empirically verified and largely depends on the problem.

C. Data Association

In the previous section, we explained that particle-based SLAM tends to be more robust compared to EKF-SLAM precisely because the data association is done on a per-particle basis. This may also be viewed as a disadvantage when designing a real-time system since the data association algorithm needs to be executed for every particle separately.

It is then essential to choose such an algorithm that gives satisfying results but is also fast enough to be computed thousands of times in every iteration. The general data association problem can be solved optimally in polynomial time. Nevertheless this solution proved to be too slow for us. Instead of a globally optimal solution, we opted to use a simple and fast greedy solution.

Algorithm 1. Data association algorithm

```
1: procedure DATAASSOCIATION(p, M)
2:     D ← Zero matrix
3:     for landmark i n p do
4:         for measurement i n M do
5:             D_{i,j} ← N_pdf(μ_landmark − μ_measurement, Σ_landmark + Σ_measurement)
6:     Sort D_{i,j} in decreasing order
7:     Assing all measurements.
8:     if measurements > landmarks then create new landmark
9:     if D_ij > threshold then create new landmark
10:    return Assignment
```

We start by computing pairwise distances between known landmarks and current measurements. This distance is given by the probability density function of the multivariate normal distribution (N_{pdf}). Next, these pairwise distances are sorted in decreasing order and measurements are assigned to landmarks. If there are more measurements than landmarks, all unassigned measurements become new landmarks.

The associations are further refined by removing pairs where the distance is higher than a given threshold.

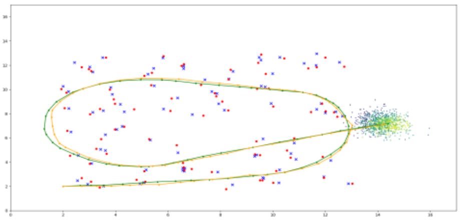


Fig. 6. Simulating FastSLAM 1.0. The green and yellow curves show the true and estimated position respectively. Blue crosses denote the real landmark positions, while the red dots show the noisy sensor measurements.

This greedy algorithm will not always return the optimal solution and thus can misassociate measurements with landmarks. Nevertheless, due to the eff ciency of this solution we can counteract the incorrect associations by using a suff cient amount of particles in FastSLAM.

We are currently considering using multiple object tracking techniques (MOT) to track the landmarks in the camera images instead of computing the association after. This could potentially give us even more speed and accuracy, but we do not have a working version yet.

D. Results

We have validated the described SLAM algorithm in simulations that can simulate noisy control commands and noisy sensors. As mentioned above, using too few particles leads to divergence since it is more likely that no particles accurately model the system. Increasing the noise has the same effect since the data association tends to make more mistakes. When we use expected system noise, the algorithm can operate in real-time with a high degree of accuracy.

6. PATH FINDING

For a proper navigation and movement between the cones, it is f rst necessary to know where the track leads [8]. For these purposes, we have developed an algorithm capable of f nding the boundaries of such track as well as the centerline between them based on the detected cones and their colors.

A. Algorithm

Suppose that we detected most of the cones in advance, B denotes the set of blue cones and Y is the set of the yellow ones. The coordinate system is not f rmly connected to the car but it is global instead. Therefore positions of the cones are constant and the position of the car changes. Let $\vec{s}_0 = (x_0, y_0)$ and $\vec{s}_1 = (x_1, y_1)$ be coordinates of the end and the front of the car. We obtain the f nal centerline by interpolation of the elements of $\{\vec{s}_i\}_{i=2}^{N}$.

This algorithm can be slightly modif ed to f nd a short way through a small set of cones detected within a single on-camera frame. This modif cation allows navigation in a previously unknown environment like during the f rst lap of a race.

For further processing of path, path is interpolated using third order B-spline.

Algorithm 2. Path finding algorithm

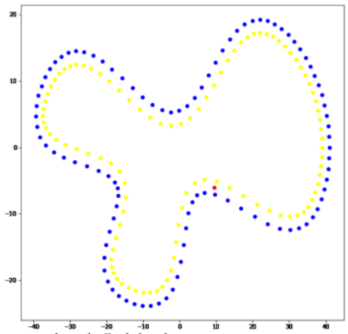
$i = 1$
while path not connected **do**
  Find parameters (k,c) of normal line to $\vec{s}_i - \vec{s}_{i-1}$ at point $\vec{s}_i$.
  Separate the cones that are in front of car

$$\hat{B} = \{\vec{b} = (x, y) \in B : sign(y - k \cdot x - c) = 1\}$$
$$\hat{Y} = \{\vec{y} = (x, y) \in Y : sign(y - k \cdot x - c) = 1\}$$

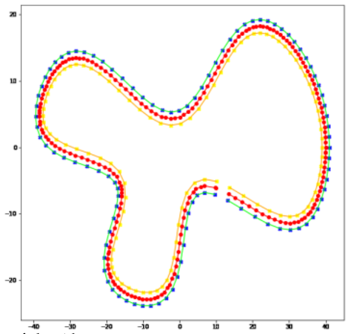
  Find closest blue and yellow cone

$$\vec{b} = \arg\min_{\vec{b} \in \hat{B}} \|\vec{s}_i - \vec{b}\|$$
$$\vec{y} = \arg\min_{\vec{y} \in \hat{Y}} \|\vec{s}_i - \vec{y}\|$$

  Calculate center $\vec{s}_{i+1}$ between $\vec{b}$ and $\vec{y}$
  $i = i + 1$



(a) Randomly generated track. Red dot denotes start.



(b) Visualization of algorithm output.

Fig. 7. Path f nding on randomly generated track.

B. Results

We tested this algorithm on both handmade as well as on randomly generated tracks. The estimation of the route looks robust

(Table 1). Missing cones and non-constant spacing are not a big problem for the algorithm. Currently, we want to force the car to follow the centreline but in the future we are planning to f nd a more optimal race track.

percentage of missing cones	0%	10%	20%	30%
track 1	0	19.50	9.38	39.50
track 2	0	24.01	28.41	49.01

Table 1. The mean square error divided by track width between the real centerline and the estimated and interpolated centerline.

7. MOTION CONTROL

In order to explain our motion control algorithm we f rst must introduce a vehicle dynamics model. We use a widely used single track model d escribed as follows:

$$F_x = F_{x,r} + F_{x,f}\cos\delta - F_{y,f}\sin\delta - F_{x,aero} \quad (9)$$

$$F_y = F_{y,r} + F_{y,f}\cos\delta + F_{x,f}\sin\delta \quad (10)$$

$$M_z = l_f F_{x,f}\sin\delta + l_f F_{y,f}\cos\delta - l_r F_{y,r} \quad (11)$$

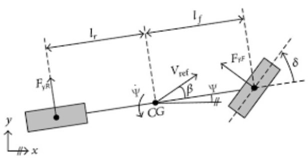


Fig. 8. Single track model

Where δ is steering angle, subindices x, y or z stand for force in x, y or z direction of coordinate system respectively. f and r stand for front and rear wheel axis respectively. l_f and l_r is distance between center of gravity of vehicle and front or rear wheel axis respectively. See 8.

A. Speed prof le generator

After receiving a planned path speed, a speed prof le generator starts. Speed prof le generation consists of three steps.
First, we set a maximum cornering speed satisfying the condition given by Kamm's circle:

$$F_x^2 + F_y^2 \leq \mu F_z \quad (12)$$

For speed generation, we use a simplif ed model. We do not consider acceleration or deceleration at this point. The only longitudinal force considered is the dissipative force.

$$F_x = F_{DIS} \quad (13)$$

$$F_y = mv^2\kappa \quad (14)$$

$$F_z = mg + F_{aero} \quad (15)$$

The maximum cornering speed is then set to a real positive solution. For safety reasons, we may limit speed further with the def ned speed limit.

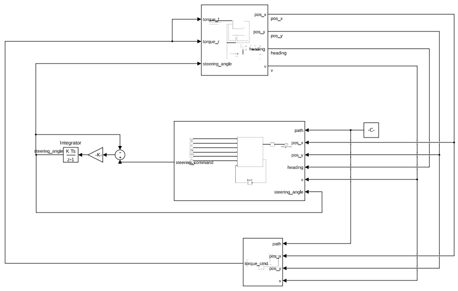


Fig. 9. Simulink diagram of trajectory tracking system and simulation

The second step is a backward pass. In this pass, planned speed is lowered based on the braking capability of the car. The algorithm starts at the last point of the path. For every previous point, the maximum speed is determined by the maximum available braking force. The maximum available braking force is set as a minimum from a maximum force based on Kamm's circle and maximum allowed force. The maximum allowed force is set as a maximum braking force car can provide. For safety reasons, the maximum allowed braking force limit is undervalued to provide the car with better maneuvering capability than planned.

The last step is a forward pass. In this pass, planned speed is lowered based on the acceleration of the car. The algorithm starts at the f rst point of the path. For every following point, the maximum speed is limited by maximum acceleration, which is again determined based on Kamm's circle as maximum available acceleration or limit (maximum power from power train). The maximum force is again lowered for safety reasons.

For a detailed description of the algorithm see [p. 26-30 9].

B. Trajectory tracking

For trajectory tracking purposes, we adapted Stanley control laws, both lateral and longitudinal, introduced by [10]. The controller was developed and tested while simulating the dynamics of the car. Unfortunately, none of the experiments could have been executed outside. However, our vehicle dynamics model was created based on real data, so we expect high f delity.

For the Driverless team, we continued in previous works of former team member [11]. We see a great opportunity to further developing the trajectory tracking system. The current design was chosen as the most comfortable option to start with. Once our team is allowed to work, we plan to validate our system in real-world conditions, followed by the development of more sophisticated control laws such as Model Predictive Control.

8. AUTONOMOUS SAFETY

Autonomous safety is of a great concern in our design concept. Most of the safety monitoring is carried out by the EBSS unit C.2. If we recognize that any problem occurred in our car or the RES Stop signal has been sent, then we engage our EBS system C.

EBS system consists of two parts. First, there is a pneumatic actuator which serves as EBS itself. As a redundancy of this system we are using the service break. Both components are very heavily monitored. In the pneumatic part we are checking pressure at every point, where something can occur (by valves, reduction valve etc.). The service break has two monitoring devices attached to it.

9. CONCLUSION

In this paper, we have presented in detail the full autonomous system of our f rst ever driverless racecar. The formula is equipped with stereo cameras together with a CNN-based object detector YOLOv2 to detect cones on the track. A particle-based SLAM algorithm FastSLAM 1.0 is used to incrementally build the map of the car's surroundings allowing it to take full advantage of its racing capabilities.

Path planing f nds the center line trajectory based on cones and their colour even with an incomplete map. The motion control algorithm, which is based on a single track model of the car, translates the high level map provided by path planning into lower commands for the engines.

The whole autonomous pipeline runs on an Nvidia Jetson AGX Xavier computing unit providing us with enough computing power to run computationally demanding tasks in real-time. Unfortunately, due to the current situation we were not able to test the system in real life conditions, however we have verif ed the individual systems extensively in computer simulations.

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Appendix [F] – Engineering Design Report eForce Driverless 2020

ENGINEERING DESIGN REPORT
EFORCE DRIVERLESS 2020

eForce FEE Prague Formula Driverless
Czech Technical University in Prague
Car number: 66
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tel.: +420 721 264 273
email: marek.szeles@eforce.cvut.cz

Introduction

In the Czech Republic, eForce FEE Prague Formula is the oldest and at present time still the only Formula Student Electric team. Ever since 2016, there were ideas to start the development of a Driverless vehicle. Unfortunately, the great challenges the team was facing at a public east European university meant that no one was able to truly start off the project with realistic financial and personal support. Finally, in 2019 a group of senior members decided it was time to develop a prototype and took it as their personal initiative. This document, along with the other Engineering Design documents, describes the outcomes of this endeavour, which is now going on for the second calendar year. The goal of the project was simple – to find a sustainable new division that will create the first Czech autonomous racing vehicle in Formula Student.

Figure 1: First eForce Driverless vehicle visualization

Vehicle Overall Concept

In order to create the first Czech autonomous formula, we knew we needed to use one of our older vehicles and retrofit it with the necessary upgrades. Developing a brand-new vehicle would simply be too costly. We could choose between two vehicles which were ready to drive at the start of the Driverless project: last year's vehicle, FSE.08 and the vehicle from the 2018 season, FSE.07. In the end, we chose the latter, because it is proven to have excellent performance (overall winner FS Czech 2018) and also because FSE.08 was needed for further driver testing.

FSE.07 is the seventh-generation electric car built by the eForce FEE Prague Formula team, designed mainly with a focus on reliability and performance. The requirements for conceptual changes were based on extensive testing of the previous vehicle (FSE.06) and simulations using IPG Carmaker and our custom lap time simulation. It is a four-wheel drive vehicle with front in-wheel motors and rear inbound motors. The chassis is a carbon fiber composite monocoque. The vehicle features 10-inch tires and an advanced aerodynamic package with high downforce.

This year, emphasis is put on ergonomics to make the driver more comfortable and therefore more concentrated on the driving itself. To meet ergonomic and torsional stiffness requirements, our carbon fiber monocoque was redesigned. Last year's overheating front brakes problem was solved, and front wing stiffness was increased for more consistent downforce.

To improve competitiveness during the endurance event, the battery pack capacity was increased based on simulation results. Based on last years' experience, the battery pack cooling system was redesigned and used a new type of cells to improve power efficiency. New state of charge (SOC) estimation was developed to improve our race strategy. Battery management system (BMS) was designed with an aim for better maintainability and data logging to help us understand battery pack even further.

Testing procedures were improved, and sensor numbers were substantially increased, e.g suspension displacement, tire and brake caliper temperature. These data are crucial for further analyses and to sustain future improvement. Custom made telemetry with live feed video is used for testing purposes. To improve EMC, CAN physical layer was redesigned.Vehicle dynamics control (VDC) utilizing torque vectoring was developed using model-based design in Simulink. VDC improves cars agility as well as stability and driving precision.

Design specifications:

- Lateral Acceleration [G]: (-2.5 – 2.5)
- Longitudinal Acceleration [G]: [-1.8 -1.3]
- Top speed [km/h]: 120
- Design Weight [kg]: 197.4
- Weight distribution (68kg driver) [front/back]: 50/50
- Aerodynamic Drag: 1.3
- Aerodynamic Lift: -3.3

Team Management

The traditional organization of the eForce Team only included three divisions – Mechanical, Electrical, and Project groups as seen on figure 2.

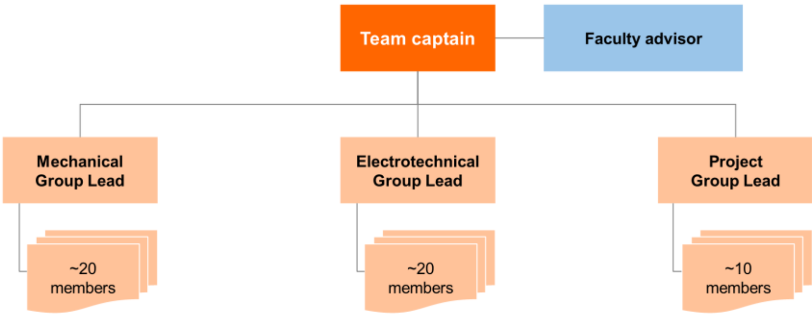


Figure 2: Traditional high-level team organization chart

The new organization structure, as shown on figure 3, adds an additional group/division focusing on autonomous vehicle development, consisting of cca. 10 members.

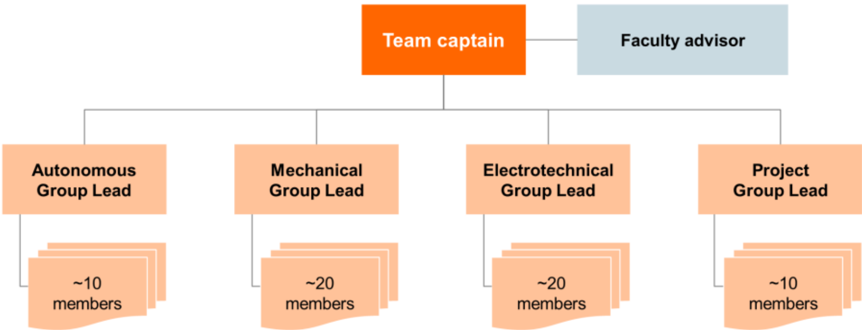


Figure 3: New high-level team organization chart

The project development requires significant amounts of dedicated work. Predicting how much time would each task require is always hard, but a high-level holistic estimation at the beginning of the season was to create an approximately 10 man-unit strong team with a good combination of more experienced students that will carry the technological side of the project while expecting to graduate soon, and some more junior, but dedicated students that will serve as a "second generation", gathering experience during the first season so that they could take over the project as experts at its end.

This goal has mostly been achieved by now, as we have 15 students dedicated to the driverless division at the end of the first season, out of which 5 are more senior students and 2 are eForce electric alumni who serve as mentors.

Since the aim is to create a sustainable autonomous team, knowledge management is one of the most crucial aspects that will ensure the long-term functioning of the team. It shall be done using three pillars: tutorials, mentoring and shared data storage, as seen on figure 4.

Figure 4: Know-how management plan

Monocoque and ergonomics

FSE.07 has a complete monocoque carbon fiber chassis and a Rohacell 71WF foam core sandwich. The monocoque was made by prepreg technology in a cleanroom.

The last year's monocoque had two weaknesses. It had insufficient torsional stiffness that caused a lazy response of the car. The second one was a nonergonomic position of the steering wheel. The driver's exhaustion was at that time a serious concern as many potential drivers did not fit into seat due to this limitation. Redesign of the upper part of the monocoque removed these two deficiencies.

Ergonomic measurements have been made and the steering wheel was moved up by 51 mm and rotated to point its rotational axis to the driver's shoulders. This position is more comfortable for the driver due to the significant additional clearance between the steering wheel and his thighs, therefore causing less fatigue.

The sidewalls of the cockpit were changed to have a more convex form and were also extended. Rohacell core was used inside sidewalls to increase the torsional stiffness. Front bulkhead support had to be enlarged as there was a risk of deformation by suspension forces. Using FEM (Finite element method) results in using a 15 mm thicker core than in the previous vehicle.

After FEM analysis, the torsional stiffness of monocoque is calculated to kt = 3205 Nm/°, which is about 977 Nm/° more compared to the last season's vehicle. This year's monocoque with main and front hoops weighs 26.1 kg, but is more suitable for our suspension and driver needs, therefore better for lap time performance of the car.

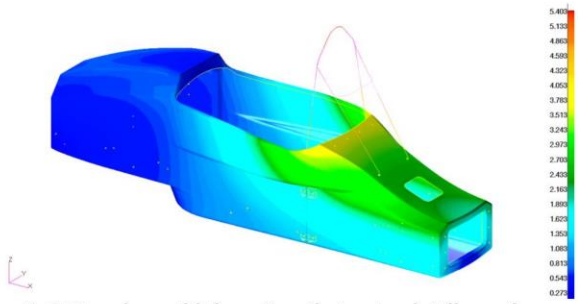


Figure 5: FEM analyses of deformation, the torsional stiffness of monocoque

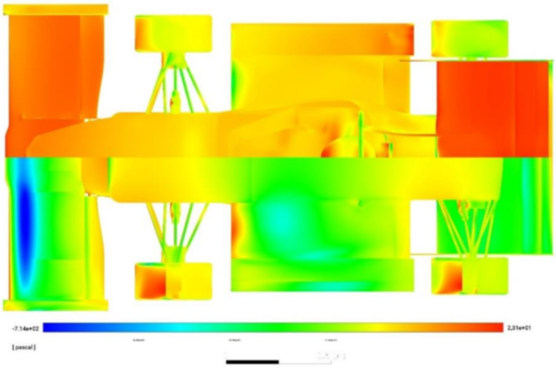


Figure 6: Contours of static pressure, lower and upper surface

Aerodynamics and cooling

FSE.07 aerodynamic devices consist of the front wing, splitter, side wings, and rear wing. The primary goal of this season in aerodynamic devices development was to shift the aerodynamic load on front/rear wheel axes to reach a 50/50 distribution compared to the previous 58/42 to improve stability and vehicle handling. Optimization of the number of elements in the aerodynamic devices was also considered to decrease its mass and to make assembly more precise. The secondary goal was to increase downforce and improve lift to drag ratio.

ANSYS Fluent was used for aerodynamic devices development. An SST k-omega turbulence model was used with an appropriate mesh that meets required y+ value. Mesh and boundary condition dependency on results were also examined. CFD simulations were verified on the 2017 car using suspension displacement measurements on the coast down testing. The concept of aerodynamic devices was verified using lap time simulations (MATLAB, IPG Carmaker).

The focus was not only on the increase of rigidity but also on the improvement of its aerodynamic properties. The new front wing has a less aerodynamic influence on the rear wing. The number of elements of the front wing was reduced from 11 to 7 in addition to improving its downforce and decreasing its drag. Performed FEM simulations confirmed allowed deflection stated in the FSAE rules.

The built-in cooling of the side wings was also improved by optimizing the internal duct, its inlet, and outlet position. Settings were verified in a wind tunnel. We were able to achieve a 50 % increase in the mass flow through the heat exchanger.

Due to a new front wing and other aerodynamic device improvements, an aerodynamic balance was improved to the targeted values. The downforce coefficient was improved by 17 %, the lift to drag ratio by 8 %, while the number of manufactured components was decreased by 30 %.

Vehicle dynamics

The FSE.07 vehicle has motors powerful enough to easily spin the wheels and lose traction. A driver can't distribute the exact torque needed for each wheel to ensure that all four are gripping. Therefore, a slip ratio controller was implemented to improve accelerations and drivability. The redistribution of motor torques leads to a yaw torque that manipulates the yaw rate and can be used as another lateral control input called torque vectoring. To further increase vehicle performance, above-standard suspension with a custom feedforward + feedback torque vectoring design was introduced.

Custom made model-based design ECU was developed and called Vehicle Dynamics Control Unit (VDCU). The software is programmed using MATLAB/Simulink and generated as code in the C programming language.

Powertrain

The concept of four-wheel drive was left unchanged as it was proven successful and driver aids can be utilized for maximum performance. Drive simulations and tests were performed to understand the powertrain envelope and find the goals for FSE.07. The aim was to decrease powertrain weight while maintaining continual power output. This was fulfilled by newly developed custom motors by our partner TG Drives, by cooling system redesign and higher transmission ratio. Powertrain peak power is 88kW.

Wheel assembly

Rear-drive

For the rear-drive, water-cooled high-speed motors are used with a maximum velocity of 10000 [rpm], maximum power 35,32 kW and maximum torque is 48Nm. Each motor weighs 8 kg. Each gearbox weighs 1,77 kg with a gear ratio of 6.71. The design was conducted in KISSsoft and the gears were simulated in Patran/Nastran.

Front-drive

For the front-drive, we used high-speed motors, cooled by water, with a maximum velocity of 9000 [rpm] and maximum power output of 8,76 kW and maximum torque is 16,2Nm. Each motor weighs 3,5 kg. The front-drive motors are integrated into the wheel hubs. Our planetary gearboxes are utilized to transfer torque directly to the wheels and are integrated into the front upright. The front gearbox has a gear ratio of 6.95.

Accumulator

In previous years, the battery pack was designed around installation dimensions and to minimize its weight. These requirements resulted in a strictly limited output power of battery pack and smaller capacity, which led to the need to significantly limit the power output in the endurance event. With the new design of the FSE.07 battery pack, the aim was to reduce the losses.

The casing is made of a composite sandwich using para-aramid fiber material due to electrical insulation. The battery pack is built using eight separate battery stacks connected in series. Cells in stacks are connected 12s8p so the maximum tractive voltage is 408V. Energy storage is 7,1kWh with a maximum power of 98kW and total weight 48kg.

First of all, research of the battery cell was carried out. The Sony VTC5 18650, which we used, were surpassed only by Sony VTC5a 18650. According to datasheets, VTC5a manages a higher current load (35A versus 30A) and has a lower internal resistance (7-15mOhm versus 8-18mOhm) at the same capacity and weights only 2g more. It was found from measurements that VTC5a cells had a lower internal resistance of 10mOhm (VTC5 13mOhm), but also showed a lower capacity (VTC5a-2360mAh vs. VTC5-2450mAh).

The configuration of 9P instead of 8P increased overall capacity to 8,1kWh. By changing the battery cell type from VTC5 to VTC5a and increasing parallel-group cells, losses declined by 30% under the same conditions. The battery pack's weight gain is 21% (7kg), but we've been able to counterattack this gain by reducing the weight of other vehicle components. The power limit could increase from 50kW to 60kW and therefore power-to-weight ratio proportionally increases from 0.25kW/kg to 0.3kW/kg.

Motor controllers

We are using Lenze DCU60/60 motor controller. Each one is a dual motor controller.

The motor controller is suitable to control two motors independently with shaft position feedback. The control method is Field Oriented Control – with Maximum Torque per Amper implementation. Motor controller power modules are water-cooled. Unfortunately, the motor controller has not implemented discharge, so we developed our own that is compliant with FSG rules.

Electronics and Signal Processing

All control units, except for motor controllers and main computation units used for autonomous driving, are self-developed. The development process is composed of several phases. The design of a new control unit begins with defining the function the new component is required to perform. Afterwards, a scheme is drawn according to these specifications. At this point in the design process, the control unit being developed must be scrutinized by a senior team member. If the review is passed successfully it is possible to advance to the PCB layout stage. Finally, the last check by a senior team member is necessary before the control unit may be manufactured.

Every sensor present in the car is equipped with a hardware anti-aliasing filter to increase the accuracy and reliability of the obtained data.

All data received by Nvidia Jetson Xavier is stored on its SSD. Firstly, this allows for debugging and replication of error-causing situations in a controlled environment, and secondly, CAN data can be used for MATLAB/Simulink applications. Finally, the collected data is naturally utilized to refine the performance of the neural network and autonomous model algorithms.

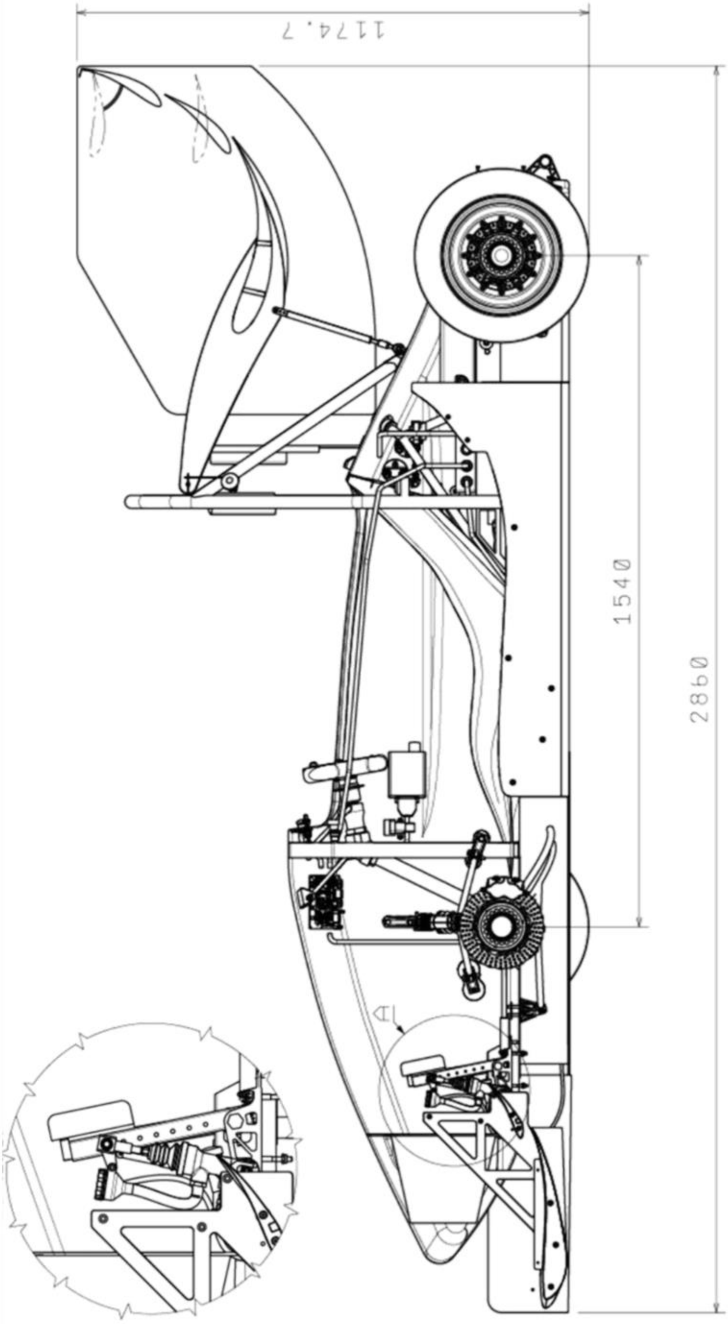
Dashboard

The main goal of a new dashboard design was to develop simple, clear and intelligible driver's interface. The dominant part of the dashboard is a bi-color LED bar graph, which shows the charge level of the battery pack. The dashboard also contains a few functional indicators and switches. Thanks to the illumination sensor it is able to regulate LED brightness by PWM. On the dashboard's PCB a 3D printed reflector is attached that directs the light emitted by LEDs followed by layers of foils which disperse the light and define the final shape of indicators.

Summary

This season's goals were to make the vehicle more agile, predictable and stable especially for the skidpad event. For the acceleration event, a slip ratio controller with launch control was developed to secure optimal wheel slips. Drivers for skidpad and acceleration are commonly less experienced and this system allows them to learn the formula handling quicker. These requirements pushed us towards extending the linear region of steering wheel sensitivity and to increase the maximum lateral acceleration. Transient behavior and a feed forward loop is used using steering wheel speed input to help to damp the yaw rate response. All these changes have made this year's vehicle better performing, while improving the handling attributes at the same time.

eForce Driverless (66), Engineering Design Report, FS Online 2020



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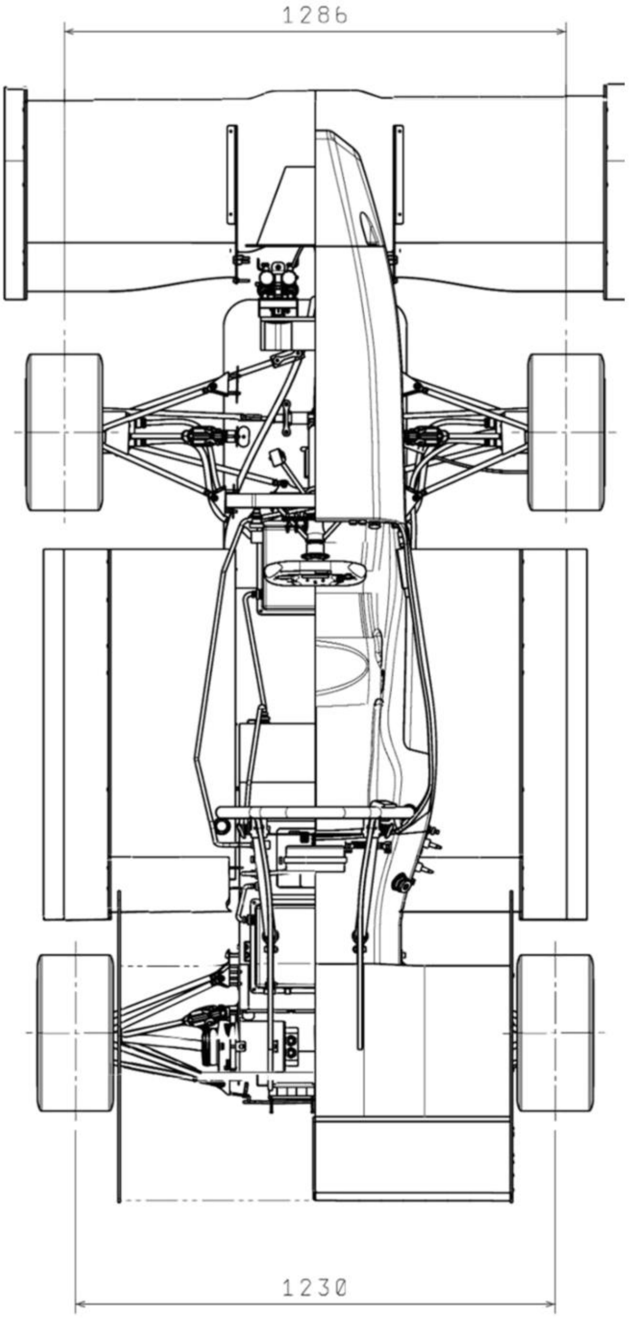
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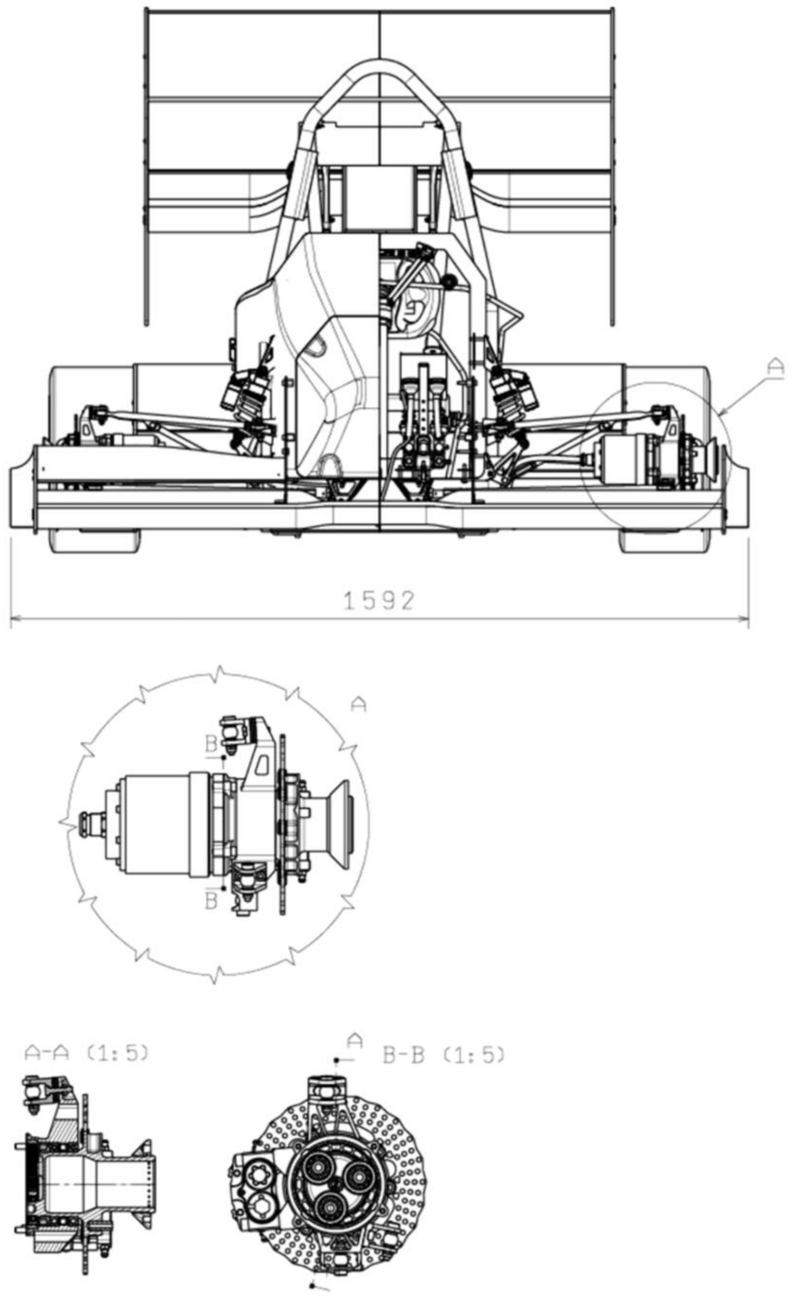
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Appendix [G] – Design Spec Sheet eForce Driverless 2020

Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Dimensions	Front	Rear
Overall Length [mm]	2860	
Overall Width [mm]	1592	
Overall Height [mm]	1174	
Wheelbase [mm]	1540	
Track [mm]	1286	1230
Weight without driver [kg]	133	133

Suspension Parameters	Front	Rear
Suspension type	Short - Long Arm, pull rod leads from upper arm	Short - Long Arm, pull rod leads from upper arm
Design ride height (chassis to ground) [mm]	30	30
Center of gravity design height [mm]	250	
Suspension design travel - jounce [mm]	30	30
Suspension design travel - rebound [mm]	25	25
Wheel rate (chassis to wheel center) [N/mm]	28	34
Roll rate (chassis to wheel center) [degrees/g]	428	
Jounce damping (chassis to wheel center) [Ns/mm]	58	58
Rebound damping (chassis to wheel center) [Ns/mm]	50	50
Sprung mass (without driver) natural frequency [Hz]	3.1	3.4
Motion type	Progressive	Progressive
Motion ratio (spring travel/wheel center travel) [mm/mm]	1,05-1,2:1	1,05-1,2:1
Camber coefficient in bump [deg/mm]	33	34
Camber coefficient in roll [deg/deg]	0.635	0.64
Static toe [degrees]	-0.2	0.2
Static toe adjustment method	Via adjustment bolt on steering rod	Via adjustment bolt on steering rod
Static camber [degrees]	1.2	1
Static camber adjustment method	Via shim plates inserted between upright and upper arm	Via shim plates inserted between upright and upper arm
Front caster angle [degrees]	4.71	
Front caster angle adjustment method	Adjustable end rod length	
Front kingpin inclination [degrees]	4.4	
Front kingpin inclination adjustment method	Adjustable end rod length	

Design Spec Sheet - DV-E category

page 1 / 7

Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Kingpin offset [mm]	26	
Kingpin trail [mm]	11	
Static ackermann [%]	15	
Static ackermann adjustment method	Via adjustment bolt on steering rod	
Anti dive / Anti lift [%]	20.1	18.6
Roll center position static (above ground) [mm]	27.3	31.7
Roll center position at 1g lateral acceleration [mm]	14.4	12.6
Other significant suspension parts		

Tyres and Wheels	Front	Rear
Wheels	10" dia., 7" width, ET30, Al rim from Keiser	10" dia., 7" width, ET30, Al rim from Keiser
Tyres - dry, make	Avon Tyres	
Tyres - dry, size	7.0/16.0-10	7.0/16.0-10
Tyres - dry, compound	A92	
Tyres - rain, make	Avon Tyres	
Tyres - rain, size	7.0/16.0-10	7.0/16.0-10
Tyres - rain, compound	A92	

Steering system	Front	Rear
Steering location	Before the front axle	
Steering ratio (steering wheel / outer wheel) [deg/deg]	5.9	
Steering arm length [mm]	56	

Brake System / Hub & Axle	Front	Rear
Rotors (incl. outer and inner diameter [mm] of friction surface)	Diameter 195mm, thickness 4mm, floating	Diameter 185mm, thickness 3,5mm, floating
Master cylinders (incl. diameters [mm])	Custom design, dia 16,8mm front brakes, dia 15mm rear brakes	
Calipers (incl. diameters [mm])	ISR 22-048-OB, EN AW 7075-T6, piston dia. 4x25mm	ISR 22-049-OC,EN AW 7075-T6, piston dia. 2x25mm
Hub bearings	2 angular ball bearings, ID 60, OD 85, O mounting	2 angular ball bearings, ID 70, OD 100, O mounting

Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Upright assembly	Al machined upright, Al machined hub	Al machined upright, Al machined hub
Axle type, size, and material	2 wishbones, tube 14x1mm; 25CrMo4 steel welded	2 wishbones, tube 14x1mm; 25CrMo4 steel welded
ABS	None	

Ergonomics	
Driver size Adjustments	Multiple size seat with padding option, longer head restraint (for tall and short drivers)
Seat (materials, padding)	Carbon and kevlar fibre sandwich seat, changable foam padding
Driver visibility (angle of side view, mirrors?)	100°to either side, no mirrors
Shift actuator (type, location)	None
Clutch actuator (type, location)	None
Instrumentation	3" screen in steering wheel, LEDs for warnings and errors, lighted buttons and switches

Frame	
Frame construction	Composite monocoque with TIG welded main hoop and front hoop
Material	CFRP - prepreg, Rohacell foam core, special plywood inserts, 4130 steel (25CrMo4 steel),ertalon 66-GF30
Joining method and material	Steel round tubes 28x1,5, 30x2, aluminium square tubes 35x2, laminated in mould as a whole
Targets (Torsional stiffness or other)	3000
Torsional stiffness [Nm/deg]	3205
Torsional stiffness validation method	None
Bare frame weight with brackets and paint [kg]	26
Crush zone material	Dyvinicell H80, CF tube, Al iniciator
Crush zone length [mm]	202
Crush zone energy capacity [Joules]	8154
Additional safety features	-

Tractive System	**Front**	**Rear**
Motors Manufacturer / Model	TG-Drives, TGM4-0470	TG-Drives, TGN5-1600
No. of motors	2	2
Motor Driven Wheels	Mounted on upright, each independently driven	In frame, each independently driven
Type of motors	PMSM	PMSM

Design Spec Sheet - DV-E category page 3 / 7

Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Max RPM [1/min]	9000	10000
Max Torque [Nm]	16.2	48
Max Torque until RPM [1/min]	4870	7170
Max power [kW]	2x8,76	2x35,32
Significant motor modifications	Custom cooling system	Custom cooling system
Type of motor controller(s)	Lenze schmidhauser DCU 60/60	Lenze schmidhauser DCU 60/60
Motor Speed Sensors	Resolver in the end of the shaft of motor	Resolver in the end of the shaft of motor and magnetic senzor after the drive-axis
Nominal Motor Voltage	280VAC	260VAC
Coolant System and Radiator location	Radiators located in sidepods	
Accumulator Cell Manufacturer and Type	Li-Ion, Sony, US18650VTC5a	
Nominal Cell Voltage [V]	3.7	
Nominal Cell Capacity mAh	2600	
Accumulator Cell Technology	NCA	
Accumulator Cell Configuration	96s9p	
Accumulator Voltage when fully charged [V]	408	
Combined Accumulator Capacity [kWh]	8.08	

Drivetrain	
Drive type	Two planetary gearboxes on rear axle, two planetary gears in front uprights
Differential type	Electronical
Final drive ratio	6,95 front; 6,71 rear
1st gear [km/h]	None
2nd gear [km/h]	None
3rd gear [km/h]	None
4th gear [km/h]	None
5th gear [km/h]	None
6th gear [km/h]	None
Half shaft size and material	Outer diameter 20mm, inner diameter 16mm, material 42CrMo4
Joint type	Tripod joint

Electronics	
Driver aids	Yaw controller (feedforward + feedback) utilizing torque vectoring, Slip ratio controller

Design Spec Sheet - DV-E category page 4 / 7

Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Data logging	Vector GL1010, CANoe for bus analyses. Self developed GUI and scripts for drive data analyses in MATLAB
Telemetry system	Online telemetry with video feed
electric auxilliaries (fan, waterpump)	2x water pump for cooling circuit with 2x fan located in sidepods. 3x Brushless DC high power fan for accumulator cooling.
CAN bus	500kbps + 1000kbps CAN buses with shielded cable
Battery	6s1p Li-Ion, Sony, US18650VTC5
Control System Voltage [V]	24 V
Other significant electronic parts	Steering wheel with large display and touchscreen for vehicle parametrization and diagnostics. Dashboard with optimized positions of

Driverless	
Bus System(s)	CAN, Ethernet
Kind of brake actuator	Emergency brake system - Pneumatic actuator (FESTO - DSNU-40), Service break - 3x SAVOX SB-2230SG
Kind of steering actuator	Power steering kit - KARTEK 220W motor
Processing unit(s)	Nvidia Jetson AGX Xavier
Floating Point Operations Per Second of all processing units that are working for the DV system [GigaFLOPS]	1,410 GFLOPS
Power consumption of all processing units that are working for the DV system [W]	60 W at peak
Weight of the DV system [kg] (including all sensors, actuators, wiring, processing units, etc.)	12.6
Highlights of the DV system	Combining LiDar and camera data to get better mesurments of diastance.
Programming languages / frameworks / special libs that are used for the DV system	C,C++, Python / ROS2 dashing / our own libraries for Lidar, Stereolabs Zed
Camera(s)	Stereolabs Zed, Intel Realsense Depth Camera D435i (2x)
Radar sensor(s)	None
Lidar sensor(s)	Ouster OS1-64

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Other sensors	None

Aerodynamics (if applicable)	Front	Rear
Wing (lift/drag coef., material, weight)	Cl/Cd = 8.8; 253 N downforce at 16 m/s, i. e. 35.4 % of total downforce; 5 parts; about 3,3 kg; Airex core for main profile (FEM optimized)	Cl/Cd = 1.8; 237 N downforce at 16 m/s; i. e. 33.1% of total downforce; 5 parts; about 3.6 kg
Undertray (downforce/speed)	Monocoque flat floor, splitter, side wings, vortex generators. These devices provide 249 N downforce at 16 m/s, i. e. 35% of total downforce.	
Wing mounting	Front wing mounted with composite holders, AOA adjustability; rear wing mounted with composite elements to mainhoop, flaps AOA adjustable.; side wings: Screwed to side impact.	

Design Top5	
Top 1	Battery pack
Top 1 Comment	By changing the cell from VTC5 to VTC5a and increasing parallel group cells, losses declined by 30% under the same conditions.
Top 2	CFRP Monocoque
Top 2 Comment	FEM analyses proved, the torsional stiffness of monocoque is calculated to kt= 3205 Nm/°. It is about 977 Nm/° more than the last season.
Top 3	Aerodynamics
Top 3 Comment	Due to a new front wing and other aerodynamic device improvements, an aerodynamic balance was varied to the required values 50/50. The downforce coefficient was improved by 17 % and the lift to drag ratio by 8 %.
Top 4 (optional)	Data telemetry
Top 4 Comment	Wireless bridge with 1Mb bandwidth do transfer data from CAN bus. The telemetry on the base station transfer data back to CAN bus. We are then using for CAN analysis self developed CAN-to-USB converter with self-developed data analysis program.
Top 5 (optional)	Simultaneous Localization and Mapping
Top 5 Comment	Already in our first season we managed to implement SLAM, specifically a FastSLAM algorithm. This fast and reliable soution can opearate in real-time with a high degree of accuracy to detect the track layout and the vehicle's position in it.

Optional Information	
Body work?	
Special bit A?	

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Car Number: 66

University: CTU in Prague

FORMULA STUDENT ONLINE

Special bit B?	

Design Spec Sheet - DV-E category

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Appendix [H] – Concept Design Challenge Report eForce Driverless 2020

Concept Design challenge Report

EForce driverless 2020

eForce FEE Prague Formula Driverless
Czech Technical University in Prague
Car number: 66

Bc. Marek Szeles
tel.: +420 721 264 273
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Introduction

One of the biggest challenges in the development of electric vehicles is energy storage because it is the main factor which limits range and performance of an electric vehicle.

Our current situation

Currently we use in our vehicle a battery pack composed of Li-ion Sony VTC5A cell with overall capacity 8.2 kWh. The battery pack is designed for maximal voltage 403V and monitored with BMS units. Limitations in our design are cooling system efficiency, size and weight of battery pack which limit performance of our vehicle. Furthermore, the charging of our battery pack is a time-consuming procedure and energy recuperation is not possible with the current accumulator pack and motor combination.

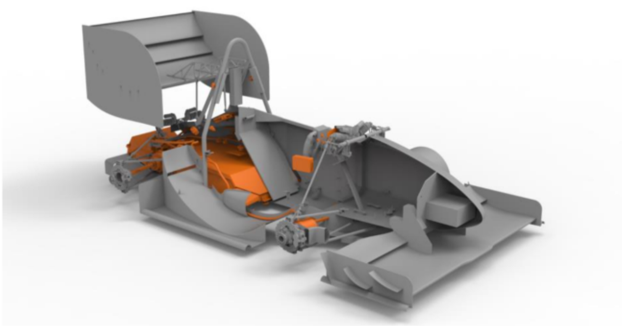


Figure 1. eForce DV01 battery concept

Energy storage concepts

Nowadays, the most used energy storage concept in electric vehicles is a battery pack composed of battery cells. These cells are typically Lithium-ion batteries and they are designed for high discharge current. This concept brings several limitations. Firstly, energy density of Li-ion cells is around 200Wh/kg, which makes battery packs heavy. Charging and discharging of Li-ion cells produces heat and this attribute affects maximal current available for powertrain system and overall dynamics of vehicle. Heat management is one of the Li-ion battery pack's biggest challenges. In the recent battery pack efficiency study, it was confirmed that battery packs with active heat management have better performance and capacity degradation is much slower in comparison with passive cooled battery packs.

Solid-state batteries are a promising technology that uses solid electrodes and a solid electrolyte. In this moment, they are in development process which affects their overall capacity and cost negatively. Expected power density of solid-state batteries is around 500 Wh/kg in the next 5 years with much better heat management and safety in comparison with traditional Li-ion batteries.

Maximal current limitation problem could be solved by double-battery concept which combines standard high capacity Li-ion battery packs and ultracapacitors for short-term high peak current demand. Advantage of this concept is possible high efficiency energy recuperation because ultracapacitors also provide high current charging.

One of the promising technologies are hydrogen fuel cells. This concept combines fuel cells for electricity production and a small capacity batter pack to power electric motors. Main advantage of this concept is its high energy density. Fuel cell energy density with included weight of all required components (e.g. fuel tank, fuel cell, pipes) is around 500 Wh/kg.

Implementation of concepts

Optimized Li-ion battery pack

The first possible energy storage option is continuous development of our recent battery pack with the latest models of battery cells and other components. Li-ion battery cells are continuously under development and their performance is increasing.

Design – battery pack based on our current solution with implementation of the latest technology. Using the latest and most powerful battery cell with higher energy density, thus decreasing weight and volume of a battery pack. Actual battery segment is composed in 96s9p formation. This formation could be optimized according to new battery cell characteristics. Evolution of BMS and control units for better efficiency. Development of new battery cooling system for heat management of battery pack with possible active cooling system. Effective cooling system increasing overall performance of the car and increasing amount of possible recuperated energy from breaking.

Vehicle concept – This concept fits our vehicle and changes in chassis and suspension are minimal. Changes will be required in monocoque and aerodynamic components according to required air flow for battery cooling system.

Rules – This concept is compatible with actual Formula Student rules.

Development resources – This concept will require a specialist in battery packs, battery management system, CFD specialist for battery cooling systems.

Cost – Actual cost of 8.2 kWh battery pack is around $13 000 with our own electronics and package included.

Performance – Overall performance is limited in high current demand situation, for example during acceleration.

Risks – Development risk of this concept is limited due to our long-time experience in battery packs development.

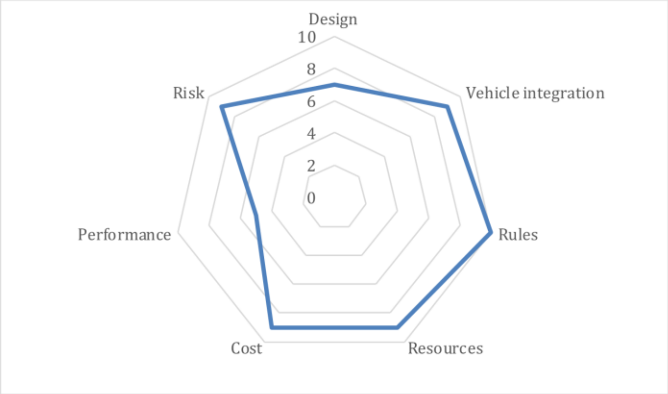


Figure 2. Optimized Li-ion battery pack score (Higher is better)

Solid-state battery pack

Solid-state batteries are a promising concept which is turning into reality and after a few years, commercial solid-state batteries should be available.

Design – Battery pack composed of solid-state battery cells with similar architecture to our current solution.

Vehicle concept – This concept can be implemented in our vehicle without effect on the overall vehicle concept. Furthermore, high power density of solid-state batteries reduces overall size and weight of the battery pack and their placement can be optimized for the perfect balance of our vehicle. For the effective heat management of battery pack, changes will be required in monocoque and aerodynamic components according to the required air flow for battery cooling system.

Rules – This concept seems to be compatible with actual Formula Student rules.

Development resources – This concept will require a specialist in battery packs with knowledge of solid-state batteries, battery management system specialist, CFD specialist for battery cooling systems.

Cost – In this moment, cost of solid-state batteries makes them unusable. Predicted price level is similar to predicted Li-ion price level in 2025.

Performance – We can increase our performance with this type of battery due to predicted higher battery cell discharge current and better heat characteristics.

Risks – Development risk of this concept is high. Solid-state batteries are still under development and they are not available for automotive industry yet. Possible delay in solid-state battery development and delay of mass-market introduction could delay our whole design and development.

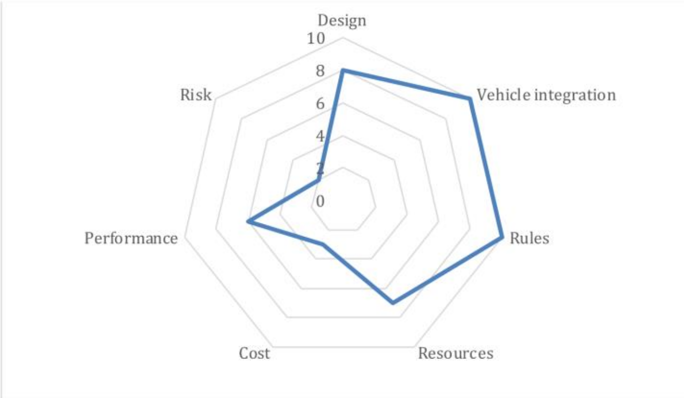


Figure 3. Solid-state battery pack score (Higher is better)

Dual battery concept

Ultracapacitors can be used in our concept for the compensation of high-peak current demand due to their ability of high-peak discharge current.

Design – Standard high capacity Li-ion battery pack with higher described design. Second small capacity battery composed of ultracapacitors for high-peak discharge current compensation. Capacity should be designed for maximal current demand for few seconds during vehicle acceleration. For this concept a new control unit must be developed for energy distribution between these batteries and new BMS units will be required.

Vehicle concept – This battery concept is challenging for our overall vehicle concept because new components with significant weight and size are added. According to the rules ultracapacitor battery must be protected with firewall. In our concept this means another load to the rear suspension. Added battery requires higher air flow for cooling system and heat management of new battery. This requires changes in monocoque and aerodynamic components according to required air flow.

Rules – According to the rules it seems that this concept is compatible. Ultracapacitors battery must fulfill tractive system energy storage rules which means battery must be placed in fire retardant accumulator container constructed of steel or aluminum.

Development resources – This concept requires higher personal resources. Each battery requires a specialist in battery packs and a battery management system specialist. Further resources will be required in control and optimization of energy distribution between these batteries. CFD and aerodynamics specialist will be required for battery cooling system too.

Cost – Dual battery concept requires higher investment due to the combination of two battery types. The cost of ultracapacitors is up to $6000 per 1 kWh. Further investment will be required because of difficult energy distribution control modules.

Performance – This concept seems to be the best option for our powertrain performance because it could be possible to use maximal power output of our motors.

Risks – High risk of this concept is control and optimization of energy distribution between batteries. Insufficient energy distribution could decrease final vehicle performance.

Figure 4. Dual battery concept score (Higher is better)

Hydrogen fuel cells

Design – Hydrogen fuel vehicle consist of fuel cells, hydrogen fuel tank, pressure system and compensation battery pack. Supercapacitor solution seems to be the best solution.

Vehicle concept – This energy storage radically affects the current vehicle concept and the whole car should be redesigned for efficient placement of hydrogen fuel tank and fuel cells.

Rules – Fuel cells are prohibited in recent Formula Student rules.

Development resources – Development resources would be enormous because our team lacks experience with this concept.

Cost – Cost is higher than currently used Li-ion battery pack. Additional investment will be required for fuel cell development and integration equipment.

Performance – Performance is comparable with current Li-ion battery pack solution.

Risks – Hydrogen is a highly flammable fuel and possible leak could be dangerous.

Figure 5. Fuel cell concept score (Higher is better)

Summary

According to the described concepts, as seen on Figure 6., the most suitable concept is continuous development of our Li-ion battery pack, followed by solid-state battery concept. Thanks to similarity of these concepts, it is possible to upgrade Li-ion cell to solid-state cells. This approach minimalizes possible delay caused by development of solid-state batteries and after the mass-market introduction of solid-state battery cells, we can take advantage of a lighter and more powerful technology. Overall car performance and range could increase thanks to lighter battery pack with higher energy density.

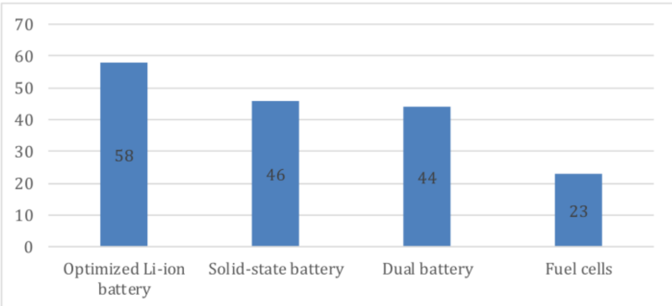


Figure 6. Overall score comparison

Appendix [I] - Business Plan Executive Summary eForce Driverless 2020

Team identification: eForce Driverless, 66

eForce Driverless Business Plan Executive Summary

In 2020 the World was shaken by the Covid-19 pandemic. During this trying time, it became clear that traveling together in trains, buses and cars can be very dangerous. The fear of traveling is at an all-time high, but alas, we cannot stay locked down forever as traveling is essential.

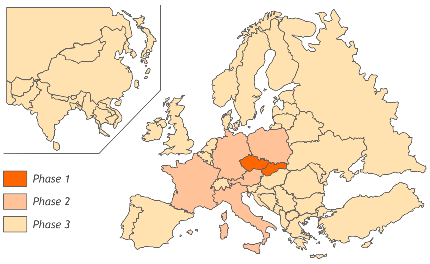
Our main goal is to enable people to travel without fear once again by providing a safe alternative to conventional means of traveling. By altering our racing formulas for the railways, we create a new on-demand travel option where passengers can safely travel in high-tech carriages, each consisting of 8 isolated compartments.

Business strategy

The first step is the installation of our network in the Czech Republic and Slovakia. We'll start with 3 regions – Prague, Brno and Bratislava – each operated by 5 vehicles.

Phase two expansion will follow a year after establishing the network domestically. As we'll branch into other European countries, we'll provide our vehicles as well as know-how on operating the network. Our target for the end of this phase is to have 100 operating vehicles in 7 countries.

Phase three will begin in a five-year horizon after executing phase two. We'll expand to the rest of the world with a focus on Asian markets.



Target segments

People who travel to cities on a daily basis often encounter various commuting problems. Let's take a look at two of our typical customers and how our service would improve their life.

Paul is a businessman. He lives in the suburbs and drives to work every day. Unfortunately, he can't avoid rush hour traffic, which means he must get up early, he spends a lot of extra petrol a day and gets irritated even before his workday begins. Instead Paul could save money and some nerve as well as reduce his carbon footprint by ordering our ride.

Marie is a student and lives with her parents in the countryside. She goes to school by train. She has a choice: either wake up at 5AM and come to school well in advance or comfortably wake up at 6:30AM but arrive at school 10 minutes after the bell rings. With our service Marie could sleep in and get to school on time without spending more than she can afford.

Market Positioning

Even with a margin of 28% eForce is still cheaper than other means of transport while offering more comfort and better performance with a focus on safety. According to our forecasts, eForce will be able to replace conventional trains in European Union in less than 10 years.

Investment case

We'll need an investment of 3 000 000 € which will cover the three main costs in the first three years. Those are manufacturing expenses (68%), manpower (25%) and marketing expenses (7%). For that we are proposing a 39% share in the company.

In the base case financial forecast, we expect to reach 1.8M € already in the 2nd year of operation and over 10M € by the 7th year. Based on our sensitivity analysis, this revenue allows the investor to break even within 3-5 years and provide them with a Net Present Value between 2.9 and 12.7M € in a 7-year investment horizon.