Racing for Sustainability: Mitigating the Adverse Impact of the Formula 1 Race Schedule

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Executive Summary

Formula 1, the pinnacle of motorsport, has long been celebrated for its cutting-edge technology, and global appeal. However, its environmental impact, particularly in terms of carbon emissions from logistics and transportation, has drawn increasing scrutiny. This dissertation undertook the task of estimating the carbon footprint of transport logistics and optimizing the Formula 1 race schedule to minimize its carbon footprint while navigating complex operational and commercial constraints. The research methodology leveraged various data sources, including historical race information, weather data, and carbon emissions calculators, to develop a comprehensive understanding of the factors influencing Formula 1's carbon footprint. It utilized advanced optimization algorithms, including Greedy Algorithms, and Ant Colony Optimization, to generate alternate race calendars that prioritize sustainability. The alternate race calendars consistently demonstrated substantial reductions in both total travel distance and carbon emissions compared to the official 2023 schedule. The Greedy algorithm, tuned to real-world operational criteria, yielded a calendar with a 31.5% reduction in travel distance and a 31.7% lower carbon footprint. The Ant Colony Optimization algorithm produced even more impressive results, with a 47% decrease in travel distance and a 45.6% reduction in carbon emissions. These findings hold profound implications for Formula 1's sustainability goals. By adopting optimized schedules, the sport can achieve a dual benefit: environmental responsibility and operational efficiency. Reduced travel distances align with Formula 1's commitment to becoming Net Zero Carbon by 2030, while improved logistics offer cost-effective advantages.

Introduction

Background

Formula 1, considered to be the pinnacle of motorsport racing, is a series deeply rooted in motorsport history. The establishment of the FIA (Fédération Internationale de l'Automobile) World Championship in 1950, marked the beginning of a prestigious era of high-speed competition and innovation. The inaugural season of Formula 1 comprised of six Grand Prix races, all held in Europe. Over the decades, the series has experienced exponential growth in terms of both its global reach and technological advancements. What started as a European-centric championship has transformed into a truly global spectacle. The 2023 Formula 1 season represents a significant milestone in the sport's history. With a calendar featuring twenty-four Grand Prix races across twenty-one different countries, spanning five continents, it is one of the most extensive and ambitious race schedules in Formula 1 history. This rigorous schedule would have the teams travelling thousands of kilometers between races over a span of nine months.

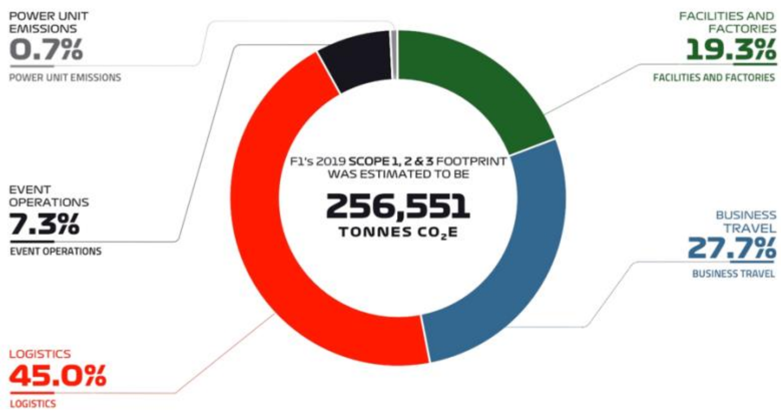
Formula 1, despite its global popularity and prestige, has faced substantial criticism from environmentalists and ecologists over the years. This criticism primarily centres around the significant environmental impact attributed to the sport's operations, which include the carbon emissions from various facets of Formula 1 including the cars themselves, the energy-intensive racing infrastructure, and the extensive transportation involved due to the global race schedule (Allen, 2014; Ornstein, 2007, 2009; Purcell, 2011). As the sport has expanded globally, so too have concerns about its ecological consequences. In response to these concerns, Formula 1 has been exploring ways to improve their sustainability and mitigate its environmental impact.

Rationale For Research

Executing a mega-event such as a Formula 1 Grand Prix involves intricate logistical challenges due to the global nature of the sport, encompassing a wide range of operations including the transportation of teams, equipment, and personnel, as well as the coordination of events in different countries. A dossier on Sustainability Strategy released by Formula 1 (2019) provided insights into the sources of carbon emissions within the sport. A key revelation from the report was that while race events themselves are visually prominent and symbolize Formula 1, they only account for only 10% of the sport's carbon footprint. The majority of emissions were attributed to the logistical aspects of the sport, including equipment transportation (45%) and business travel (27.7%). Formula 1's acknowledgment of the environmental impact associated with logistics highlights the importance of addressing this area to reduce the sport's carbon footprint.

Figure 1

The Sources Of Carbon Dioxide Emissions Within Formula 1



Note. Formula 1 (2019).

With a primary objective of becoming Net Carbon Zero by 2030, Formula 1 is working to implement initiatives and strategies aimed at sustainability, such as exploring more efficient transportation methods and adopting cleaner technologies both in racing and logistical operations (Formula 1, 2019). A key point of focus must be on minimizing the adverse impact of travelling across all Grand Prix locations. Strategically planning the schedule of races can potentially reduce the total distance travelled during the season, minimizing the strain of carbon-intensive aspects such as transportation and travel. Notably, Formula 1 President Stefano Domenicalli and Managing Director Ross Brawn have advocated for grouping regional races together in future calendars in a move towards more efficient logistics, shorter travel distances, and reduced carbon emissions (Barretto, 2022).

Problem Statement And Research Question

As concerns about climate change and carbon emissions intensify, industries, including sports, are under increased pressure to reduce their ecological footprint. The critical requirement for Formula 1 to mitigate its adverse environmental impact by strategically scheduling races and reducing travel distances represents a necessary step toward embracing sustainability within the sport. Shorter travel distances from strategically scheduling races can result in reduced expenses associated with logistics, fuel, and personnel travel, while also streamlining resources for the teams and the organizers. This approach aligns with the sustainability objectives of Formula 1 to foster innovation and efficiency across the other carbon-intensive aspects of the sport, making it more resilient and responsible in an evolving environmental landscape.

Thus, the research question can be framed as: *“How can the Formula 1 race schedule be optimized to reduce the carbon footprint and mitigate the environmental impact?”*.

Objectives

1. Assess the carbon footprint of Formula 1 transport logistics.

2. Develop an optimization model for re-scheduling the Formula 1 calendar to reduce the carbon footprint within operational and commercial constraints.

Scope and Outline Of Research Methods

The scope of this study will involve collecting data from various secondary sources, including race information for all Formula 1 seasons, circuit geolocation information, daily weather data for all circuit locations, regional holiday data for all circuit locations, operational schedule data for all circuit locations, and the estimated carbon emissions generated from freight transport between races. The collected data will then be analysed to assess the carbon footprint of Formula 1 transport logistics to quantify and understand the environmental impact of the race schedule. This will then be followed by the development of an optimization model to reschedule the Formula 1 calendar in a practical approach that reduces the carbon footprint of transport logistics while adhering to operational and commercial constraints. These models will be designed to use computationally intensive mathematical algorithms to find optimal and practical race schedules.

Optimizing the race schedule for the business travel of organizers, drivers, and team personnel will not be within the scope of this dissertation as it involves a complex set of variables, including individual schedules, unique team logistics, and diverse travel requirements. This complexity makes it challenging to develop a comprehensive, practical optimization model without unlimited access to industry insider information, requiring collaboration and coordination with the various stakeholders and organizations involved in Formula 1.

Significance Of The Study

The world is facing pressing environmental challenges, including climate change, biodiversity loss, and resource depletion. These issues demand urgent action across all sectors of society, including sports. Addressing the environmental impact of Formula 1 within the broader context of sustainability and sports is essential for contributing to global sustainability goals, setting an example for other sports federations, and maintaining the relevance and influence of Formula 1 as a global leader of motorsport within a changing world (Dessart & Standaert, 2023). By taking proactive steps to mitigate its environmental impact, Formula 1 can demonstrate significant corporate and social responsibility while future-proofing the sport, ensuring its longevity sustainably.

The dissertation is structured as follows: in the next section the study delves into the literature review, detailing the current state of knowledge in sustainability, logistics, and optimization theory. The methodology section outlines the research design, data collection, and analytical approaches employed. The results and discussion section presents and interprets findings related to Formula 1's carbon footprint, alternative race schedules generated by optimization algorithms, comparisons with official calendars, and their implications for sustainability in sports. Lastly, the conclusion offers a summary of the study's main elements, with actionable insights for Formula 1 and sports event planners.

Literature Review

The Environmental Impact Of Formula 1

In the realm of sustainability and environmental management, the term "carbon footprint" plays a pivotal role. As defined by Wilby et al. (2022), the concept encapsulates a comprehensive understanding of the environmental impact attributed to an entity, whether it be an organization, a product, or an asset. This impact extends beyond mere direct emissions and encompasses the entire spectrum of greenhouse gas emissions, those released directly by the entity and those indirectly associated with its operations. The indirect attribution is a critical facet of the environmental impact assessment, as it considers emissions associated with the energy use throughout the entire supply chain and transportation. In the context of Formula 1, this implies evaluating not only the direct emissions from the race cars but also those arising from background processes such as logistics, travel, and infrastructure.

Wynes (2021) highlights the considerable degree of influence and authority that sporting organisations such as Formula 1 possess when it comes to shaping the travel logistics of their participating teams. This position of control is a vital and pivotal role for instituting change and setting new standards for sustainability across sports. Their study underscores the challenge of decarbonizing travel logistics with scientific advancements alone. While technological innovations have a crucial role to play in reducing emissions, certain sectors, such as aviation, present inherent complexities. Achieving significant decarbonization within air travel logistics requires a multifaceted approach involving logistical and operational changes that go beyond technological solutions.

By taking proactive steps to reduce their air travel emissions, sporting organisations like Formula 1 not only address one of the most visible and intractable emissions sources within their industry but also set a precedent for sustainability. This leadership role has potential to extend beyond the sports industry, and inspiring broader societal changes toward more sustainable practices.

Attitudes Towards Sustainability Initiatives

The landscape of private motorsports organizations has witnessed a notable shift towards heightened environmental consciousness. This transformation is substantiated by a body of research, including studies by Cerezo-Esteve et al. (2022), Dingle (2009), Nielsen et al. (2021), and Orr et al. (2022). Their investigations collectively reveal an industry that is increasingly cognizant of the pressing issues surrounding environmental degradation, and correspondingly, is actively exploring sustainable practices. Amidst this broader context, Formula 1 was found to be an organization facing a compelling imperative to not merely follow suit but to lead by example. These studies emphasize that the rationale for Formula 1 to adopt a sustainable stance and pioneer new strategies for mitigating its adverse environmental impact extends beyond compliance—it hinges on the cultivation of an authentic and forward-looking brand image for the entire motorsports industry.

The possibility of Formula 1 to forge a brand image that resonates with sustainability can elicit a transformative ripple effect. This sentiment is exemplified by studies conducted by McCullough et al. (2020) and McCullough et al. (2022), that underscore the profound interplay between brand image and consumer behaviour. They found that an organization’s authentic commitment to environmental stewardship not only aligns with evolving societal values but also has the capability to inspire positive behavioural shifts among the organization’s vast and passionate fanbase. Dessart and Standaert (2023), further emphasize the reciprocal relationship between an organization's brand image, and the attitudes and the behaviours of its fanbase. The global popularity of Formula 1 represents a formidable force that can be harnessed through an authentic sustainability agenda to drive positive change and fostering societal participation in eco-friendly initiatives. This confluence of factors positions Formula 1 as a powerful catalyst for transformative change in the realm of motorsport sustainability.

Optimizing Race Schedules For Sustainability

The concept of strategic schedule optimization is a key aspect in the studies by Johnson (2015) and Wynes (2021) acknowledging that a sizable portion of the carbon emissions associated with professional sports stems from the travel between competition venues. By minimizing this travel, sports organizations such as Formula 1 can make significant strides in reducing their environmental impact. These studies prescribe the necessity for a deliberate and thoughtful approach to planning and arranging sporting event schedules in a manner that minimizes the need for extensive travel. Considerations during scheduling such as grouping geographically proximate events together can reduce the likelihood of excessive travel between venues. Schedule optimization was found to not be a mere theoretical concept but a practical and actionable step toward sustainability that aligns with the broader objective of reducing carbon emissions within the sports industry. This approach can serve as a tangible and effective strategy for sports organizations such as Formula 1 to actively contribute to environmental conservation.

The Adverse Impact of Long-Distance Travel

The urgency of curbing the adverse effects of extensive long-distance travel finds strong resonance in contemporary literature (Wynes, 2021; Gammelsæter & Loland, 2022). The prevailing sentiment across these works is the imperative need to regionalize related events as a cornerstone of sustainable sports practices. Further studies regarding athlete performance, including those by Huyghe et al. (2018), O'Neill et al. (2017), and Roy & Forest (2018), emphasize the need to identify strategies that minimize long-distance travel to mitigate adverse effects such as travel fatigue, jet lag, drastic time-zone changes, and circadian imbalances, all of which can profoundly affect athletes' well-being and competitive performance. At the intersection of these concerns lies a delicate balance between sustainability imperatives and athlete welfare, that entails not only minimizing environmental harm through regionalization but also safeguarding the physical and mental well-being of the drivers and team personnel, ensuring they perform at their best while reducing the detrimental impacts of extensive travel. Regionalization of the race schedule leading to the reduction of long-distance travel emerges as a pivotal aspect of this approach, aligning with Formula 1's quest to reduce its carbon footprint while enhancing the overall experience for the drivers, teams, and fans.

The Role of Weather in Sports Scheduling

In contemporary times, the spectre of climate change has been found to cast a growing shadow over the world of sports. Orr et al. (2022) highlight the growing prevalence of disruptive events linked to climate change. Although the study underscores that deeply entrenched nature of established schedules often holding an unassailable position within the realm of sports, making them resistant to change or challenge, these disruptions, fuelled by the changing climate, are emerging as potent drivers for challenging sport organisations towards rethinking the way their schedules are devised and managed. The intersection of climate change and sports scheduling is beginning to reshape the landscape of sports organization practices. Orr (2021) offers a more forward-looking perspective, suggesting that rescheduling sports events can serve as a potent tool not only for mitigating the effects of climate change, such as reducing the carbon footprint associated with sports logistics, but also for adapting to unexpected climate hazards. This adaptation involves the strategic scheduling of competitions during more climate-sure times, thereby minimizing the risk of encountering adverse climate conditions that can disrupt sporting events and jeopardize safety.

Assessing The Carbon Footprints Of Sport Schedules

In a paper authored by Cooper and McCullough (2021), an innovative linear model was presented, offering a pragmatic methodology for calculating carbon footprints using readily available data. A key aspect of this model was its ability to transform complex, meandering travel routes into a simplified, Euclidean distance-based representation. This simplification, while not providing pinpoint precision, proved to be a valuable starting point for quantifying greenhouse gas (GHG) emissions related to the schedule of sporting events. A noteworthy feature of this model was its accessibility and conceptual elegance. By employing Euclidean distance, the authors effectively translated intricate travel paths into a format for simple yet efficient analysis. This conceptual model provides the foundation for an initial method of sustainability analysis, serving as a springboard for deeper investigations into carbon emissions if necessary. Cooper and McCullough acknowledged that, while precision is a commendable goal, obtaining market-specific input data of absolute accuracy may be challenging.

Nevertheless, they argued that even with rough estimates, the analysis could still illuminate a comprehensive picture of an event's emissions profile. This pragmatic perspective underscores the importance of practicality in sustainability assessments, emphasizing the value of starting with available data and refining models as more precise information becomes accessible. The authors further encouraged researchers within the realm of sport ecology not to view the absence of laser-focused input data as a limitation. Instead, they highlight the incremental progress achievable through accessible data and iterative refinements, fostering a dynamic and continuously improving approach to sustainability analysis in sports.

Adoption Of Optimization Models For Sport Sustainability

Recent years have been marked by significant strides in the utilization of mathematical and computational techniques in the strategic orchestration of sports competitions (Durán, 2021). This evolving trend underscores the growing recognition of the role that data-driven and algorithmic approaches play in enhancing the organization and efficiency of sporting events. Optimizing sports event schedules is a multifaceted challenge that requires a versatile toolkit of computational methods. From traditional mathematical approaches to adopting modern metaheuristic techniques, the field of sports scheduling is continuously evolving to preserve the delicate balance between logistical optimization and equitable treatment of all stakeholders, while resolving the prevalent intricacy of optimization problem.

Kendall et al. (2010) observed that most successful outcomes within both academia and industry practice, arise from an amalgamation of various methods often combining elements of integer programming, constraint programming, and metaheuristics. They found that this multifaceted approach leverages the strengths of individual techniques, leading to sport schedules that excel both in terms of logistical efficiency and fairness considerations.

Working towards a practical application of this approach, Johnson (2015) embarked on an ambitious endeavour to gauge the potential reduction in the carbon footprint of Major League Baseball (MLB) by optimizing the travel logistics of a single MLB team. The central objective of their research was to ascertain the extent to which carbon dioxide emissions could be curtailed by reconfiguring travel schedules through the implementation of a Travelling Salesman Problem (TSP)-type optimization model, serving as the computational engine to chart the most environmentally efficient paths for travel. An insightful facet of their study was the recognition that gathering insights into scheduling preferences and operational requirements was instrumental in constructing schedules that would garner acceptance among stakeholders. The results of their research highlighted the need for sporting organisations such as Formula 1 to develop short-term strategies aimed at curbing carbon dioxide emissions from air travel, especially while waiting for the development and adoption of fuel-efficient technologies and alternative fuels. This forward-thinking approach aligns with broader sustainability goals that acknowledge the urgency of mitigating environmental impact.

Gaps In Existing Literature

In their comprehensive systematic review, Cerezo-Esteve et al. (2022) embarked on a rigorous examination of the existing body of research concerning the influence of major events on the natural environment. A striking revelation from their study was the dearth of substantial research dedicated to understanding the environmental repercussions of major events such as the

Olympics or Formula 1. Despite the sheer magnitude and significance of such mega sporting events, it emerged that the scientific exploration of their long-term environmental impact remained relatively limited. This observation underscores a critical knowledge gap in the intersection of event management and environmental science. Within the existing literature, the review revealed a relative scarcity of studies that delved into the intricate interplay between major events and the natural environment. While these events often leave indelible marks on the social and economic landscape, their quantifiable ecological footprint appeared to be less explored and documented. This gap raises pertinent questions about the sustainability of hosting and organizing such events in an era where environmental concerns have come to the forefront. Wilby et al. (2022) highlight a dearth of comprehensive studies that explore the strategies and initiatives aimed at adapting to and mitigating the environmental impact of sporting events.

Research that does addresses the carbon emissions associated with mega-sporting events has, for the most part, concentrated on a specific dimension—carbon emissions due to the transportation used by fans. This focus, as evidenced by studies such as those by Chirieleison et al. (2020), Watanabe et al. (2023), and Ito & Higham (2023), provides valuable insights but tends to overlook the intricate web of logistics and equipment transport, which constitute substantial components of the environmental impact associated with sports.

The cross-sectional examination of logistics, specifically the magnitude of its contribution to the environmental footprint of sports, stands as an emerging frontier. The finer nuances of logistics—encompassing facets such as transportation, venue management, resource utilization, and supply chain dynamics—remain relatively uncharted territory in terms of their role in shaping this impact. The research landscape is characterized by a relative paucity of comprehensive studies that delve deeply into the logistical intricacies of sporting events and their corresponding environmental implications. As sports continue to evolve and strive for sustainability, the critical logistical components that underpin sporting events are poised to play a pivotal role in achieving environmental objectives. Understanding how logistics can be optimized for reduced environmental impact holds the promise of not only minimizing harm but also fostering sustainable practices and innovations that can be disseminated throughout the sports industry.

Pioneering research by Mourão (2018) on the emissions of Grand Prix races marked a significant step forward in comprehending the environmental implications of motorsports. However, it is worth noting that the scope of this study was circumscribed, primarily focusing on the emissions from Formula 1 cars during the race. The broader indirect environmental impacts of Formula 1, encompassing logistical and equipment-related facets, have largely remained uncharted territory in research.

In the context of the environmental impact of sport logistics, especially that of an annual, global series such as Formula 1, the research landscape is marked by discernible knowledge gaps. Addressing these gaps stands as a critical endeavour, one that holds the potential to inform and guide more comprehensive and sustainable practices not only within Formula 1, but the entire motorsports industry, a sector with a profound reach and impact on a global scale.

Conceptual Framework

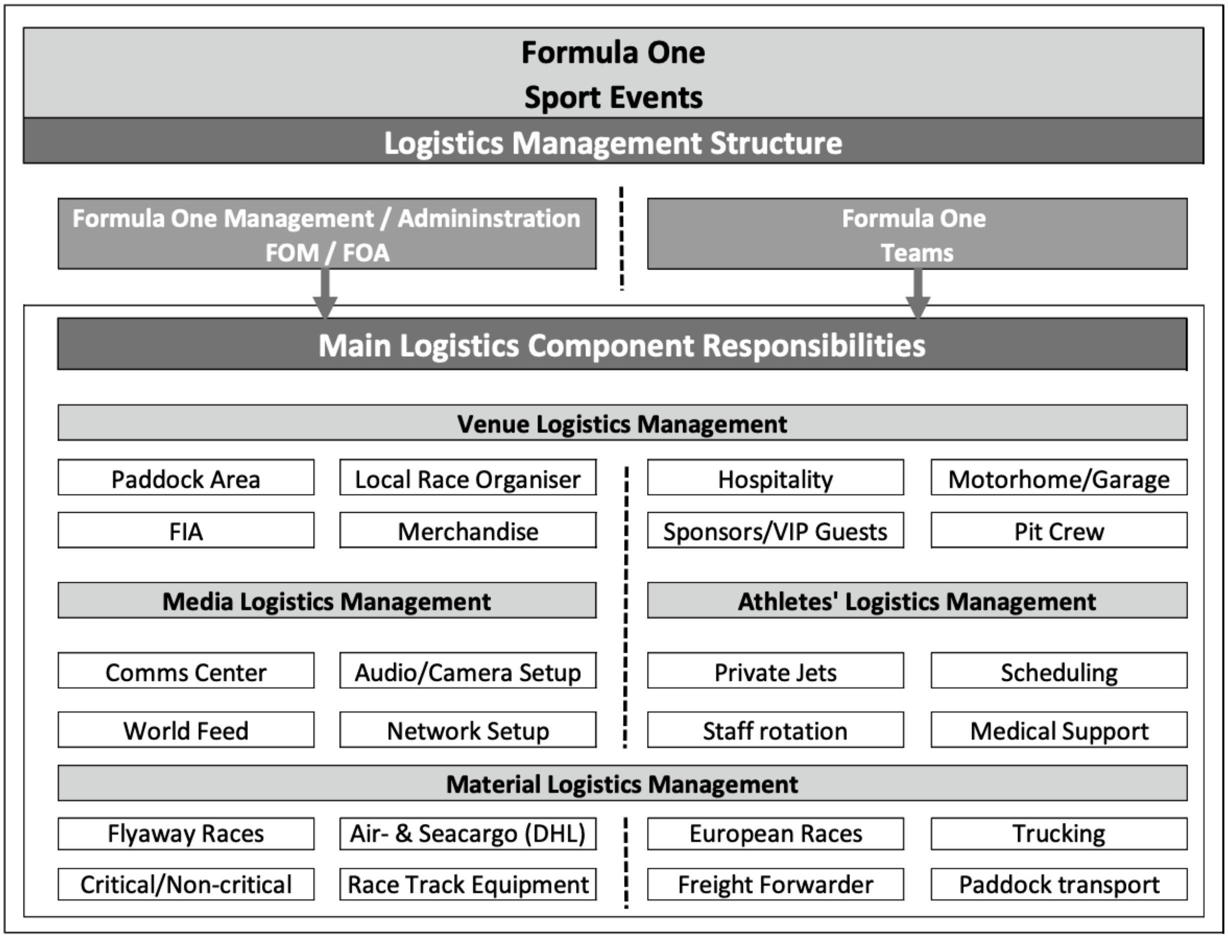
Motorsport events have long captivated the imagination of global audiences, drawing participants and spectators from diverse corners of the world. Yet, despite their ubiquity, it is only in recent times that the logistics underpinning these events have garnered scholarly attention. This shift reflects a growing recognition of the complexity and significance of logistical operations in the successful execution of major motorsports spectacles.

Building upon their earlier research (Herold et al., 2019), a Formula 1-specific evolution of the Sports Logistics Framework introduced by Herold et al. (2022) delves into the role of logistics, a critical component of motorsports operations, and its implications for sustainability. It considers how the intricate logistics involved in Formula 1, including the transportation of cars, equipment, and personnel across the globe, contribute significantly to its environmental impact. As the first empirical, framework-based study dedicated to unravelling Formula 1's background logistics, their research marked a pivotal departure from traditional approaches, shedding light on the multifaceted logistical challenges and considerations that underlie the seamless conduct of every Grand Prix race.

By offering a structured lens through which to examine the logistical dimensions of sporting events, encompassing facets such as venue management, transportation, accommodation, security, and more, this framework not only provided a deeper understanding of the logistics involved but also laid the groundwork for future investigations in the field.

Figure 2

The Sports Logistics Framework Adapted For Formula 1



Note. Herold et al. (2022)

To manage the numerous logistical responsibilities of Formula 1, two primary entities take the lead role: Formula One Management (FOM), the governing body responsible for organizing and managing the races, and the individual Formula 1 teams, each with their unique logistics requirements and strategies.

As seen above in the Material Logistics Management section of the framework, three primary modes of transport are used within Formula 1 logistics: road, air, and sea transport, which are distinguished and elucidated based on individual requirements that vary with each circuit. The most judicious choice of transport employed in preparation for a Grand Prix race is determined by considering factors such as distance, geographic location, urgency, and logistical efficiency.

Within Europe, where a significant portion of the Formula 1 calendar is based, the logistics network is well-oiled but highly complex. Essential cargo, which encompasses a wide array of equipment and materials, is transported between races using an impressive fleet of up to 300 trucks. This ensures that everything required for a race weekend efficiently arrives at each European circuit on schedule.

For races at circuits outside of Europe, also known as flyaway races, the decision regarding whether to transport items by air or sea, hinges on their criticality to the racing teams. In particular, the international transport of all teams and their equipment is centrally organized by the FOM, who partners with DHL, Formula 1's official logistics partner. High-priority components, including the race cars themselves, their essential parts such as chassis, engines, tires, wings, as well as crucial technological gear like computers and IT racks, make the journey via air. These items are loaded onto six or seven Boeing 747s, ensuring their timely arrival at race destinations. On the other hand, non-critical items like furniture, kitchen equipment, tables, tools, and various other team essentials are shipped via sea transport. This approach is particularly relevant for races taking place far in advance, often up to three months before the event. Teams usually dispatch five rounds of cargo shipments to international races. An effective material logistics management strategy ensures that all these items arrive at their destinations promptly, all while keeping costs in check. Throughout an entire Formula 1 season, teams ship approximately 660 tons of air freight and 500 tons of sea freight.

By offering a detailed account of how these modes of transport are strategically employed, the conceptual framework by Herold et al. (2022) lifts the veil on the profound complexities that underlie the seemingly seamless operations of Formula 1 logistics, highlighting its pivotal role behind the sport's grand spectacle.

Summary

Sustainability in sports is not merely an environmental concern but also a strategic move for organizations aiming to cultivate authentic brand images and satisfy increasingly eco-conscious fan bases. Research underscores the need for sports organizations, including Formula 1, to embrace sustainability practices as part of their commitment to reducing their environmental impact. This aligns with broader global efforts to mitigate climate change.

While the immediate focus often falls on aspects like race car emissions, it's clear that the larger share of emissions arises from logistical operations, such as equipment transport and team travel. Recognizing this, there's a growing consensus within the academia that optimizing scheduling to minimize travel distances between race locations presents a compelling avenue for reducing emissions. Furthermore, recent research has advocated for the importance of conscious rescheduling efforts to adapt to climate change.

In addressing the logistics of sporting events, particularly the complex challenge of scheduling, mathematical and computational techniques have emerged as powerful tools. Recent studies demonstrate that combining these techniques with sustainability goals can yield viable solutions that mitigate the carbon footprint of sports events.

Methodology

Research Philosophy And Approach

In line with the aim of the dissertation, optimising the Formula 1 race schedule to reduce the carbon footprint of transport logistics, the research methodology aligns with the philosophy of positivism, emphasizing objectivity and empirical observation as the foundations for scientific inquiry. Within the context of the dissertation, positivism drives the collection and analysis of quantifiable data. The utilization of empirical evidence such as historical race schedules, carbon emission data, and other relevant metrics serve as the basis for assessing the carbon footprint of Formula 1's transport logistics and developing optimization models for reducing the total distance travelled between races.

Building upon the research philosophy of positivism, the methodology of this dissertation adopts a quantitative research approach. The quantitative approach is well-suited to the objectives of this study as it relies on systematic data collection and numerical analysis to derive objective insights and measurable results. The optimization model development and analysis would rely on mathematical equations and quantitative measurements to identify the most effective strategies for reducing the carbon footprint. This approach ensures a rigorous and empirical examination of Formula 1's environmental impact and the optimization strategies implemented for scheduling. Using quantitative metrics to compare emissions reductions, travel distances, and other factors between different scheduling options, the most effective strategies for carbon reduction can be identified.

Data Collection And Pre-Processing

To ensure a robust foundation for analysis and optimization, data collection for this dissertation was conducted through a comprehensive and diverse range of secondary sources:

Ergast Developer API

A pivotal resource for Formula 1 data, this application program interface was used to collect historical race information for all seasons of Formula 1, as well as geolocation data for each circuit. This data served as the backbone for the study, offering historical context and spatial information critical to the research.

The historical race data set contained details such as race dates and locations for 1101 races from all 74 seasons of Formula 1 between the period of 1950 to 2023. While this data set also contained columns such as a URL for the Wikipedia page of the race, and date-time information for individual sessions such as Practice and Qualifying for each race, these columns were removed as this information was not required for any analytical processes. Furthermore, all records containing information for Indianapolis 500 races (N = 11) were removed from the data set. While briefly a part of the Formula 1 series between 1950 and 1960, these races were neither exclusively Formula 1 events, nor officially classified by Formula 1 as Grand Prix, often being held during the same weekend as a Grand Prix taking place in Europe. To avoid the possibility of significant variations and potential distortions, these races were excluded from all analytical processes.

The circuit information data set contained details such as the location, country, latitude and longitude for all 77 tracks that hosted a Formula 1 Grand Prix. While this data set also contained columns such as a URL for the Wikipedia page of the circuit, and altitude information, these columns were removed as this information is not required for any analytical processes.

The race and circuit information data sets were then joined using the names of the circuits to link each race with its corresponding geolocation information. For efficiency, the distance travelled between each race was calculated using pairs of coordinate data and the Euclidian distance-based representation as prescribed by Cooper and McCullough (2021).

OpenMeteo – Historical Weather API

This open-source collection of historical weather data, offering free access for non-commercial purposes, was used to collect daily historical weather information (N = 10,957) spanning a period of 30 years between 1993-2022, for all 45 circuit locations that hosted Grand Prix races during this period, using geolocation coordinates from the circuit information data set. This information is crucial for understanding the impact of weather conditions, as well as identifying periods of weather conditions that are favorable for transportation and race operations, serving as a baseline for scheduling optimization decisions.

The historical weather information data set contained details such as daily high/low/mean temperatures, precipitation, rainfall, and snowfall. While this data set also contained columns such as weather codes, sunrise/sunset times, wind speed/direction, shortwave radiation, and evapotranspiration, these columns were removed as this information is not required for any analytical processes. The weather condition parameters that were retained align with the methodological prescriptions of climate impact assessment studies by Ross and Orr (2021, 2022). Their research on mitigating the adverse impact of climate during sports events also highlighted the importance of setting optimal boundary conditions by identifying the number of days of rain, snow, and precipitation during each month, as well as the number of days where temperatures exceed specific thresholds. Temperatures above 25.5° C and 27.7° C were termed as moderate, and high-risk conditions respectively.

Using these parameters, two new data sets were created from the daily historical data set: a 30-year monthly average of weather conditions, and monthly average conditions during each year between 1993-2022 for all 45 circuits that hosted Grand Prix races during this period. These comprehensive data sets form the foundation for understanding the typical weather conditions during the event months at each circuit location.

DHL Carbon Calculator

Utilizing the DHL carbon accounting and controlling system based on proprietary internal transport and efficiency data, the Carbon Calculator is a simple, free-to-use tool that calculates the Well-to-Wheel (WtW) greenhouse gas emissions generated by DHL shipments. Well-to-Wheel emissions can be defined as all greenhouse gas emissions generated during the lifecycle of the fuel used, from production to combustion. As the official logistics partner of Formula 1 for freight transport, DHL is a reliable and precise source for quantifying an estimate of the carbon footprint associated with transport logistics between race locations.

Using the freight weight and mode of transport parameters detailed in the conceptual framework defined by Herold et al. (2022), the WtW carbon footprint of freight transport was manually calculated and collected as a data set for all Formula 1 Grand Prix races during the period of 2013-2023. The DHL Carbon Calculator as well as the carbon footprint data set created, are valuable aids for quantifying the environmental impact of Formula 1 transport logistics, especially for analyzing and assessing variations between different race schedules.

Various Official Government And Cultural Websites

Guided by the recognition of considering operational requirements to create viable sports schedules as described by Johnson (2015), information regarding national and regional holidays at all circuit locations in the 2023 Formula 1 race schedule were identified and manually gathered as a data set from each location's official government or cultural websites.

Various Motorsport Governing Body Websites

Additionally, data on motorsport events scheduled to take place at the same circuits as Formula 1 races during the 2023 season was manually collected from official motorsports governing body websites. This is vital for ensuring the practical viability of any proposed race calendar adjustments, aligning with the research findings of Johnson (2015) regarding operational considerations.

To ensure the reliability and accuracy of all the data sets gathered from the various secondary sources described, randomly selected blocks of information were manually cross-referenced against multiple sources of information, as a rudimental test of data consistency.

Gaps In Data

The 2023 Formula 1 calendar, in its initial iteration, comprised a total of 24 races scheduled across 24 different circuits. However, unforeseen circumstances led to the cancellation of both the Chinese and Emilia Romagna Grand Prix. It's worth noting that these races, despite not taking place, were integral considerations during the formulation of the original race schedule, based on meticulous planning that encompassed logistical arrangements, circuit availability, and commercial commitments.

For the process of re-scheduling the race calendar, it is paramount to maintain consistency in the gaps between races, and the number of races. To achieve this, the model will adhere to the original list of race locations. This strategic decision acknowledges and respects the initial intentions and constraints that guided the creation of the 2023 race calendar. By using the originally planned 24-race calendar as the foundation for re-scheduling, this approach leverages the extensive groundwork and preparations that were invested in the initial planning phase. Moreover, this approach not only streamlines the optimization process but also recognizes the web of logistics and operational intricacies that underlie the functioning of Formula 1's race schedule.

Operational And Commercial Constraints

The process of implementing operational and commercial constraints commenced with cross-referencing the Formula 1 race calendar against the national and regional holiday schedules of host countries. This initial step was instrumental in pinpointing potential conflicts that could arise when scheduling races. Subsequently, a comprehensive evaluation ensued to determine whether there were any concurrent motorsport events that coincided with Formula 1 race dates.

Table 1

A Representation Of Grand Prix Rounds Affected By Operational And Commercial Constraints

Circuit	Rounds Affected By Operational Constraints
Austin	1, 4, 22, 24
Bahrain	3, 4, 22
Shanghai	19
Barcelona	6, 16, 17
Zandvoort	5, 6, 8
Spa	6, 7, 8, 11, 13, 18

Note. This table is a representation of rounds affected by operational and commercial constraints.

This scrutiny was vital in assessing the likelihood of scheduling conflicts that could disrupt the planned Formula 1 events. With this data at hand, constraints and preferences were methodically set to preclude the scheduling of races on conflicting dates, thereby mitigating logistical and operational challenges. This not only ensures the smooth execution of Formula 1 Grand Prix but also prevents any unwarranted disruption of local activities and commitments at race locations.

Development Of The Optimization Model

The optimization model for race calendar scheduling is designed to strategically arrange Formula 1 races within a schedule while considering multiple factors such as travel distance reduction, operational constraints, and optimal weather conditions. The aim of the model is to achieve a balance between environmental sustainability, operational efficiency, and logistical feasibility by considering a multidimensional set of factors to generate race schedules that balance the diverse goals of the Formula 1.

To optimize the position of race locations within the schedule, the model follows a scenario where race dates are pre-determined while circuit locations are not. The pre-determined race dates, taken from the existing 2023 Formula 1 race schedule are influenced by factors such as television broadcasting schedules and contractual agreements with broadcasters. By implementing these pre-determined dates, the model ensures that the Formula 1 races are arranged in a way that respects these operational constraints. This approach also helps maintain a balanced flow throughout the Formula 1 season, while ensuring that races are scheduled in a logical sequence without causing disruptions or undue gaps between events.

Identifying Optimal Weather Windows

The meticulous process of assessing and identifying periods of optimal weather conditions for all circuit locations commenced by scrutinizing the local monthly weather conditions during the month in which each Grand Prix during the period of 1993-2022 occurred. The selection of the 30-year period between 1993-2022 for collating historical weather conditions aligns with congruent research by Ross and Orr (2021). This data then served as the foundation for establishing an acceptable range of weather conditions for Formula 1 events.

Table 2

The Acceptable Range Of Average Monthly Weather Conditions

Parameter	Lower Limit	Upper Limit
Mean Temperature	7.15°C	30.59°C
Max Temperature	11.23°C	34.61°C
Min Temperature	2.32°C	27.48°C
Mean Rainfall	0 mm	9.99 mm
Mean Snowfall	0 cm	0.04 cm
Total Rainfall	0 mm	305.18 mm
Total Snowfall	0 cm	1.2 cm
No. of Days of Moderate Heat (>25.5°C)	0 days	25.25 days
No. of Days of High Heat (>27.7°C)	0 days	5.98 days
No. of Days of Rainfall	0 days	29.47 days
No. of Days of Snowfall	0 days	1.06 days

The acceptable range of weather conditions was strategically quantified and determined by considering a range of 3 standard deviations from each parameter of the average weather conditions of all historical Grand Prix races that took place between 1993-2022, ensuring the encapsulation of variability within observed weather conditions over the years. The use of standard deviations to determine acceptable ranges was preferred over the implementation of inter-quartile ranges due to the overrepresentation of European races during this time period, resulting in the quantiles of weather parameters being heavily skewed towards their extremely mild weather conditions.

For all the circuit locations featured in the 2023 Formula 1 race schedule, a comprehensive analysis was conducted. This analysis delved into the 30-year average monthly weather conditions at these circuit locations, identifying months where the 30-year average monthly weather fell within the acceptable range of average monthly weather conditions experienced during Formula 1 races between 1993-2022. This approach was chosen over individually analyzing the average weather conditions during historical races at each race location as newly added circuits like Jeddah, Qatar, and Las Vegas would have limited to no historical race weather data to define their optimal weather windows. Notably, the Marina Bay Street Circuit in Singapore stood out as the sole circuit where no month throughout the year had all weather parameters fall within the acceptable range of conditions. This was primarily due to the circuit's tropical location resulting in consistently high numbers of moderately hot days year-round. Acknowledging this sub-optimality, the Singapore race location was given the lone exception of disregarding the number of days of moderate heat, resulting in the identification of months with acceptable weather conditions across all the other parameters.

Table 3

A Representative Extract Of Optimal Weather Windows At Circuit Locations

Circuit	Months with Optimal Weather Conditions
Austin	March, April, May, October, November
Bahrain	March, April, November
Jeddah	March
Vegas	March, April, October, November
Montreal	May, June, July, August, September
Baku	April, May, June, September, October

As an outcome of this historical weather analysis, the weather windows of months with optimal conditions were quantitatively determined for each circuit, and subsequently integrated into the optimization model as rigid constraints to ensure that all races are scheduled within their optimal weather windows. Validation of these findings was performed by comparing the identified optimal months of each race location with their respective historical race dates. As every single race between 1993-2022 at circuits featured in the 2023 calendar occurred during the location's optimal weather windows, the robustness of this process was affirmed.

To further gauge these results, a sensitivity analysis was conducted. This involved adjusting the number of standard deviations used to establish the average weather range threshold. While 1 and 2 standard deviations produced exceedingly stringent constraints, especially for races in the Middle East and tropical locations like Miami and Singapore, the use of 3 standard deviations was found to be the most suitable threshold for accommodating the varied weather conditions present across all circuit locations. This approach, based on average monthly weather conditions and standard deviations, offers a quantitative foundation for identifying potential optimal weather conditions, enriching the precision of the optimization model.

Mathematical Principles And Concepts

Scheduling Formula 1 races involves a complex interplay of factors such as carbon emissions reduction, operational constraints, optimal weather conditions, and logistical considerations. The number of possible combinations for race dates and circuit locations can be massive, making manual analysis infeasible. Optimization algorithms are computationally efficient for such large-scale problems and excel in handling such intricate relationships. By systematically exploring numerous combinations of variables, these algorithms can identify optimal or near-optimal solutions within a reasonable time frame, given specific constraints and an objective function. In this context, the objective function is to minimize the overall travel distance between races. Three optimization algorithms are implemented in this model: Greedy Algorithm, Guided Local Search, and Ant Colony Optimisation.

Greedy Algorithm. A simple and intuitive approach for optimization, the Greedy Algorithm makes locally optimal choices at each step with the hope of finding a global optimum. In each iteration, the algorithm selects the best available option based on a certain criterion. While greedy algorithms are easy to implement and computationally efficient, they might not always produce the optimal solution. By providing quick approximations that are acceptable for many practical applications, the Greedy Algorithm can be useful for generating initial solutions that serve as starting points for more complex optimization algorithms (Curtis, 2003).

Guided Local Search. Starting with an initial solution and iteratively refining it by applying local search operators, this optimization algorithm combines local search techniques with global guidance to find improved solutions. By adapting the guidance based on the quality of solutions encountered during the search, the algorithm is useful for complex optimization problems where the landscape might have multiple local optima. Guided Local Search could help refine a race schedule by iteratively adjusting circuit locations based on the global guidance learned from previous iterations, improving the overall schedule over time (Voudouris & Tsang, 1999).

Ant Colony Optimisation. A metaheuristic algorithm used to solve combinatorial optimization problems, this algorithm simulates the way real ants discover paths between their colony and food sources. In the context of optimization, artificial ants traverse a solution space, leaving pheromone trails that other ants follow. The amount of pheromone on a path influences the likelihood of other ants choosing that path. Over iterations, paths with higher pheromone concentration become more attractive. Ant Colony Optimisation is particularly effective for solving problems with a large search space and is known for finding near-optimal solutions, especially when dealing with complex routing or scheduling problems. The algorithm simulates scheduling through the selection of circuit locations by artificial "ants" based on factors like travel distance, weather conditions, and operational constraints. The attractiveness of a location, represented by strong pheromone trails, guides the algorithm towards better options over iterations (Dorigo & Stützle, 2019).

These algorithms were implemented within the model for creating individual variations of the 2023 Formula 1 race calendar. With no constraints whatsoever, guided local search was used to schedule an optimal solution that minimised the total distance travelled. The Greedy and Ant Colony Optimisation algorithms were used for approximate and heuristic race calendars respectively, while adhering to all operational and commercial constraints, with an aim to produce viable solutions that minimised the total distance travelled.

Implementation Of The Model

For all the circuits in the 2023 Formula 1 calendar, a Euclidian distance-based matrix was created to serve as a quantifiable representation of the geographic relationships between pairs of circuits locations (Cooper & McCullough, 2021). This matrix allows the model to make informed choices when selecting consecutive race locations that result in the least travel distance, reducing logistical complexities and resource consumption.

Figure 3

A Representative Extract Of The Euclidian Distance Matrix

	Bahrain	Hungaroring	Interlagos	Miami	Silverstone	Vegas	Zandvoort
Bahrain	0	3,629	11,814	12,186	5,158	12,943	4,805
Hungaroring	3,629	0	10,295	8,574	1,531	9,665	1,177
Interlagos	11,814	10,295	0	6,596	9,523	9,788	9,808
Miami	12,186	8,574	6,596	0	7,044	3,493	7,409
Silverstone	5,158	1,531	9,523	7,044	0	8,320	380
Vegas	12,943	9,665	9,788	3,493	8,320	0	8,578
Zandvoort	4,805	1,177	9,808	7,409	380	8,578	0

Note. This figure is for visual representation only. The actual matrix has a dimension of 24x24.

Guided Local Search. Implemented using Google's OR-Tools, an open-source optimization library for the Python scripting language, the heuristic search parameters of the algorithmic solver utilised the raw Euclidian distance matrix to compute an ideal yet possibly unrealistic race calendar that completely minimises the total distance travelled between races, while not being held back by constraints such as optimal weather windows and operational constraints.

Using a combination of the optimal weather windows of each circuit location, the regional holidays and the clashing motorsport events, a candidate list of feasible tracks were identified for each pre-determined date slot in the 2023 Formula 1 calendar. This list serves as the operational constraints for guiding the development of feasible yet optimized schedules using the greedy and ant colony optimisation algorithms.

Table 4

A Representative Extract Of Viable Candidate Circuits For Select Grand Prix Rounds

Round	Viable Candidate Circuits
11	Barcelona, Imola, Monaco, Monza
14	Budapest, Melbourne, Mexico City, Suzuka
7	Shanghai, Montreal, Zandvoort
2	Jeddah, Lusail, Vegas, Bahrain
24	Abu Dhabi, Melbourne, Shanghai
5	Singapore, Silverstone, Imola, Monza

Note. This figure is for representation only.

Greedy Algorithm. After selecting an initial race location from the candidate list of circuits for the first round of the schedule, the algorithm, written using the Python scripting language, iteratively progressed through the remaining tracks for each subsequent round, choosing the feasible candidate location that locally has the shortest distance from the current location. It’s important to note that the success of the Greedy Algorithm's implementation relies on the definition of the distance metric, constraints, and the initial circuit location chosen (Curtis, 2003). To work around this, the algorithm was executed multiple times using all possible options for the initial race location, resulting in a varied set of race calendars.

Ant Colony Optimisation. Iteratively implemented in Python by simulating the foraging behaviour of 'ants', each representing a potential race calendar configuration, the algorithm explores the solution space while continuously refining the race schedule for improving the performance of subsequent iterations. Parameters of the algorithm such as the number of iterations, number of ants, evaporation rate, pheromone and heuristic factors are initialized before execution, along with a pheromone matrix that represents the attractiveness of each race location relative to any current location (Dorigo & Stützle, 2019). Each ant is guided by the pheromone values and heuristic information, the inverse of the distance relative to the current location, to construct a viable race schedule by selecting circuit locations from the list of feasible race locations for each subsequent round. Then, the total distance travelled by each ant is calculated using the distance matrix and the pheromone matrix is updated based on the ant's path and the distance travelled, with the shortest sequence of paths being reinforced with higher pheromone levels. After each iteration, consistent global pheromone evaporation within the pheromone matrix limits the algorithm from converging to sub-optimal solutions. The algorithm keeps track of the best solution found so far and its associated distance, updating this information whenever a better solution is encountered.

Model Validation

Using the SPSS statistical analysis software, correlation analysis was performed to explore any significant statistical relationship between the total distance travelled between races and the expected carbon emissions generated due to transport logistics. This was implemented by calculating the Pearson's correlation coefficient to indicate the strength and direction of the linear relationship between the two variables. Establishing a statistical relationship between the total distance travelled and carbon emissions generated is essential for quantitatively validating the impact of travel distances on environmental considerations and thus evaluating the performance of the solutions generated by the optimization model.

The alternate race schedules generated by the algorithms implemented within the optimization model are compared against the existing 2023 Formula 1 calendar using metrics such as the total distance travelled between races, and the expected carbon emissions generated from logistics transport. This comparison provides a quantitative basis for assessing any possible improvements achieved through optimization in terms of logistical efficiency, operational viability, and environmental sustainability.

Research Ethics And Concerns

As the data collected, processed, analysed, and implemented within this methodology is gathered from the publicly available, free-to-use secondary sources listed earlier in this section, there exist no immediate conflicts, concerns or implications related to data privacy, confidentiality, or stakeholder relations.

Limitations

The limitations of the methodology are as follows:

1. Unlike transport logistics by road and air which involve moving directly from one race location to the next, sea freight shipping represents a significantly more complex process. As described in the conceptual framework devised by Herold et al. (2022), Formula 1 teams ship 5 identical sets of non-critical freight to minimise their dependence on costly air transportation. The pattern of movement of these identical sets freight from one flyaway race location to the next is not publicly available information and too complex to accurately model without access to industry insider information. For this reason, the carbon emissions generated from sea freight logistics are entirely left out to streamline the complexity of the model.
2. While the race schedule for the 2023 season of Formula 1 was designed well in advance, the model takes the schedule of other motorsport events at Formula 1 circuits into consideration while determining operational constraints. This was done as there is no straightforward method to identify the circuit’s order of preference when scheduling events. In reality, Formula 1 likely receives priority when scheduling races at circuits.

3. Although most Grand Prix races take place during daytime, there are notable exceptions, with few circuits hosting night races. The timing of these races can potentially influence the impact of changing weather conditions throughout the day. To streamline the model, this methodology considers all Grand Prix races to be taking place during daytime.
4. The business travel aspect of Formula 1, involving the movement of drivers and team personnel between races is not considered within the scope this dissertation. This is due to the fact that while most equipment logistics involve moving directly from one race to the next, the intricacies of business travel is far more complicated, with drivers and team personnel travelling back to their respective homes between races whenever possible. There exists a significant possibility that the inner workings of business travel are taken into consideration by Formula 1 when scheduling races. Access to industry insider information regarding the complexity of this aspect of Formula 1 could add another layer of dimensionality to improve the viability of the scheduling optimization process.

Summary

Addressing the critical need for sustainable logistical practices in Formula 1, the methodology focuses on optimizing the race calendar to mitigate environmental impact. This entails the assessment of the carbon footprint of Formula 1 transport logistics and developing an optimization model to reschedule races. The model implemented optimisation algorithms such as Guided Local Search for optimal solutions without constraints, Greedy algorithm for feasible schedules adhering to operational constraints, and Ant Colony Optimization for viable and near-optimal solutions that adhere to diverse constraints. The total distance travelled between races locations and expected carbon emissions from transport logistics serve as performance metrics to quantitatively evaluate the efficiency and environmental impact of alternate race schedules developed by the model.

By systematically integrating these elements, the methodology provides a robust framework to optimize race calendars, aiding in advancing sustainable practices within Formula 1 while considering operational feasibility and environmental concerns. This approach contributes to a data-driven decision-making process that aims to balance sporting excellence and environmental responsibility.

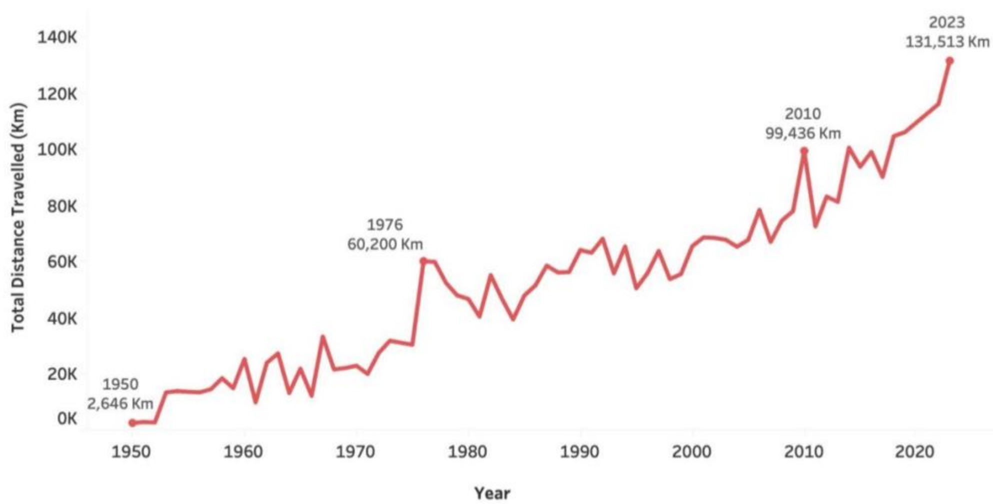
Results And Discussion

This section delves into the empirical findings derived from the application of advanced optimization methodologies, and their implications pertaining to the aim of reducing the carbon footprint and adverse environmental impact of Formula 1, shedding light on the potential for sustainable race schedule planning within the sport.

Historical Analysis: Total Distance Travelled In Past Seasons

Figure 4

The Total Distance Travelled Between Races During Each Season Of Formula 1

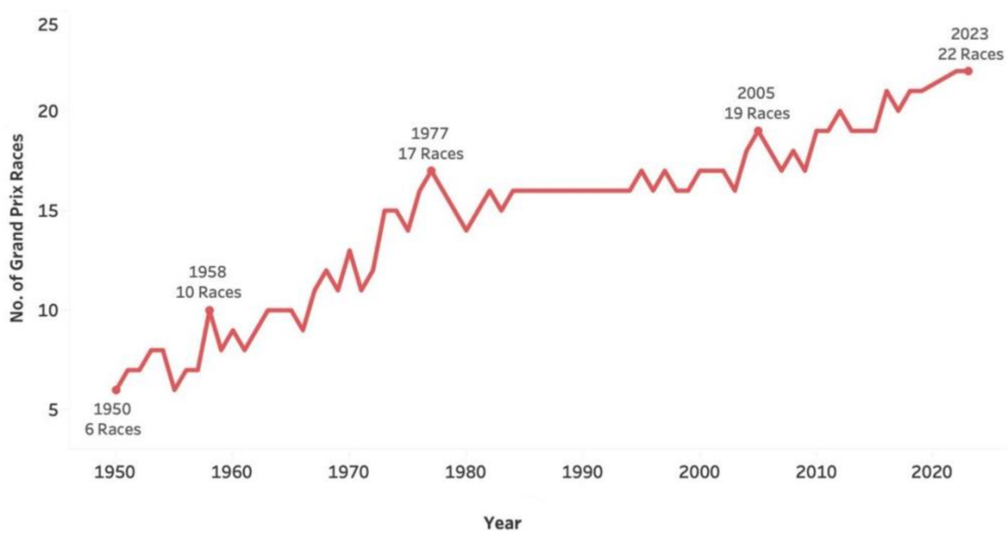


Note. The pandemic impacted seasons of 2020 and 2021 are excluded for better clarity.

As seen in the above graph, Formula 1 as a series, has witnessed a steady escalation in the total distance covered between races as the seasons have progressed. This growing trajectory has reached an apex in the 2023 season, where the cumulative travel distance between race locations surged to unprecedented levels. This escalation underscores the growing logistical complexities and operational demands faced by the sport, accentuating the urgency of addressing the environmental implications of extensive travel. This rise in distance underscores the evolving dynamics of Formula 1, reflecting factors such as the addition of new race locations, resulting in the extension of the race schedule, and the increasing global scope of the sport.

Figure 5

The Number Of Grand Prix Races During Each Season Of Formula 1

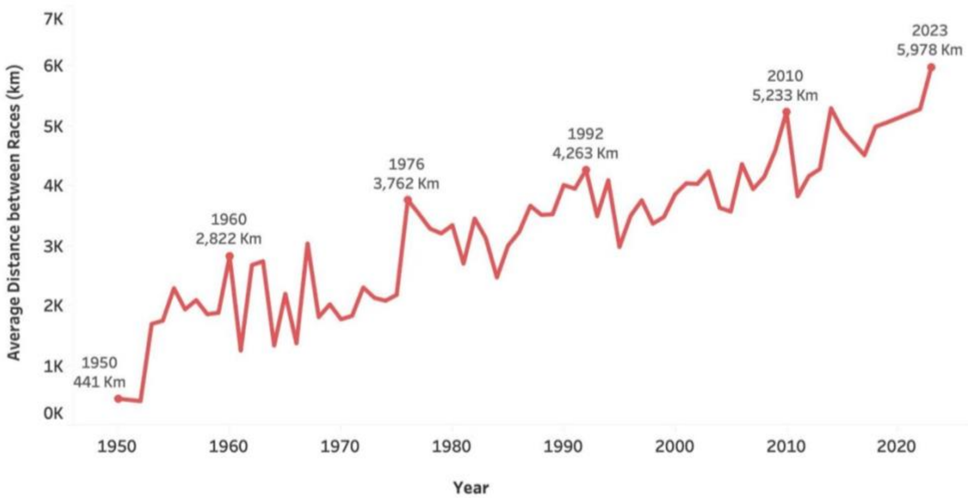


Note. The pandemic impacted seasons of 2020 and 2021 are excluded for better clarity.

Similarly, the number of races in each season of Formula 1 has experienced a gradual expansion over the course of its evolution, reaching a zenith in the 2023 season which boasts the largest race schedule in the sport's history. While the escalation in the number of races signifies the sport's efforts to increase its global reach and popularity, as well as engaging the growing appetite for competitive events, it also amplifies the increasing challenges in terms of logistical complexity, operational demands, and environmental considerations.

Figure 6

The Average Distance Travelled Between Races During Each Season Of Formula 1



Note. The pandemic impacted seasons of 2020 and 2021 are excluded for better clarity.

Surprisingly, the rapid increase in the total distance covered between races during each season cannot be simply attributed to a corresponding increase in the number of races scheduled. As seen in the graph above, the average travel distance between races in Formula 1 has also exhibited a consistent and upward trajectory, with the 2023 season emerging as a standout yet again, featuring the highest average travel distance between races ever recorded in the sport's history. This alarming benchmark accentuates the imperative need for optimizing race schedules to strike a harmonious equilibrium between sporting competitiveness, operational viability, and sustainability goals.

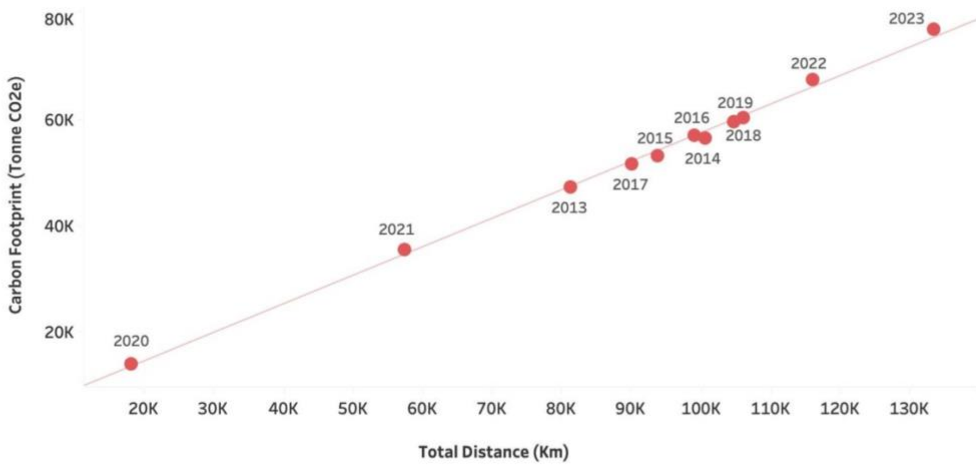
It should be noted that the pandemic-impacted seasons of 2020 and 2021 were excluded from all the above graphs as its more meaningful to analyse the seasons that align with Formula 1's usual operations and scheduling. These seasons suffered from pandemic-induced changes, such as cancelled races, rescheduled events, and altered race locations, resulted in an atypical pattern that deviated from the typical trajectory. The reduced total travel distance and number of races during these pandemic-affected seasons do not accurately represent the normal operations and trends of Formula. Including these seasons could potentially distort the understanding of the sport's regular dynamics and long-term trends.

The observed seasonal trends of Formula 1, specifically the steady increase in the number of races per season and the escalating average distance travelled between races, hold significant implications in the context of the overarching objectives to reduce travel distances and carbon emissions within the sport. Not only does the larger calendar contribute to higher overall carbon emissions due to increased travel, but it also amplifies the logistical complexities and operational strains associated with coordinating such a demanding schedule. As the distances between races expand, so do the potential environmental consequences. Each additional kilometre travelled potentially translates into higher emissions and resource consumption, exacerbating the sport's ecological footprint. Considering these trends, it becomes increasingly clear that optimizing the race calendar is a crucial avenue for mitigating these challenges (Johnson, 2015; Wynes, 2021). Strategies that focus on consolidating races within closer geographical proximity, optimizing travel routes, and implementing efficient logistics can directly address the escalating distances travelled and, consequently, carbon emissions from transport logistics.

Exploration Of Total Distance Travelled And The Carbon Footprint

Figure 7

Scatter Plot *Of The Total Distance Travelled During Each Season And The Carbon Footprint*



Note. This figure includes all Formula 1 seasons during the period of 2013-2023.

Statistical analysis to explore the existence of possible correlation between the carbon footprint and the total distance travelled using the SPSS statistical analysis software highlighted that the two variables exhibited a near-perfect linear relationship, $r = .999$, $p < 0.001$. As seen in the scatter plot above, the observed strong linear relationship, supported by a very strong and significant Pearson's Correlation coefficient, serves as a critical insight into the interplay between operational logistics and environmental impact within the context of Formula 1. The correlation coefficient's strength signifies that as the total distance travelled between races increases, there is a corresponding increase in the carbon footprint, suggesting a direct association between these factors.

This finding aligns with common-sense expectations that greater distances travelled typically translate to higher carbon emissions due to increased energy consumption from transportation, logistics, and other related activities. Moreover, this information can be leveraged to inform strategic decisions within the realm of Formula 1's sustainability efforts. The strong correlation highlights the potential for optimizing the race calendar to achieve a dual objective: reducing carbon emissions by minimizing travel distances and enhancing operational efficiency.

The Impact Of The 2023 Formula 1 Race Schedule

Table 5

The Original Race Schedule Of The 2023 Season Of Formula 1

Round	Date	Grand Prix	Circuit
1	Mar 05	Bahrain	Sakhir
2	Mar 19	Saudi Arabia	Jeddah
3	Apr 02	Australia	Melbourne
4	Apr 16	China	Shanghai
5	Apr 30	Azerbaijan	Baku
6	May 07	Miami	Miami
7	May 21	Emilia Romagna	Imola
8	May 28	Monaco	Monaco
9	Jun 04	Spain	Barcelona
10	Jun 18	Canada	Montreal
11	Jul 02	Austria	Spielberg
12	Jul 09	United Kingdom	Silverstone
13	Jul 23	Hungary	Budapest
14	Jul 30	Belgium	Spa
15	Aug 27	Netherlands	Zandvoort
16	Sep 03	Italy	Monza
17	Sep 17	Singapore	Singapore
18	Sep 24	Japan	Suzuka
19	Oct 08	Qatar	Lusail
20	Oct 22	United States	Austin
21	Oct 29	Mexico	Mexico City
22	Nov 05	Brazil	Sao Paulo
23	Nov 19	Las Vegas	Las Vegas
24	Nov 26	Abu Dhabi	Yas Marina
Total Distance Travelled		**133,591.55 Km**	
Carbon Footprint		**76,720.73 Tonnes of CO2**	

Note. Estimated carbon footprint is from freight transportation by road and air only.

Descriptive statistics for the 2023 Formula 1 season underscore the magnitude of the logistical and environmental challenges faced by the sport. Traveling to 24 race locations across 21 countries is a testament to Formula 1's global appeal and reach, but it also signifies the extensive distances covered over the course of the season. The total distance travelled between races, exceeding 133,000 kilometres, is a substantial figure that highlights the operational complexities associated with coordinating a worldwide race calendar. This distance entails significant energy consumption, resource allocation, and emissions generation. The carbon footprint resulting from travel logistics, estimated at over 76,000 tonnes of CO2, underscores the adverse environmental implications of Formula 1's operational activities.

In light of these statistics, optimizing the race calendar to reduce travel distances and associated carbon emissions becomes paramount. Strategic scheduling can play a pivotal role in achieving a more sustainable balance between the sport's global presence and its commitment to environmental responsibility. These figures serve as a compelling call to action for Formula 1 to harness data-driven insights and advanced optimization methodologies to drive positive change within the sport.

Suboptimalities in terms of travel distances and logistics within the 2023 race schedule is exemplified by the prevalence of numerous inter-continental trips, including multiple journeys to North America, the Middle East and the Asia-Pacific regions, contributing significantly to the enormous total travel distance. Clustering races in regions can improve operational efficiency and optimize resource allocation, while simultaneously reducing the need for additional long-distance journeys.

Alternate Race Schedules Generated By Optimisation Algorithms

Guided Local Search

The use of the Guided Local Search optimization algorithm to generate hypothetical race calendars with the sole aim of minimizing the total distance travelled between races, without considering any operational constraints, provides valuable insights into the theoretical limits of optimization (Voudouris & Tsang, 1999). This exercise can yield schedules that, while minimizing distance on paper, may not be suitable for real-world implementation due to operational and logistical challenges.

Table 6

An Alternate 2023 Race Schedule Generated Using Guided Local Search

Round	Date	Race	Circuit	Constraint
1	Mar 05	Australia	Melbourne	-
2	Mar 19	Singapore	Singapore	-
3	Apr 02	China	Shanghai	-
4	Apr 16	Japan	Suzuka	-
5	Apr 30	Azerbaijan	Baku	-
6	May 07	Abu Dhabi	Yas Marina	Weather
7	May 21	Qatar	Lusail	Weather
8	May 28	Bahrain	Sakhir	Weather
9	Jun 04	Saudi Arabia	Jeddah	Weather
10	Jun 18	Hungary	Budapest	-
11	Jul 02	Austria	Spielberg	-
12	Jul 09	Emilia Romagna	Imola	-
13	Jul 23	Italy	Monza	-
14	Jul 30	Monaco	Monaco	-
15	Aug 27	Spain	Barcelona	-
16	Sep 03	Belgium	Spa	-
17	Sep 17	Netherlands	Zandvoort	-
18	Sep 24	United Kingdom	Silverstone	Event Clash
19	Oct 08	Canada	Montreal	Weather
20	Oct 22	Las Vegas	Las Vegas	-
21	Oct 29	United States	Austin	-
22	Nov 05	Mexico	Mexico City	-
23	Nov 19	Miami	Miami	Event Clash
24	Nov 26	Brazil	Sao Paulo	-
Total Distance Travelled		**49,337.02 Km**		

While the total distance travelled between races is drastically decreased using this optimisation algorithm, the importance of considering feasibility when scheduling is underscored by the fact that some of the races, highlighted in red, do not satisfy viable operational criteria. These suboptimalities include the scheduling of races during extreme weather conditions such as the hot months in the Middle East or the start of winter in Canada, and during periods of circuit unavailability due to prior commitments as seen with the races in the United Kingdom and Miami.

Nevertheless, this exercise serves as a valuable exploration of the extreme limits of travel distance minimization within scheduling. Optimizing a Formula 1 race schedule is a complex task that involves balancing multiple objectives and constraints. Achieving the absolute minimum travel distance might not be the most practical or feasible goal when considering all relevant factors, thus highlighting the need for a holistic approach that considers a wide range of constraints and objectives.

Greedy Algorithm

The use of the Greedy optimization algorithm, fine-tuned to consider both weather and operational constraints, offers a more promising approach to Formula 1 race scheduling. It takes a comprehensive view of logistical and environmental factors, aligning with the sport's sustainability goals while ensuring practical implementation.

Table 7

An Alternate 2023 Race Schedule Generated Using The Greedy Algorithm

Round	Date	Race	Circuit	Type
1	Mar 05	Las Vegas	Las Vegas	Flyaway
2	Mar 19	Saudi Arabia	Jeddah	Flyaway
3	Apr 02	Singapore	Singapore	Flyaway
4	Apr 16	China	Shanghai	Flyaway
5	Apr 30	Azerbaijan	Baku	Flyaway
6	May 07	Canada	Montreal	Flyaway
7	May 21	Miami	Miami	Flyaway
8	May 28	United States	Austin	Flyaway
9	Jun 04	Mexico	Mexico City	Flyaway
10	Jun 18	Brazil	Sao Paulo	Flyaway
11	Jul 02	Australia	Melbourne	Flyaway
12	Jul 09	Japan	Suzuka	Flyaway
13	Jul 23	Hungary	Budapest	Road
14	Jul 30	Austria	Spielberg	Road
15	Aug 27	Emilia Romagna	Imola	Road
16	Sep 03	Italy	Monza	Road
17	Sep 17	Monaco	Monaco	Road
18	Sep 24	Spain	Barcelona	Road
19	Oct 08	Belgium	Spa	Road
20	Oct 22	Netherlands	Zandvoort	Road
21	Oct 29	United Kingdom	Silverstone	Road
22	Nov 05	Qatar	Lusail	Flyaway
23	Nov 19	Bahrain	Sakhir	Flyaway
24	Nov 26	Abu Dhabi	Yas Marina	Flyaway
Total Distance Travelled		**91,442.04 Km**		
Carbon Footprint		**52,344.12 Tonnes of CO2**		

Note. Estimated carbon footprint is from freight transportation by road and air only.

By considering weather and operational constraints, the Greedy Algorithm produces viable schedules by constraining the model to ensure that races are scheduled when the weather is suitable while avoiding potential conflicts with regional holidays, clashing events, or venue unavailability. Additionally, tuning the algorithm to group European races together results in a logistically efficient strategy that minimizes the need for unnecessary air transport. Reducing the reliance on air transport aligns with Formula 1's sustainability goals by potentially reducing carbon emissions associated with logistics.

It's important to acknowledge that while the results of the Greedy optimization algorithm are operationally viable, the algorithm may not produce a near-optimal race calendar due to inherent limitations within the myopic nature of the algorithm, resulting in poor local optimization that fails to guarantee absolute optimality (Curtis, 2003). While the Greedy Algorithm provides valuable insights and improvements, it's essential to recognize its limitations, and explore more advanced methods to achieve race schedules that are both operationally viable and near optimal.

Ant Colony Optimisation

Due to its inherent heuristic nature, the Ant Colony Optimisation algorithm can simultaneously explore the global solution space in search of the best one while gradually adapting and improving its performance with every subsequent iteration (Dorigo & Stützle, 2019). This property allows it to work within complex constraints to potentially find innovative solutions that are near optimal yet operationally viable. As a non-deterministic algorithm, Ant Colony Optimisation balances the element of randomness with the probabilistic decision-making process, which can lead to creative and diverse solutions.

Table 8

An Alternate 2023 Race Schedule Generated Using Ant Colony Optimisation

Round	Date	Race	Circuit	Type
1	Mar 05	Saudi Arabia	Jeddah	Flyaway
2	Mar 19	Brazil	Sao Paulo	Flyaway
3	Apr 02	Mexico	Mexico City	Flyaway
4	Apr 16	Las Vegas	Las Vegas	Flyaway
5	Apr 30	United States	Austin	Flyaway
6	May 07	Miami	Miami	Flyaway
7	May 21	Canada	Montreal	Flyaway
8	May 28	Italy	Monza	Road
9	Jun 04	Monaco	Monaco	Road
10	Jun 18	Emilia Romagna	Imola	Road
11	Jul 02	Austria	Spielberg	Road
12	Jul 09	Hungary	Budapest	Road
13	Jul 23	Spain	Barcelona	Road
14	Jul 30	Belgium	Spa	Road
15	Aug 27	Netherlands	Zandvoort	Road
16	Sep 03	United Kingdom	Silverstone	Road
17	Sep 17	Azerbaijan	Baku	Flyaway
18	Sep 24	Singapore	Singapore	Flyaway
19	Oct 08	Australia	Melbourne	Flyaway
20	Oct 22	Japan	Suzuka	Flyaway
21	Oct 29	China	Shanghai	Flyaway
22	Nov 05	Qatar	Lusail	Flyaway
23	Nov 19	Bahrain	Sakhir	Flyaway
24	Nov 26	Abu Dhabi	Yas Marina	Flyaway
Total Distance Travelled		**70,764.62 Km**		
Carbon Footprint		**41,723.50 Tonnes of CO2**		

Note. Estimated carbon footprint is from freight transportation by road and air only.

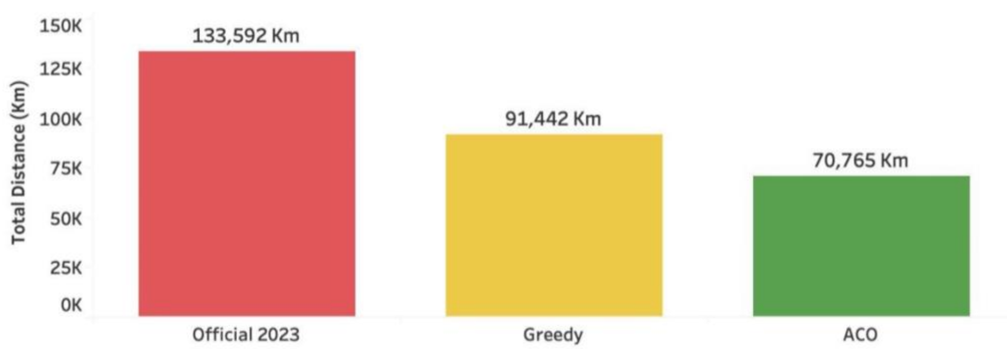
The best result achieved by the Ant Colony Optimization algorithm, produced a race schedule with significant regionalization of race locations. This clustering of nearby race locations significantly reduces travel distances between races within the same region, drastically improving the efficiency of transport logistics while minimising its corresponding carbon footprint by reducing the requirement for long-haul international flights from extensive cross-continental travel. Racing within the same region can also often mean more consistent weather conditions from one race to the next. This reduces the need for drastic adjustments to cars and setups due to weather variations. A crucial advantage of scheduling races within close proximity is the enhanced operational efficiency, as teams, equipment, and personnel can move more smoothly between races, reducing downtime and logistical challenges.

While both the Greedy and Ant Colony Optimisation algorithms aim to optimize for viable Formula 1 race schedules within operational constraints, they do so through different approaches. The simple Greedy Algorithm focuses on local optimization and efficiency for initial approximations, while the more complex Ant Colony Optimisation explores a wider solution space through probabilistic and heuristic methods to generate solutions that are much closer to the global optimum.

Comparison With The Current Formula 1 Race Schedule

Figure 8

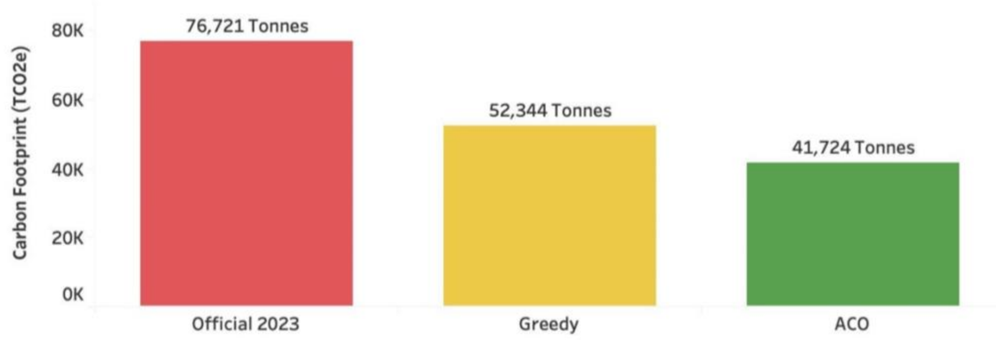
Comparison Of The Total Travel Distances Of The Official And Alternate Race Schedules



As seen in the graph above, the race schedules generated by the Greedy and Ant Colony Optimisation algorithms represent significant improvements over the 2023 Formula 1 race schedule, reducing the total distance travelled between races by 31.5% and 47% respectively.

Figure 9

Comparison Of Estimated Carbon Footprint Of The Official And Alternate Race Schedules



Note. Estimated carbon footprint is from freight transportation by road and air only.

Similarly, the best results of the Greedy and Ant Colony Optimisation algorithms successfully minimise the estimated logistics carbon footprint of the 2023 Formula 1 race schedule by 31.7% and 45.6% respectively.

These results underscore the importance of data-driven optimization in Formula 1 scheduling. By leveraging historical data, weather considerations, and operational constraints, the solutions generated by optimisation algorithms highlight the possibility of creating viable race calendars that are both operationally efficient and environmentally responsible. It's important to recognize that achieving such substantial reductions in travel distance and carbon emissions necessitates the requirement for a drastic shift in the approach towards race scheduling.

Consideration of factors such as regionalization, minimising inter-continental travel, assessing optimal weather conditions, and strategic adjustments to streamline operational logistics all play a role in achieving these impressive results. Moving forward, these findings provide valuable insights into how Formula 1 can continue to optimize its race calendar to meet its sustainability goals while maintaining its global appeal and competitive excellence.

The 2024 Formula 1 Race Schedule

Introduced relatively recently by Formula 1, the official proposed race schedule for the 2024 season, characterized by a strategic shift towards the regionalization of race locations, reflects a commendable effort by Formula 1 to mitigate its adverse impact. Although the calendar maintains the same number of races as in the 2023 season, the rescheduling of race locations has resulted in a noteworthy reduction in both travel distance and carbon footprint.

This race schedule demonstrates a marked improvement in terms of environmental sustainability when compared to the 2023 race calendar. Aligning with Formula 1's goal of becoming Net Zero Carbon by 2030, this revision of the existing schedule signifies a tangible step toward achieving the sport's ambitious environmental objectives.

Table 9

The Official Proposed Race Schedule Of The 2024 Season Of Formula 1

Round	Date	Race	Circuit
1	Mar 02, 2024	Bahrain	Sakhir
2	Mar 09, 2024	Saudi Arabia	Jeddah
3	Mar 24, 2024	Australia	Melbourne
4	Apr 07, 2024	Japan	Suzuka
5	Apr 21, 2024	China	Shanghai
6	May 05, 2024	Miami	Miami
7	May 19, 2024	Emilia Romagna	Imola
8	May 26, 2024	Monaco	Monaco
9	Jun 09, 2024	Canada	Montreal
10	Jun 23, 2024	Spain	Barcelona
11	Jun 30, 2024	Austria	Spielberg
12	Jul 07, 2024	United Kingdom	Silverstone
13	Jul 21, 2024	Hungary	Budapest
14	Jul 28, 2024	Belgium	Spa
15	Aug 25, 2024	Netherlands	Zandvoort
16	Sep 01, 2024	Italy	Monza
17	Sep 15, 2024	Azerbaijan	Baku
18	Sep 22, 2024	Singapore	Singapore
19	Oct 20, 2024	United States	Austin
20	Oct 27, 2024	Mexico	Mexico City
21	Nov 03, 2024	Brazil	Sao Paulo
22	Nov 23, 2024	Las Vegas	Las Vegas
23	Dec 01, 2024	Qatar	Lusail
24	Dec 08, 2024	Abu Dhabi	Yas Marina
Total Distance Travelled		**121,396.07 Km**	
Carbon Footprint		**69,101.69 Tonnes of CO2**	

Note. Estimated carbon footprint is from freight transportation by road and air only.

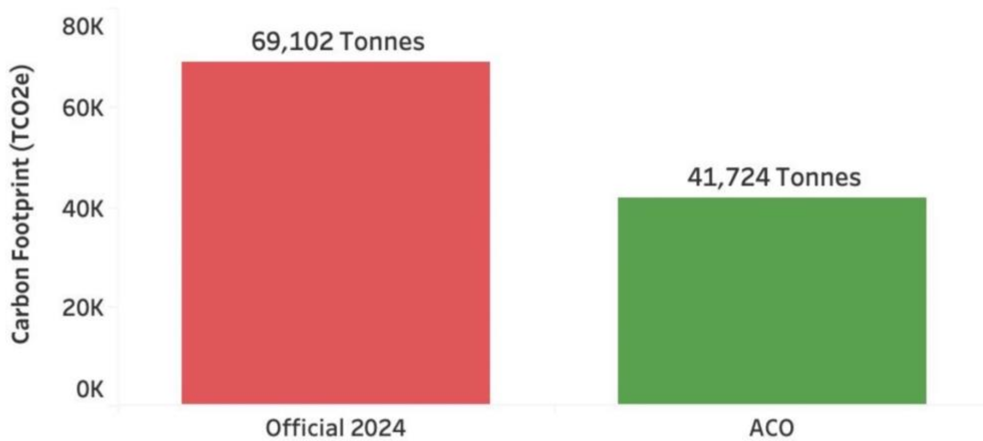
The strategic adjustments made in the 2024 Formula 1 race calendar to enhance regionalization by relocating races in Japan, Azerbaijan, and Qatar are noteworthy steps toward sustainability. While these changes demonstrate Formula 1's commitment to optimizing travel distances and reducing carbon emissions, there is still scope for further improvement of the race schedule.

Figure 10

Comparison Of The Total Travel Distance Of The Proposed And Alternate Race Schedules

Figure 11

Comparison Of The Carbon Footprint Of The Proposed And Alternate Race Schedules



Note. Estimated carbon footprint is from freight transportation by road and air only.

With a 41.7% reduction in total travel distance between races, and a 39.6% reduction of the logistics carbon footprint, the best result of the Ant Colony Optimisation algorithm quantitatively outperforms the proposed 2024 race schedule, underscoring the potential of data-driven decision-making and scheduling optimization for driving positive change within the sport.

This comparison shows that environmentally responsible scheduling does not have to compromise the practical aspects of race planning. These findings present a compelling case for further exploration and should encourage Formula 1's commitment to strive for achieving sustainability by exploring possibility of adopting powerful scheduling optimization techniques for future seasons.

The prevalent existence of multiple inter-continental trips to North America and Asia Pacific regions in the 2024 race schedule, that seem to have been carried over from the 2023 race schedule represent missed opportunities for Formula 1 to further reduce their adverse environmental impact. By consolidating the scheduling of regional races to take place within a single cross-continental trip, Formula 1 can minimize the need for multiple journeys to the same region, thus contributing to further reductions in travel distances and emissions.

By continuously analysing data, harnessing highly accurate weather forecasting systems, leveraging advanced optimization techniques, and collaborating with stakeholders, Formula 1 can strive toward achieving its sustainability goals while maintaining its competitive excellence and global appeal. A more environmentally responsible race calendar can resonate positively with fans and sponsors who are increasingly concerned about sustainability (Dessart & Standaert, 2023). Formula 1's efforts to reduce its carbon emissions can enhance its brand image and attractiveness to environmentally conscious audiences and partners. As a global leader in motorsports, Formula 1 has the potential to influence other motorsport series and industries by demonstrating the feasibility and benefits of sustainable scheduling.

Conclusion

In the pursuit of understanding and mitigating the environmental impact of Formula 1, this research aimed to estimate the carbon footprint due to travelling between races, and to optimize the sport's race schedule. The overarching objective was clear: to minimize the carbon footprint while respecting the operational and commercial complexities inherent to Formula 1. Through a systematic investigation, employing a combination of data analysis and optimization algorithms, this study has identified actionable insights and alternative race calendars that offer a tangible path toward fostering logistical sustainability.

The findings of this research speak to Formula 1's commitment to sustainability and its ambition to become Net Zero Carbon by 2030. Across multiple optimization models, we discovered that it is not only possible but also practical to significantly reduce both the total travel distance and the associated carbon emissions within the sport. These alternative race calendars, generated using the Greedy and Ant Colony Optimization algorithms, demonstrated substantial improvements over the official 2023 schedule as well as the official proposal for the 2024 schedule.

The practical implications of these findings are profound. By adopting data-driven approaches to optimize schedules, Formula 1 can achieve a dual benefit of environmental responsibility and operational efficiency. Reduced travel distances translate into minimized carbon footprints, aligning with global sustainability goals. Simultaneously, more efficient logistics enhance cost-effectiveness, benefiting not only the sport but also its stakeholders, including teams, sponsors, and fans (McCullough et al., 2020).

Beyond Formula 1, this research extends to the broader landscape of sports and mega-events. It showcases the potential of strategic scheduling in mitigating the environmental impact of large-scale sporting activities. Formula 1 serves as a noteworthy case study, illustrating the power of optimization models to drive eco-friendly practices and contribute to the broader shift toward environmental responsibility in the sports industry.

However, it is essential to acknowledge the limitations of this research. Data availability, weather model accuracy, and assumptions within the optimization algorithms present challenges that warrant further exploration. Future research within the context of this topic should focus on further refining the optimization models, harnessing highly accurate first-party data, and incorporating industry insider information to accurately model shipping logistics used for freight transport, as well as the intricacies of business travel of drivers and team members, and their potential role within scheduling considerations.

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