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Architectural Responses to Heat: Passive Cooling Strategies in Motorsport Facilities for Tropical Regions

Respons Seni Bina terhadap Haba: Strategi Penyejukan Pasif di Kemudahan Sukan Permotoran bagi Kawasan Tropika

Hakimi Hasrulnizam, Mohd Nasurudin Hasbullah*, Farid Al Hakeem Yuserrie

Department of Built Environment Studies and Technology, Faculty of Built Environment, Universiti Teknologi MARA, Perak Branch, Malaysia

Corresponding author email: nasur136@uitm.edu.my

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ABSTRACT - This study explores the effectiveness of passive cooling strategies in climate-responsive motorsport facility design within tropical climates, focusing on Malaysia. Despite progress in sustainable infrastructure, there is a lack of research on passive design suited to hot and humid environments, where performance often takes precedence over environmental responsiveness. A comparative case study of six circuits Sepang, Dato Sagor, Kuala Selangor, Melaka, Mandalika (Indonesia), and Chang (Thailand) was conducted using observational data, environmental analysis, wind speed measurements, sun path studies, and thermal material evaluations. The findings show that circuits employing strategies such as strategic orientation, natural ventilation, shading, insulated materials, and integration with vegetation or water features achieved superior thermal comfort and reduced dependence on mechanical cooling. In contrast, local circuits lacking these features exhibited thermal inefficiencies. The study offers design recommendations, including climate-sensitive material selection and passive ventilation methods, contributing to sustainable motorsport architecture and offering a framework for future tropical design.

INTRODUCTION

Motorsport is a dynamic and innovative industry, contributing significantly to tourism, technological advancement, and sustainable development. In Malaysia, the Sepang International Circuit serves as a major hub, hosting global events like MotoGP and formerly Formula 1, boosting economic growth and national visibility (Ab Wahab et al., 2020). However, motorsport still faces challenges, including societal stigma and a lack of structured education, particularly in niche disciplines like drifting. Historically, motorsport has influenced not only automotive progress but also urban and architectural development. The 1939 Futurama exhibition in the U.S., supported by the government and car manufacturers, envisioned a modern, car-centric future and shaped urban planning and architectural aesthetics (Miller, 2020). Le Mans, beginning in 1920, became a symbol of endurance, technology, and international competition (Glen Smale, 2023). Even earlier, the Paris–Bordeaux–Paris race in 1895 laid the foundation for competitive road racing (Henry Kelsall, 2021). Architectural evolution in motorsport is evident when comparing early tracks like Australia's Aspendale Racecourse which lacked safety and comfort (Uknowledge & Wojcik, 2022) with modern proposals like the Madrid Motorsport Facility that prioritise identity and user experience (Stuart Codling, 2017). In Malaysia, motorsport dates back to the Malayan Grand Prix (1962–1982), showing early national interest even before the official F1 era (Ferlonso, 2013). While motorsport is often criticised for pollution, studies show diesel exhaust is highly carcinogenic and harmful to respiratory health (Bhandarkar, 2010). In response, the FIA has introduced carbon offset strategies targeting net-zero emissions by 2030 (Jääskeläinen, 2024), alongside efforts

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to align architecture and operations with sustainable goals (Bram Weggemans, 2021; Balestrieri et al., 2023). These initiatives signal a shift toward environmentally responsible and climate-responsive motorsport facility design.

LITERATURE REVIEW

Passive cooling vs active cooling

Active cooling in architecture refers to mechanical systems such as air conditioning and chilled beams that remove heat using electricity, often prioritizing immediate thermal relief over long-term sustainability (Bröthaler et al., 2021). These systems are highly effective but come with significant energy consumption. A recent development is the integration of artificial intelligence in HVAC operations, enabling systems to adapt in real time using machine learning and physiological data gathered through wearable devices. These AI-driven systems consider environmental conditions (e.g., temperature, humidity, airflow) and user signals (e.g., heart rate, sweat levels) to optimize thermal comfort settings (Ihianle et al., 2022). This advancement is especially useful in multi-occupancy environments where individual comfort needs vary.

In addition, active chilled beams (ACBs) have emerged as efficient cooling solutions. These systems utilize ceiling temperature control and air induction, reducing the required cooling capacity while improving indoor climate accuracy thus contributing to energy efficiency in architectural design (Filipsson et al., 2020). However, implementing such systems independently of passive strategies can introduce significant cost and integration challenges, especially in large-scale or retrofit projects (Joshi & Moghal, 2022).

In tropical climates like Malaysia, users often prefer active cooling due to its efficiency in delivering consistent comfort. However, this widespread reliance increases energy consumption and environmental impact, particularly through vapor-compression systems that raise greenhouse gas emissions. In contrast, passive cooling techniques such as shading, ventilation, and building orientation reduce mechanical dependence, minimize carbon footprints, and draw from traditional local design knowledge (Khosla et al., 2025).

Nonetheless, passive systems alone are often insufficient in high-heat areas like server rooms or electronic hubs. For example, server management spaces typically reject fully passive strategies due to their inefficiency in managing internal heat loads. However, combining passive approaches such as effective server layout and raised flooring with mechanical systems has proven to significantly enhance cooling performance (Cai & Gou, 2024). This hybrid model underscores the value of integrated cooling approaches, particularly in energy-intensive spaces.

In motorsport facilities, active cooling is generally limited to essential zones such as CCTV marshal rooms or server control areas. This selective application presents opportunities to expand passive cooling strategies—like cross ventilation, deep roof overhangs, and thermal mass materials across other functional spaces. The value of traditional architecture becomes relevant here, where passive methods historically optimized user comfort using local environmental conditions. These include features such as elevated floors, wide openings, porous materials, and strategic shading elements that can be adapted into modern sustainable design (Toroxel & Silva, 2024).

Overall, passive and active systems are not mutually exclusive. Their integration such as skin façades combined with mechanical ventilation or shading devices supplemented by fans can produce efficient, responsive, and sustainable solutions. Especially in hot-humid climates, a hybrid strategy represents the most effective approach, balancing environmental integrity, user comfort, and long-term energy performance.

Building Orientation and Solar Positioning

Building orientation plays a crucial role in implementing passive cooling strategies, especially in tropical regions where structural positioning significantly affects thermal comfort and indoor climate performance. Designers typically establish orientation early in the design phase, particularly for exterior elements such as windows, clerestories, skylights, and solar arrays that interact with solar energy.

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When properly considered, orientation reduces unwanted heat gain, enhances natural ventilation, and minimizes reliance on mechanical systems, thereby contributing to energy efficiency and thermal comfort in tropical architecture (Rock & ASHRAE, 2020). Additionally, orientation influences the size, proportion, and placement of openings relative to latitude, which affects energy demands. Passive cooling strategies help optimize these variables to improve daylighting and ventilation while lowering dependence on artificial systems (Charalambides & Wright, 2013).

In regions with climates similar to Malaysia, such as Brazil, studies show that neglecting sun orientation during the design stage can result in severe thermal discomfort, highlighting the importance of solar-aware design for both efficiency and comfort (Benincá et al., 2023). Beyond thermal regulation, orientation impacts indoor air quality and airflow patterns, which are essential for mitigating disease transmission, including airborne illnesses like COVID-19 (Habibi, 2022). The pandemic revealed limitations in existing sustainability rating systems and emphasized the need for rethinking spatial layout to reduce the spread of illness. Building orientation for passive airflow and solar exposure became a renewed priority during this period, reinforcing its role in promoting thermal comfort, energy efficiency, and healthier indoor environments, while also reducing the risk of Sick Building Syndrome (Phapant et al., 2021). Furthermore, proper orientation enhances the performance of renewable energy systems, such as solar panels, by maximizing sun exposure and supporting energy-efficient design (Mehleri et al., 2010).

Thermal Mass and Material Consideration

Heavy mass materials in building structures can significantly influence energy efficiency and occupant comfort by regulating indoor temperatures. This is because thermal mass absorbs, stores, and gradually releases heat, thereby reducing reliance on mechanical cooling and heating systems, ultimately lowering energy consumption and improving the sustainability of buildings, particularly in climates with high temperature variations like Malaysia (Andjelković et al., 2013).

Thermal mass, defined as a material's ability to absorb, store, and release heat, plays a critical role in architecture—especially when using heavy materials like concrete. These materials significantly impact a building's energy performance and occupant comfort by reducing the need for active cooling, enhancing thermal stability, and moderating indoor temperature fluctuations for a more consistent and comfortable environment (Shafigh et al., 2018). While double-skin façades (DSF) are often implemented to enhance thermal comfort by providing an insulating air layer and facilitating controlled ventilation, the choice of materials and their thermal mass can significantly influence performance. During warmer periods, high thermal mass materials used in DSFs can absorb and retain excessive heat, potentially leading to overheating—especially on upper floors. This can increase cooling energy demands and, in some cases, diminish the effectiveness of the DSF in reducing indoor heat, thus compromising its intended passive cooling benefits (Fallahi et al., 2010).

Shading Devices to Combat Heat

Sun shading devices are architectural elements designed to control solar radiation, reduce heat gain, and improve indoor comfort. They are essential to passive cooling strategies, as they limit direct sunlight on building surfaces. Over the years, various assessment methods ranging from basic to advanced have been incorporated into technical standards to evaluate and improve shading system performance (Corrado et al., 2004). The effectiveness of these devices depends heavily on their placement and environmental context, including sky view factor (SVF) and the presence of natural shading like tree cover. In naturally shaded areas, artificial shading may have minimal impact, but in exposed zones, their role is critical. Therefore, early design-stage positioning is key to achieving optimal thermal comfort (Lam et al., 2023). Studies in Jordan and Morocco have shown that well-integrated shading strategies such as louvers, overhangs, and vertical fins not only enhance daylighting but significantly improve thermal conditions, as demonstrated through simulations and real-world applications (Alwetaishi et al., 2021). In Malaysia's tropical climate, effective shading design must also consider natural elements. Trees, in particular, contribute to thermal comfort by providing shade, reducing solar exposure, improving visual comfort, lowering heat transfer, and enhancing energy efficiency. These combined benefits demonstrate that shading devices do more than block heat—they influence façade identity and interior spatial quality, making them integral to holistic passive design (Zulkarnain et al., 2021).

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METHODOLOGY

This study employs a qualitative research methodology combined with a thematic literature review and a case study strategy to explore the implementation of passive cooling strategies in motorsport facilities within tropical climates. These methodological choices are justified based on the need for in-depth contextual understanding of design elements, climatic interactions, and architectural performance rather than statistical generalization.

Qualitative Methodology Justification

A qualitative research approach is adopted in this study to explore how passive cooling strategies are implemented and experienced in motorsport facilities. Qualitative research is defined as a systematic process of collecting, organizing, and interpreting non-numerical data derived from interviews, observations, or documents, aimed at uncovering deeper meanings and contextual insights into social phenomena (Grossoehme, 2014). It focuses on subjects in their natural settings, emphasizing rich descriptions, patterns, and themes rather than statistical data. Another interpretation describes qualitative research as the systematic analysis of textual content or observed behaviours to understand lived experiences and contextual dynamics shaped by culture and interaction. It often involves designs such as ethnography, grounded theory, and case studies, utilizing in-depth interviews, focus groups, and participant observation to explore subjective perspectives and hidden patterns (Zou & Xu, 2023). In this study, the qualitative approach enables a deeper investigation into the architectural and environmental dimensions of motorsport facilities, supported by literature and real-world case studies, without overreliance on user preferences. This minimizes bias from diverse opinions and maintains focus on spatial, structural, and climatic responses. Grounding the analysis in documented design and environmental data strengthens objectivity and avoids overinterpretation. Additionally, this approach reduces the risk of social desirability bias—where participants may respond in socially acceptable ways rather than truthfully—which can distort findings in studies on sensitive topics or where social conformity pressures exist (Bispo Júnior, 2022). As it does not require numerical analysis or complex surveys, qualitative methodology simplifies the research process and is especially effective in exploratory studies like this, where contextual interpretation is more valuable than statistical generalization.

Thematic Literature Review Method

A thematic literature review is employed in this research to systematically identify, analyse, and synthesise recurring themes and strategic approaches found within academic publications, technical reports, and architectural studies related to passive cooling, tropical climate design, and motorsport facility planning. By examining literature across these domains, key focus categories such as building orientation, natural ventilation, and shading strategies are extracted and categorised. These thematic elements are used to develop a conceptual framework that guides the research, ensuring it is rooted in established knowledge while also identifying gaps and opportunities for innovation in passive cooling strategies within tropical motorsport architecture.

According to Oruthotaarachchi & Wijayanayake (2021), a thematic literature review is a systematic approach to analysing existing literature by organizing and synthesising research findings based on specific recurring themes or topics. This method not only offers a structured overview of the current body of knowledge but also helps in identifying patterns, inconsistencies, and gaps within the research landscape, thereby guiding the direction for future investigations. This method is crucial in identifying research gaps, aligning thematic findings with real-world case studies, and providing a solid theoretical foundation to support sustainable design recommendations. It ensures that the research is both contextually grounded and academically relevant, particularly in addressing the needs of tropical climate architecture and passive cooling strategies.

Case Study Strategy

This research incorporates a case study strategy to explore the real-world application of passive cooling strategies in motorsport architecture. A case study, as defined in qualitative research, is an in-depth investigation of a particular real-world context or phenomenon within its natural setting. It is especially useful when the boundaries between the phenomenon and the context are not clearly evident. This

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method allows researchers to explore complex issues through detailed contextual analysis of a limited number of events or conditions and their relationship (Brown, 1998).

Based on this definition, a case study approach enables the research to focus specifically on what needs to be discovered, allowing for a targeted, evidence-based understanding of passive cooling strategies as they apply to motorsport facilities. Rather than generalising findings, this method prioritises depth, making it ideal for examining design and environmental performance within specific architectural settings.The case study method is highly valuable for architecture-related research because it enables the exploration of complex, multi-layered design conditions that cannot be easily generalised through broad surveys or numerical data alone. This approach allows researchers to delve deeply into specific architectural contexts, revealing nuanced relationships between form, function, environment, and user interaction. At the same time, it minimises reliance on public opinion, which may be limited due to a lack of architectural knowledge. As such, it becomes the responsibility of architecture students or researchers to critically evaluate and interpret the case studies themselves, ensuring that the analysis is grounded in professional understanding and design-specific insights (Söylemez et al., 2024).

Case Study Selection

This study investigates six motorsport facilities selected for their relevance to tropical climate design and varying implementation of passive cooling strategies. The Sepang International Circuit (SIC), designed by Hermann Tilke and completed in 1999, features a tensile membrane roof and open-air grandstand that promote shading and ventilation, serving as a benchmark for passive cooling in large-scale venues (Behnejad et al., 2023). In contrast, Litar Perlumbaan Dato Sagor in Perak lacks climate-responsive features, offering only basic roofing with minimal ventilation or insulation, reflecting how cost-driven, "build-to-complete" approaches compromise thermal comfort and sustainability (Bynum, 1983). Similarly, Litar Lumba Rakyat Kuala Selangor, with uncovered pits and limited vegetation, demonstrates the thermal discomfort experienced at grassroots facilities due to insufficient passive strategies. The Melaka International Motorsport Circuit (MIMC) also lacks effective climate adaptation, with exposed pit zones and minimal shading, highlighting common issues in mid-scale circuits. In Indonesia, Pertamina Mandalika International Circuit, opened in 2021, integrates shading devices, ventilated buildings, and landscape planning, although it still relies on active cooling in key zones; it illustrates the balance between modern performance and environmental responsiveness in tropical architecture (Nilawan Apriani, 2023). Lastly, Chang International Circuit in Thailand employs basic metal roofing and canopies but relies heavily on active cooling, revealing a limited application of passive strategies despite its international-grade status. Collectively, these case studies provide a comparative foundation to assess how motorsport facilities across Southeast Asia address—or fail to address—thermal comfort and sustainability through passive cooling design.

FINDING & DISCUSSION

Building Orientation consideration

Building orientation plays a critical role in the thermal performance and passive cooling potential of motorsport facilities, particularly in hot and humid climates such as those in Southeast Asia. The orientation of paddocks, grandstands, garages, and spectator zones significantly influences heat gain, wind flow, and daylight exposure, thereby affecting user comfort and energy efficiency. This study finds that climate-responsive orientation can mitigate solar radiation, enhance ventilation, and improve shading effectiveness. In high-performance circuits like Sepang International Circuit and Chang International Circuit, major structures are strategically oriented to reduce direct sun exposure during peak hours, resulting in better thermal comfort and reduced dependence on mechanical cooling systems. Conversely, community-level facilities such as Litar Dato Sagor and Litar Lumba Rakyat Kuala Selangor often neglect orientation considerations, leading to user discomfort and poor environmental performance.

To improve future motorsport developments and retrofits, orientation should be considered at the earliest design stages. Strategies such as aligning buildings with prevailing wind, minimizing east- and west-facing façades, and integrating sun-path-based shading are essential for reducing heat gain and optimizing natural ventilation. In tropical climates, morning and afternoon sun angles contribute significantly to thermal discomfort in open and semi-enclosed spaces. Avoiding direct solar alignment

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by offsetting building orientation from the sun's trajectory can act as a passive control measure, reducing direct exposure, improving thermal comfort, and lowering cooling demand.

Openings and spectator decks exposed to both east and west tend to accumulate heat throughout the day, causing radiant temperature build-up and increasing reliance on mechanical cooling. To avoid this, major structures should be oriented along the north-south axis where possible and supported by design strategies such as shading devices, vegetation buffers, or architectural overhangs. This orientation reduces direct sunlight penetration, maintains cooler ambient temperatures, and improves energy performance. Ultimately, strategic orientation planning enhances passive cooling effectiveness, supports sustainability goals, and ensures better user comfort in motorsport facility design within tropical environments.

Natural Ventilation Consideration

Natural ventilation is a key passive cooling strategy for motorsport facilities in tropical climates, where high temperatures and humidity affect thermal comfort. Through open-air planning, strategic voids, and orientation, natural airflow helps reduce heat buildup and improves environmental quality. Facilities like Sepang International Circuit benefit from open stands and tensile roofs that enable cross-ventilation, while Chang and Melaka circuits use overhangs, semi-open layouts, and vegetation to enhance airflow and limit heat retention.

In contrast, Litar Dato Sagor and Litar Lumba Rakyat Kuala Selangor show limited ventilation planning. While the former slightly benefits from nearby river breezes, its minimal design restricts airflow. Litar Lumba Rakyat uses temporary tents that lack any structured ventilation. Similarly, Pertamina Mandalika Circuit, despite its tensile roofing, suffers from enclosed zones and limited roof clearance, restricting vertical air movement. These cases show how spatial design can significantly impact ventilation performance.

Claudio Borri et al. (2009) highlight that moderate wind speeds (9–25 km/h) are ideal for thermal comfort. Sepang and Melaka, which recorded steady breezes above 9 km/h, illustrate how even moderate airflow can improve passive cooling in open-air environments. Additionally, increasing building porosity is essential to avoid wind blockage (Procino et al., n.d.). Solid walls at venues like Litar Dato Sagor and MIMC obstruct airflow and prevent pressure differentials needed for natural ventilation. A porous layout with strategic openings enhances cross-ventilation, reduces heat retention, and improves indoor air quality. These design approaches are critical in tropical, open-air facilities like motorsport venues, where sustainable thermal comfort depends heavily on passive airflow.

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It is my hope that this study contributes meaningfully to the field of sustainable motorsport architecture and inspires future research in enhancing thermal comfort and environmental performance. I aspire to continue this journey and one day become a specialist in circuit and motorsport facility design.

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Dr. Farid Al Hakeem Bin Yuserrie served as the main supervisor for this research, providing continuous guidance, critical feedback, and detailed reviews of the content throughout the dissertation process. His role was instrumental in shaping the structure, academic rigor, and overall direction of the study.Ts. Mohd Nasurudin Hasbullah contributed by inspiring the research focus and helping to establish the baseline study. He also played a key role in reviewing the formatting and ensuring the document adhered to academic and submission standards.The author was responsible for conducting the research, site analysis, literature review, data interpretation, and the final compilation of the Paper.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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