

# ESTABLISHING THE SUSTAINABLE ASSET MANAGEMENT MATURITY MODEL (SAMMM) FOR SAUDI METRO SYSTEMS (ISO 55001-ALIGNED) THROUGH RELIABILITY-COST-CARBON SCORECARDS

## ESTABELECIDAMENTO DO MODELO DE MATURIDADE DE GESTÃO SUSTENTÁVEL DE ATIVOS (SAMMM) PARA SISTEMAS DE METRÔ DA ARÁBIA SAUDITA (ALINHADO À ISO 55001) POR MEIO DE INDICADORES DE CONFIABILIDADE-CUSTO-CARBONO

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### Abstract

In this context, Saudi Arabia metro operators are expected to provide reliable passenger service while keeping lifecycle expenditure under control and concurrently making measurable progress towards national decarbonization targets. This paper presents and elaborates a Sustainable Asset Management Maturity Model (SAMMM) that is tailored for Saudi Arabia metro systems and aligned with the requirements of ISO 55001 for asset management systems. SAMMM goes beyond “conformance” by combining: i) a capability assessment based on ISO clauses, ii) a five-level maturity ladder, and iii) an integrated set of RCC scorecards using MCDA. The proposed approach provides an auditable link between strategic intent, such as the pathways of the Saudi Arabia Green Initiative, and day-to-day asset decisions like maintenance strategies, renewal planning, and procurement. To make the model actionable, the paper defines KPI families, normalization rules, weight elicitation, and governance practices, and a practical implementation roadmap supported by visual management tools such as framework diagram, maturity ladder, and ISO clause radar chart. Riyadh Metro serves here as an illustrative context to demonstrate how SAMMM can structure progress from early-stage data stabilization to predictive maintenance and low-carbon procurement, while concurrently maintaining high reliability.

**Keywords:** Asset Management. Metro Systems. Sustainability. Maturity Model. Multi-Criteria Decision Analysis. Reliability. Lifecycle Cost.

### Resumo

Nesse contexto, espera-se que as operadoras de metrô da Arábia Saudita forneçam um serviço confiável aos passageiros, mantendo os custos do ciclo de vida sob controle e, simultaneamente, fazendo progressos mensuráveis em direção às metas nacionais de descarbonização. Este artigo apresenta e detalha um Modelo de Maturidade de Gestão Sustentável de Ativos (SAMMM) adaptado para os sistemas de metrô da Arábia Saudita e alinhado aos requisitos da ISO 55001 para sistemas de gestão de ativos. O SAMMM vai além da “conformidade” ao combinar: i) uma avaliação de capacidade baseada nas cláusulas da ISO, ii) uma escala de maturidade de cinco níveis e iii) um conjunto integrado de indicadores de desempenho de custo-benefício (RCC) usando Análise Multicritério de Decisão (MCDA). A abordagem proposta fornece uma ligação auditável entre a intenção estratégica, como os caminhos da Iniciativa Verde da Arábia Saudita, e as decisões cotidianas sobre ativos, como estratégias de manutenção, planejamento de renovação e aquisição. Para tornar o modelo acionável, o artigo define famílias de indicadores-chave de desempenho (KPIs), regras de normalização, ponderação e práticas de governança, além de um roteiro prático de implementação apoiado por ferramentas de gestão visual, como diagrama de estrutura, escala de maturidade e gráfico de radar das cláusulas da ISO. O Metrô de Riade serve aqui como um contexto ilustrativo para demonstrar como o SAMMM pode estruturar o progresso desde a estabilização de dados em estágio inicial até a manutenção preditiva e a aquisição



*de baixo carbono, mantendo simultaneamente alta confiabilidade.*

**Palavras-chave:** *Gestão de Ativos. Sistemas de Metrô. Sustentabilidade. Modelo de Maturidade. Análise de Decisão Multicritério. Confiabilidade. Custo do Ciclo de Vida.*

## 1 INTRODUCTION

Urban rail networks are long-life, capital-intensive assets whose public value depends on disciplined operation and maintenance over decades. For metro operators, sustained reliability is not optional: service interruptions can create immediate social and economic impacts while safety obligations impose strict controls on how maintenance and renewals are planned and executed (Zhang, Shuyang, et al 2021). In the meantime, lifecycle costs can drift upward due to reactive maintenance, poorly controlled outsourcing, unmanaged obsolescence, and siloed data systems (Sandborn, Peter 2015). Meanwhile, transport infrastructure is now expected to play its part in national emissions strategies and to demonstrate progress through credible measurement. Riyadh Metro provides a timely context for this challenge (Alotaibi et al 2018). According to public sources, this is a fully automated network comprising 176 km and 85 stations, with operations scheduled to begin in December 2024. At this scale, the need for standardized asset information, disciplined work management, and consistent decision-making across many asset classes-rolling stock, signaling, traction power, stations/buildings, and civil infrastructure-becomes an increasing challenge. In the Saudi Arabia context, these operational expectations coincide with an explicit national direction on climate and sustainability. The SGI describes a target to reduce CO<sub>2</sub>e by 278 million tonnes per year by 2030 and a pathway "towards net zero by 2060". Whereas those targets apply economy-wide, metro systems contribute both directly-operational energy use, maintenance activities-and indirectly by enabling modal shift away from higher-emitting road transport. ISO 55001 provides internationally recognized requirements for establishing, implementing, maintaining, and improving an asset management system (AMS) designed to realize value from assets (Hastings, Nicholas Anthony John 2021). ISO 55001's structure places emphasis on organizational context, leadership, planning, support, operation, performance evaluation, and improvement-a management system

backbone that can be audited. However, conformance with a standard is not the same as maturity (Sather, Mike R., et al. 2018). A metro organization may well document its procedures yet still have systemic issues concerning inconsistent failure coding (González-Prida, Vicente, et al. 2022), weak asset criticality definitions, limited spares governance, or fragmented energy and carbon data. On the contrary, a highly experienced maintenance team may deliver acceptable service performance yet be well short of the documentation and governance required for resilience, scaling, and auditing (Ghodeswar, et al 2008). A maturity model translates requirements and best practice (Rosa, Isabel Da, and Miguel Mira Da Silva 2015) into staged capability levels, enabling a "current state to target state" roadmap. GFMAM emphasizes that maturity looks beyond ISO 55001 compliance to the characteristics exhibited at higher capability levels and encourages capability development beyond minimum conformance (GFMAM, 2024). This paper proposes the Sustainable Asset Management Maturity Model (SAMMM) to meet this need for Saudi Arabia metro systems (Mahmood, Muhammad Nateque, et al 2015). The central design choice is to integrate three outcome dimensions that matter operationally and strategically: reliability (service and asset performance), cost (total cost of ownership and budget control), and carbon (Scope 1-3 greenhouse gas emissions) (Hanski, Jyri, and Ville Ojanen 2020). The integrated framing helps avoid typical tensions: cost reduction efforts that degrade reliability, sustainability initiatives that ignore operational risks, or audit preparations that become "paper exercises" detached from performance (Pigosso, Daniela C. A., and Tim C. McAloone 2016).

## **2 LITERATURE REVIEW**

### **2.1 ISO 55001 and value realisation through asset management systems**

According to ISO 55001, an AMS is responsible for the realization of value from assets through the optimization of costs, risks, and performance within an organization (Maletič, Damjan, et al 2023). The standard itself, like other management-system standards, is organized around Clauses 4 to 10. This promotes integration with wider corporate governance. Guidelines for implementation reinforce that leadership commitment, integration into business processes, competence, and evidence-based performance evaluation are crucial to success. Indeed, in practice, the alignment of asset

management objectives with organizational objectives is facilitated in ISO 55001 by means such as policy, planning, operational controls, and management review (Da Silva et al 2022).

ISO 55001:2024 again emphasizes SAMP as a key mechanism to align the asset management with wider organizational goals and stakeholder needs (Rehak, David, et al 2025). For metro systems, alignment is of particular importance since stakeholder requirements are manifold and sometimes in conflict Vuorinen, Lauri, and Miia Martinsuo 2019: comfort and punctuality of passengers, compliance to safety, affordability, accessibility, environmental performance, and long-term resilience of the network. A SAMP should, therefore, translate these high-level needs into decision rules, renewal strategies, risk tolerances, and measurable objectives which can be managed over time (Türpe, Sven 2017).

## 2.2 Asset management maturity models

Maturity models describe, in general, progressions from ad hoc practices to managed, standardized, integrated, and optimized capability. GFMAM's Asset Management Landscape emphasizes that maturity is not about meeting the requirements of ISO 55001 but that organizations should evaluate and develop capability well beyond compliance (Boholm et al 2017). A maturity ladder provides a practical “language” for capability improvement and supports leadership decisions on where to invest-data foundations, work management discipline, asset information, competence, and continuous improvement routines (Rongen, Tibor, et al 2022).

However, many maturity models are generic and capability-centric; they do not explicitly incorporate sustainability performance. Sustainability is often treated as a parallel reporting stream, not a decision criterion, in asset lifecycle planning. For metro systems falling under national decarbonization targets (Holtz, Georg, et al. 2018), the segregation of sustainability from asset management causes misalignment: for instance, carbon reductions can be pursued without considering operational risk, while reliability improvement initiatives may ignore energy and embodied carbon implications. A combined maturity-scorecard model is valuable because it links capability development to measured outcomes and provides an explicit structure for balancing them (Tscheikner-Gratl, Franz, et al 2019).

### 2.3 Scorecards and MCDA integration needs

Scorecards are a way of translating strategy into measurable indicators. On transport infrastructure, reliability and cost metrics are established, but environmental performance often remains less integrated into planning. Even when carbon is measured, it may be at the corporate level without linkages through to specific asset decisions-e.g., renewals, maintenance regimes, or procurement choices (Salet, Willem, et al 2000). Indicators can't easily be combined because they have different units and time horizons. Reliability may respond quickly to maintenance discipline, cost performance can lag due to procurement cycles, and carbon changes can be strongly influenced by grid emissions factors and major capital renewals (Ross, Alexander Reid, et al. 2023).

MCDA presents a structured way to integrate indicators when decisions have multiple criteria and trade-offs. The methods are recognized as powerful tools for sustainability assessment, as they allow transparency in decision-making if assumptions and weights are documented (KIT, 2022). Comparative research describes widely used methods, including weighted sum models and TOPSIS, and highlights the fact that results can be sensitive to normalization and weighting (Daugavietis et al., 2022). EPRI notes that MCDA could help complement the cost-benefit analysis in cases where climate and resilience outcomes are of essence but are not easy to monetize consistently. This insight matters for metros because safety and minimum service levels are often constraints rather than variables to trade-off: the “optimization space” sits above those thresholds, where MCDA is useful for prioritizing improvements and choosing among technically acceptable options (Oh, Chang Hoon, et al. 2103).

#### 2.4 Metro Carbon Accounting Boundaries

Carbon integration requires well-defined boundaries. According to the GHG Protocol, emissions are categorized into Scope 1, representing direct emissions from owned or controlled sources; Scope 2, relating to indirect emissions through purchased energy; and Scope 3, other indirect emissions throughout the value chain. For metro systems, the balance of Scope 2 electricity usually prevails in operational emissions due to the fact that traction power and station electricity are normally purchased from the grid (Siew, Renard Y. J 2015). Scope 1 may include fuel used in maintenance fleets, backup generators, and other on-site combustion sources. The scope of Scope 3 might also be extended to cover embodied emissions from rolling stock and infrastructure procurement, upstream fuel and electricity generation, contracted maintenance services, and waste

treatment as well as end-of-life impacts. A sustainability maturity model not considering Scope 3 risks misses significant portions of lifecycle carbon impacts for systems that are undertaking expansions or major renewals. On the other hand, measuring Scope 3 accurately is difficult as it involves information from suppliers, harmonized material databases, and transparent allocation keys (De Haes, S., and W. Van Grembergen 2005). Hence, a maturity approach is fitting: early stages can focus on robust Scope 1-2 measurement and boundary setting, later stages add embodied emissions for renewals, including metrics for supplier engagement to evolve Scope 3 coverage.

### 2.5 Reliability and Energy Consumption Due to Environmental Stresses

Rail assets are exposed to environmental and climate stresses (Haes et al 2008). Research synthesizing climate risks to railway infrastructure highlights that the rise of temperature and increased extreme events affect infrastructure performance and maintenance burdens. Temperature-related risks can raise the need for maintenance and operational control complications. Rail equipment adaptation guidance also emphasizes the protection of trackside electronics and cable systems and the enabling of remote health monitoring to reduce reactive maintenance. In desert and hot climates, dust and heat accelerate wear, degrade cooling performance, and increase energy demand for HVAC in stations and rolling stock (Randjelovic, Jelena, et al 2003). These stresses influence reliability, cost, and carbon simultaneously, therefore entrenching the need for an integrated maturity framework with climate-informed planning and monitoring.

### 3. Methodology

## **3 METHOD**

### **3.1 SAMMM design principles**

SAMMM thus developed as a maturity model overlay, ISO 55001 clauses, and five principles: P1 Standards alignment: The maturity model results should align with ISO 55001 Clauses 4-10 to ensure auditable results (ISO, 2024). P2 Triple outcome focus: Focus on the results of reliability, lifecycle costs, and carbon outcomes together and not via separate programs for managing them. P3 Transparency: Define Key Performance Indicators and methods for normalization and weights for maturity model results for easy repeatability and auditability. P4 Actionability: Map maturity model results to an actioned road map with owners and accountability for specified results. P5 Saudi Arabia

contextualization: Alignment with Saudi Arabia GSI goals and Saudi Arabia metro operational requirements (Saudi Arabia Green Initiative, 2024a).

### **3.2 Development stages**

#### **Step 1: Scoping**

It is set up at the level of the metro network and involves broad categories of assets like “rolling stock, signaling, traction power, stations/buildings, civil/track, IT/OT.” There is a need to set boundaries to be able to calculate consistently key performance indicators and emission inventories. Concerning carbon, boundaries must also address control within the organization, whether the operator or the asset owner, based on the scope identified by GHG Protocol (GHG Protocol, 2004).

**Step 2: ISO clause-capability assessment.** This is conducted with regard to the seven ISO task areas: context, leadership, planning, support, operation, performance evaluation, and improvement (BSI, 2016). This is conducted by means of scrutinized reviews on the following documents for the collection of evidence: policy and procedure process, asset register, maintenance plans process, work orders process taken from the risk register process, risk assessment process and results from audit reports, training process, and management review process. This is conducted with the help of an assessment checklist (refer below for the checklist on capability assessment against the ISO clauses).

#### **Step 3: Locate the Five-Level Maturity Ladder**

The SAMMM adopts the maturity models present in the guidelines of the preceding model, which follows a five-stage maturity levels model with levels classified as Initial, Managed, Defined, Competent, and Optimizing levels, with each described with the characteristics of the required levels of behavior with respect to the factors of governance, data, execution of maintenance, and sustainability integration mentioned in the levels of each stage. The important point about SAMMM, however, lies in the fact that any improvement within the maturity levels of SAMMM must show progress with regard to capability and outcome metrics, which are incorporated in the scorecards of RCCs.

#### **Step 4: Prepare scorecards for RCC and integrate them with MCDA.**

The reliability scorecards, cost scorecards, and carbon scorecards can be prepared using minimum key performance indicators scaled between 0 to 1 on the scale (ITPS, 2022). These scorecards can be integrated with MCDA to develop the Sustainability Index (KIT, 2022).

**Table 1**

*Example SAMMM maturity descriptors (illustrative)*

Maturity level	Typical characteristics	Typical focus for next step
Level 1 – Initial	Reactive work dominates; limited standardization; fragmented data; carbon tracked only ad-hoc.	Stabilize asset register; standardize failure coding; define Scope 1–2 boundary.
Level 2 – Managed	Repeatable maintenance; basic KPI dashboards; start of Scope 1–2 inventory; corrective actions mostly reactive.	Formalize risk registers and asset criticality; integrate carbon KPIs into reporting.
Level 3 – Defined	Standardized processes and roles; routine KPI review; initial supplier engagement for embodied emissions.	Strengthen audits, management reviews, and change control; deploy targeted monitoring and analytics.
Level 4 – Competent	ISO-conformant governance; integrated data architecture; measured RS/CS/KS improvements; sustainability used in procurement.	Expand predictive maintenance; optimize renewals with lifecycle carbon and cost optimization.
Level 5 – Optimizing	Predictive/prescriptive maintenance; continuous improvement culture; low-carbon procurement embedded; sustained high reliability.	Innovate and benchmark; refine Scope 3 coverage and reduction pathways.

### 3.3 RCC scorecards and KPI definitions

“A proposed set of KPIs is recommended by SAMMM and may be expanded. Preferably, the proposed set of KPIs should strive to be (i) relevant, (ii) measurable with available or possible data, (iii) traceable or possible to relate or establish connections with asset management decisions. These may be:

Reliability scorecard (RS) R1 Service availability (%): proportion of planned services delivered with minimum interruption; target should be ideally set based on contractual requirements. R2 Subsystem Mean Time Between Failures (MTBF) for critical subsystems such as traction, braking system, doors, platform screen doors, and signaling apparatus, measured in hours or kilometers respectively. R3 Mean Time to Repair (MTTR) for critical subsystems (hours): this metric covers maintainability and spares performance. R4 Preventive maintenance completion rate (%): This shows

performance on Discipline shown during services as per schedule. R5 Failures with repeat frequency rate (%) to measure efficiency on application of Root Cause Analysis findings and Follow Through actions collectively taken.

### **Cost scorecard (CS)**

C1 Lifecycle cost index: actual versus baseline planned lifecycle cost for key asset classes (both OPEX and planned CAPEX renewal spend).

C2 Cost intensity of maintenance: cost per train-km (or passenger km), broken out by asset class, offering avenues for optimization.

C3 Spares effectiveness: critical spares availability and stockout rate, a measure of service level and rush requisition spend.

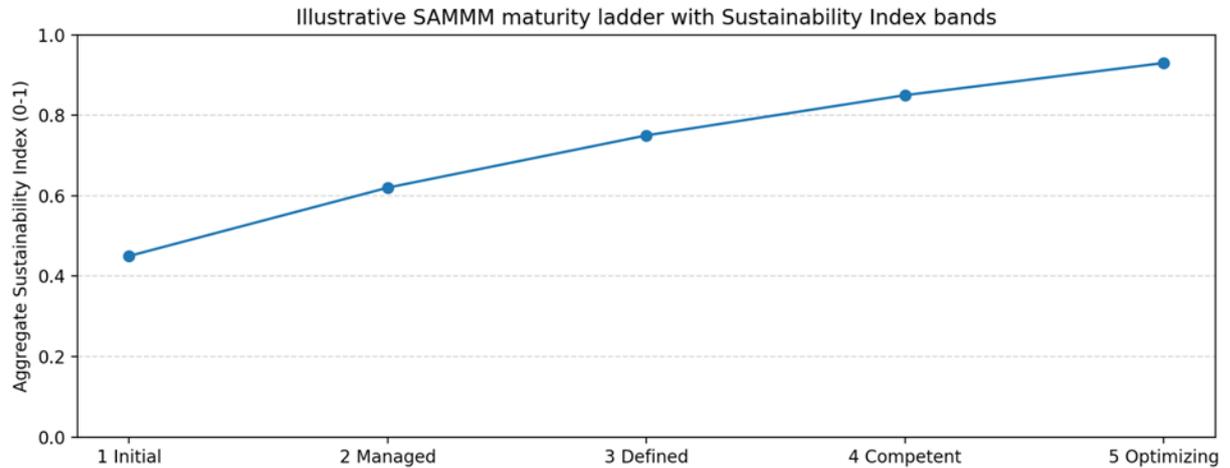
C4 Cost intensity of energy: energy cost per train-km or passenger km, accounting for tariffs and demands if applicable.

C5 Contract variance: change orders and claims, a measure of stability of scope, governance, and contract maturity.

Carbon scorecard (KS) K1 Intensity of Scope 2 electricity use: Emissions/kg CO<sub>2</sub>e/trains-km or per person-km, aligned to the Scope 2 boundaries (**GHG Protocol, 2004**) K2 Emissions from Scope 1 sources, maintenance, and generators: Emissions/kg CO<sub>2</sub>e/y, consistent reporting. K3 Embodied emission index for renewal and replacement projects, normalized through a quantity of activity (e.g., CAPEX) with progressively more mature to advanced levels, focusing on a later stage through supplier-developed EPDs or through known values for embodied carbon whenever and wherever possible. K4 Waste diversion and circular economizing proxy metric: Focused on the percentage of municipal and industrial waste sent to landfill, consistent and aligned to broader national policies and goals. K5 Supplier engagement effectiveness: Percentage of key partners reporting Scope 3 GHGs to the company, effectiveness and performance target for Scope 3, indicating maturity in the process

**Figure 1**

*Illustrative maturity ladder showing Sustainability Index (0-1) bands across SAMMM levels*



### 3.4 Normalization and index construction

To facilitate integration across different units, data normalization within a range of 0 to 1 is mandatory in SAMMM. For "benefit" variables like "availability," where higher values are ideally preferred, and "cost" variables like "emissions intensity," where lower values are ideal, data is normalized using the score range equation  $Score = (X - X_{min}) / (X_{max} - X_{min})$  and  $Score = (X_{max} - X) / (X_{max} - X_{min})$ , respectively. Lastly, values of  $X_{min}$  and  $X_{max}$  are set according to internal best practices, agreements, and credible external sources. It is essential to understand that this enables "the ability to put transparency first concerning data assumption updates and KPI updates across all levels, instead of changing the range of values according to levels that could hide improvements made by lower levels."

In every dimension, the obtained results are summed up together:  $RS = \sum a_i * r_i$ ;  $CS = \sum b_j * c_j$ ;  $KS = \sum c_k * k_k$ , where the weights are summed up to 1 for each scorecard. The Sustainability Index is calculated according to the following expression:  $SI = w_r * RS + w_c * CS + w_k * KS$ . Weights definition is performed within the stakeholder workshops and testing situations, adopting the MCDA guidelines related to the need for transparency in weights definition and sensitivity testing for added value (KIT, 2022; Daugavietis et al., 2022). A guide by EPRI recommends the application of MCDA in the

integration of climate outcomes if monetization under uncertainty is not required (EPRI, 2025).

### **3.5 Weight governance: thresholds, scenarios, and SAMMM model**

In the SAMMM model, safety issues and minimum service demands are considered as ‘constraints’ rather than ‘variables’. Thus, the reliabilities need to be ensured prior to performing ‘trade-off’s. How to perform the analysis is suggested below:

- Define ‘must-meet’ thresholds (safety and minimum service delivery).
- Use SI mostly for screening projects which need to be pursued beyond ‘must-meet’ thresholds and also for evaluating alternatives with ‘must-meet’ requirements already satisfied.
- Assign weights by evaluating ‘scenarios’ such as: effect evaluations of ‘high electricity emissions factor’ rather than ‘low emissions factor’; effect evaluations ‘volatile’ rather than ‘stable’ electricity pricing impacts; ‘high low-emissions factor’ rather than ‘low low-emissions factor’; ‘sensitivity analysis: Assess ‘priority’ stability for weights set in ‘plausibly different’ ranges. If ‘priority’ rankings’ display ‘unstable’ characteristics, then the ‘model itself’ has to be ‘strengthened’; this could be attempted either by improving ‘data quality’ or by reinforcement of ‘constraints’ (Bogentoft, Erik, et al 2001).

### **3.6 Improvement roadmap and action planning**

Action is required for maturity modeling. SAMMM translates gaps into a road map by assigning them an owner, time frame, and potential anticipated benefit for KPI. These would typically be early actions to normalize asset data, integrate work management processes, and establish an authoritative boundary for emissions and eventually expand to more comprehensive analysis when involving suppliers to manage embedded emissions and optimize replacement (Talebizadeh, Mansour, et al 2010).

## 4 PROPOSED SAMMM MODEL & GRAPHICAL REPRESENTATION

### 4.1 SAMMM levels

SAMMM assesses "maturity" through observations of governance structures and performance. The stages are:

Level 1 Initial: Reactive operations dominate; variable failure coding; primitive lifecycle planning; carbon tracked only through ad-hoc reporting. Level 2 Managed: Repeatable maintenance operations; basic analytics and dashboards; primitive asset registration framework; emerging Scope 1-2 accounting; the vast majority of actions remedial, and hence reactive. Level 3 Defined: Synchronized maintenance operations; risk registers and asset criticalities; systematic review of key performance indicators; carbon performance indicators introduced into reporting; emerging engagement with supplier around embodied carbon. Level 4 Competent (ISO-compatible) or mature: Strategic governance by leadership; audited business processes; risk-based asset replacement planning; data infrastructure; tracked progress on RS, CS, and KS; sustainability considerations built into procurement and change control. Level 5 Optimizing: Predictive and prescriptive maintenance; business of continuous improvement; optimal asset replacement planning and execution; lowered carbon procurement and maintainability by design; carbon intensity lowered, while high reliability maintained (Castella, Jean-Christophe, et al 2007).

### 4.2 Graphical representation and use in governance

The purposes of SAMMM are:

- The framework flow chart is employed to depict the contribution made by the ISO capability assessment within the determination of the gap analysis, maturity progression, RCC scorecard, and the roadmap within the context of the process for constant improvement.
- The maturity ladder graphic is employed to demonstrate the progression from one SI maturity level to another within SI in order to facilitate goal planning and prioritization.
- The radar chart is employed to emphasize the capability maturity chart on the level of the statements within the ISO business areas in order to determine the improvement barriers, such as support or appraisal, within the capabilities that have not improved.

### 4.3 Case study of Riyadh Metro

Despite the lack of operational data presentation, the case study of the Riyadh Metro project provides exact background information to explain the effectiveness of the SAMMM. First, there would be the definition of the capability by the operator and the related assets, with the boundaries of the study included. Second, there would be the evaluation of the capability by means of the use of the evidence presented by the contracts and work, and performance. Third, there would be the calculation of the baseline RCC indicators based on the information presented by the present systems. Then the fourth part will include the definition of the roadmap, consisting of 2-3 years, concentrating on the capability halted by the performance of the RATP Dev (2024).

The early stages involve foundational areas, such as: cleaning up asset databases, COMMON FAILURE CODING, aligning PM plans with asset criticality, and checking strong Scope 2 reporting for electricity. Toward more mature stages, analytics and monitoring tasks are well-suited, such as: condition monitoring on critical infrastructures, energy analytics at stations and TP, and engagement with suppliers to forecast Scope 1 embedded emissions from significant renewal programs. This is because a typical pattern will emerge: it is difficult to undertake optimization tasks on unanchored processes for data (BSI, 2016).

### 4.4 Implementation requirements: data & systems

By definition, “SAMMM requires valid asset information and performance data.”

In an ideal architecture, one could observe that there is:

- An asset register with details such as identification number, hot and cool criticality, and life cycle.
- Register of CMMS/EAM functionalities: requests for work, preventive maintenance, routine maintenance, breakdowns, and parts use.
- Operational data that monitors service delivery performance, energy use, and reliability issues.
- Carbon accounting module with alignment with scope 1 through 3 boundaries (Greenhouse Gas Protocol, 2004)

- Governorship flow, where it traces its discoveries from auditing, corrections, and the roadmap.

The adaptation directives issued to Railways have underlined that reactive maintenance could be aided in its reduction through health monitoring when exposed to stress (UIC/Alstom, 2017). In Saudi Arabia Metro Rail projects, failures due to heat and dust can be monitored, and then optimisation of such monitored factors could be achieved based on limitations related to energy and carbon footprints (ISO, 2024; BSI Standards Publication, 2016).

## 5 DISCUSSION

SAMMM integrates sustainability results within the asset management maturity process to ensure reliability, total cost of ownership, and carbon are all part of the process as a whole. This is because, unless all three are integrated, organizations end up handling multiple programs that could interact counteractively, such as handling cost, counteracting the process of managing preventative maintenance and carbon initiatives without necessarily carrying out effective risk analysis (ISO, 2024; GFMAM, 2024). SAMMM resolves the issue by employing the use of ISO clause capability (governance) that is connected to an RCC scorecard through thresholds to ensure that minimum safety and service levels are not undermined.

Climate change and environmental challenges have become even more convincing arguments for an integrated perspective to take into account. Risks associated with climate change could trigger more maintenance and process disruption and thus raise additional costs and additional emissions due to higher energy use and shorter cycles of substitution (Haghighi, 2025). The integration of such arguments into the model by SAMMM will allow organizations to treat the danger of climate change as an input and not an outside source (Haghighi et al., 2025; UIC & Alstom, 2017).

The application of the Sustainability Index seems more restricted in application as a priority approach, such as in identifying projects or options for upgrade with lower GHG emissions in the lifecycle stage by fixing reliability, or tracking changes in sustainability on an annual basis (EPRI, 2025).

## 6 LIMITATIONS AND FUTURE WORK

SAMMM involves data quality and coordination with other entities in the use of evidence-based principles for governance. As of now, newly formed entities may not possess harmonized failure reporting, measuring the use of energy, and supply chain reporting of Scope 3 emissions. Such factors could be treated as immaturity factors and not as a hindrance to the use of the model approach. Some of the proposed suggestions for the future would be to develop embodied carbon datasets with focus to the GCC states regarding the railway transport infrastructure, validation of SAMMM using the conduct of validation studies of a period of two years, and the enhancement of the MCDA to consider the uncertainty in the factors of the emission coefficients, as well as climate impact of stress, using SAMM models.

## 7 CONCLUSION

In the aforementioned proposed study, the focus of this paper was to identify and define the Sustainable Asset Management Maturity Model for Saudi Arabia Metro networks, referred to as the SAMMM, with alignment and fulfillment of ISO 55001, and also with the implementation of the integration of the foremost aspects of reliability and cost and carbon scores through Multi-Criteria Decision Analysis, referred to as MCDA. There appears to be the potential and feasibility of applying the same toward the progressive approach from ISO 55001 implementation through enhancements toward sustainable management with integration of Scope 1-3 carbon accounting, cost, and reliability, inspired by the decarbonization vision of the SGI.

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**Authors' Contribution**

All authors contributed equally to the development of this article.

**Data availability**

All datasets relevant to this study's findings are fully available within the article.

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