SUPPLEMENTARY MATERIAL

1. SUMMARY OF PRACTICAL APPLICATIONS

Table S1. Key factors for each dimension in the building projects.

Key sustainability factor	Code	Description	Sources
Energy management	ENV1	Systematic process of monitoring, analyzing, and optimizing energy consumption during the construction phase.	(Al Harazi et al., 2022; Daly et al., 2025; Francis & Thomas, 2020; Medineckienė et al., 2010; Zhang & Mohandes, 2020)
Environmental protection and decarbonization	ENV2	Prevent damage to the ecosystem and conserve natural resources during project execution, ensuring the protection of biodiversity. This includes rigorous pollution control, along with the implementation of decarbonization strategies to significantly reduce CO_2 and other greenhouse gas (GHG) emissions.	(Boakye & Adanu, 2022; Francis & Thomas, 2020; Medineckienė et al., 2010)
Water consumption efficiency	ENV3	Implementation of practices to minimize water use on site and maximize water reuse during the construction phase	(Al Harazi et al., 2022; Boakye & Adanu, 2022; Zhang & Mohandes, 2020)
Management of construction materials and waste	ENV4	Selection of local, recycled or sustainable materials, and efficient management of generated waste, seeking to reduce the ecological footprint and promote the circular economy.	(Al Harazi et al., 2022; Boakye & Adanu, 2022; Daly et al., 2025; Francis & Thomas, 2020)
Cost and schedule management	ECO1	Optimization of financial and time resources in construction to ensure project viability, controlling costs and avoiding delays.	(Al Harazi et al., 2022; Ayalew et al., 2023; Daly et al., 2025; Medineckienė et al., 2010; Mhmoud Alzubi et al., 2023)
Quality management	ECO2	Implementation of processes and standards to ensure the durability, safety and reliability of the building, minimizing defects and future repair costs.	(Al Harazi et al., 2022; Daly et al., 2025; Mhmoud Alzubi et al., 2023)
Comprehensive risk management	ECO3	Identification, assessment and mitigation of potential risks during construction to prevent problems and optimize the long-term performance of the building.	(Daly et al., 2025; Ismail, 2021; Tseng et al., 2023; Zhang & Mohandes, 2020)
Preventive maintenance	ECO4	Implementation of planned and systematic actions on the building's elements and systems (structure, installations, finishes) from its installation, in order to detect and correct problems in time, prevent deterioration and ensure its quality and durability.	(Daly et al., 2025; Mhmoud Alzubi et al., 2023)
Productivity	ECO5	Maximizing efficiency in the use of labor, machinery and time during construction to reduce costs and increase production.	(Ayalew et al., 2023; Mhmoud Alzubi et al., 2023)
Supply chain management	ECO6	Ensuring the timely availability of materials and services, optimizing flows, selecting reliable suppliers, and controlling inventories.	(Daly et al., 2025; Ismail, 2021)
Participation and collaboration	SOC1	Establishing communication channels and working together among all stakeholders (workers, communities and companies) to foster an environment of respect and informed decision-making.	(Al Harazi et al., 2022; Stender & Walter, 2019)
Occupational health and safety	SOC2	Implementation of measures and technologies to protect the physical and mental well-being of workers, minimizing risks and promoting a safe and sustainable work environment.	(Al Harazi et al., 2022; Daly et al., 2025; Stender & Walter, 2019; Tseng et al., 2023)
Impact on the community	SOC3	Positive contribution to the quality of life of local communities adjacent to the project, by minimizing negative effects (such as noise, dust or disruptions) and maximizing social benefits (such as the creation of inclusive public spaces, local employment opportunities or the development of community infrastructure).	(Al Harazi et al., 2022; Daly et al., 2025; Stender & Walter, 2019)

Table S2. Definition and bibliographic sources of the selected Construction 4.0 technologies.

Construction technology 4.0	Code	Description	Sources
Building Information Modeling	BIM	It is a collaborative work methodology based on a centralized digital model that comprehensively manages the technical, physical and functional information of an infrastructure throughout its entire life cycle.	(Follini et al., 2020; Ham et al., 2018; Merschbrock & Munkvold, 2015; Waqar et al., 2023)
Artificial Intelligence and Machine Learning	AIML	Advanced computing technologies that process and analyze large volumes of data to identify complex patterns, optimize operational processes in real time, and predict structural or energy behaviors with high accuracy.	(Debrah et al., 2022; Hu et al., 2024; Selvaraj et al., 2023; Serrano, 2022; Shapi et al., 2021)
Advanced materials for construction	AMatC	They are structural or architectural components developed through nanotechnological, chemical or biological innovation that exhibit superior physical properties —such as self-repair, high specific resistance or carbon capture— optimizing the performance of the building.	(Aboutorabi et al., 2024; Alaskar et al., 2023; Barros et al., 2023; Macías-Silva et al., 2024; Xing et al., 2025)

Table S3. Main contributions of BIM, AIML and AMatC to sustainable building.

Construction technology 4.0	Environmental dimension	Economic dimension	Social dimension	Sources
Building Information Modeling	• Integration of Life Cycle Assessment (LCA). • Energy and lighting performance simulation. • Material passports for the circular economy.	• Automated clash detection. • Optimization of schedules (4D) and budgets (5D). • Reduction of OPEX through Digital Twins (7D).	• Predictive simulation of indoor comfort. • Transparency and governance among stakeholders. • Planning and prevention of occupational risks within the model (8D).	(Lu et al., 2021; Pinheiro et al., 2018; Röck et al., 2018; Saavedra et al., 2025; Shahedi & Abrishami, 2026; Wu et al., 2022; Yin et al., 2026; Zhou et al., 2026)
Artificial Intelligence and Machine Learning	• Generative design for carbon footprint optimization. • Automated, predictive, real-time control of HVAC systems using IoT. • Forecasting of water and energy resource demand.	• Structural predictive maintenance (reduction of failures). • Construction progress monitoring via computer vision. • Predictive supply chain optimization.	• Automated monitoring of safety and Personal Protective Equipment (PPE) usage. • Intelligent, sensor-based environmental regulation for worker well-being and comfort. • Automation of routine management tasks to reduce mental workload and work-related stress.	(Aktepe et al., 2021; Amangeldy et al., 2025; Cheng et al., 2020; Li et al., 2024; Poh et al., 2018; Pour Rahimian et al., 2020; Xiang et al., 2022)
Advanced materials for construction	• Adoption of geopolymers and clinker substitutes. • Smart materials for active CO_2 capture. • Bio-based insulation with low embodied energy.	• Self-healing materials that extend service life. • Ultralight composites that reduce transportation costs. • Reduced maintenance due to anti-corrosive properties.	• Greater structural resilience against earthquakes and fires. • Photocatalytic coatings for the elimination of VOCs (volatile organic compounds). • Advanced insulation for optimized thermal and acoustic comfort.	(Aboutorabi et al., 2024; Alaskar et al., 2023; Jung et al., 2025; Kılınç et al., 2025; Ramesh et al., 2025; Raza et al., 2024; Wen et al., 2024; Xiang et al., 2022)

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Table S4. Cross matrix of technological solutions: Application cases of BIM, AIML and AMatC in the environmental dimension.

Code	Practical application	Applications in BIM	Applications in AIML	Applications in AMatC
ENV1	Simulation and modeling of energy demand	• Predictive energy modeling in early stages using integrated tools (e.g., Insight, Green Building Studio). • Parametric analysis of orientation, building envelope performance, and glazing. • Integration of digital twins for calibrating simulation models with real-world operational data.	• LSTM/GRU models for hourly or daily forecasting of heating and cooling demand. • Predictive modeling (Random Forest, XGBoost) of thermal loads based on microclimatic variables and architectural design parameters. • Hyperparameter optimization to maximize the accuracy of predictive energy models.	• Advanced thermophysical characterization of new materials to calibrate energy simulation models. • Integration of validated phase-change materials (PCMs) for passive thermal storage simulations. • Incorporation of aerogels and biocomposites with experimental reflectance and emissivity data.
	Active optimization and real-time energy control	• Integrated digital twins with IoT sensors for real-time monitoring of temperature, humidity, and occupancy. • Integration and modeling of renewable energy systems (photovoltaics and geothermal). • BIM visualization panels (dashboards) for real-time monitoring of operational setpoints and energy savings.	• Deep reinforcement learning (DQN, PPO, SAC) for intelligent HVAC and lighting control. • Metaheuristic algorithms (PSO, GWO) for dynamic optimization of operating setpoints. • Use of neural networks to predict domestic hot water demand and optimize boiler operation.	• Cementitious materials with embedded sensors (CNT, carbon black) for real-time thermal and structural monitoring. • Thermochromic and electrochromic glazing systems with dynamic transmittance control. • Use of high thermal inertia materials (such as geopolymers) to passively stabilize interior temperatures.
	Multi-objective and life cycle assessment	• BIM-LCA-LCC interoperability through the use of automated environmental and cost analysis tools (e.g., One Click LCA, Tally). • Multi-objective optimization using genetic algorithms (NSGA-II) integrated into visual programming environments (Dynamo/Grasshopper). • Visual Pareto analysis for optimal trade-off selection.	• Advanced evolutionary algorithms (NSGA-III, MOPSO) to simultaneously optimize energy, costs, emissions, and comfort. • Surrogate models based on neural networks to accelerate computational optimization cycles. • Sensitivity Analysis of Global Potential (SHAP) to identify the design variables with the greatest environmental and economic impact.	• Life cycle assessment of materials with low embodied energy (geopolymers, cross-laminated timber). • Use of biocomposites and recycled concrete to reduce the overall environmental impact of buildings. • Incorporation of highly durable materials (UHPC, FRP) to optimize long-term eco-efficiency.
ENV2	Carbon assessment and reduction	• BIM-LCA integration for quantifying embodied carbon throughout the building's entire life cycle. • Parametric material substitution in the digital model for benchmarking low-impact alternatives. • Automated quantity extraction (QTO) for predictive emissions calculations in early design phases.	• Predictive modeling (XGBoost and Random Forest) of annual operational emissions from buildings. • Time series forecasting using LSTM networks for dynamic analysis of hourly carbon footprints. • Use of Explainable Artificial Intelligence (XAI using SHAP/LIME) to identify the criticality and contribution of materials and processes.	• Development of eco-efficient concretes with clinker replacement that achieve 30% to 50% reductions in CO_2 emissions. • Synthesis of alkali-activated geopolymers from mining waste to minimize embodied carbon. • Use of certified wood and advanced biocomposites as biogenic carbon sinks.

	Optimization and active control of emissions	• Coordination of integrated energy systems (photovoltaics, aerothermal, storage) within BIM environments for dynamic control of operational emissions. • Real-time monitoring of emissions during the construction phase using integrated sensors (CO_2 and particulate matter). • Parametric simulation of decarbonization scenarios to optimize renewable energy systems and efficiency strategies.	• Adaptive control using deep reinforcement learning (DRL) to mitigate operational (HVAC) and logistical emissions on construction sites. • Predictive indoor air quality control (LSTM/GRU) for dynamic optimization of ventilation systems. • Transportation route optimization models for reducing supply chain logistical emissions.	• Improvement of indoor air quality (IAQ) through the use of ultra-low VOC biocomposites. • Active CO2 capture through the integration of adsorbent matrices (e.g., zeolites) into HVAC systems. • Active and photoactivated mitigation of ambient NOx through the deployment of photocatalytic pavements.
ENV3	Reducing demand, reusing and optimizing water use	• Integration of water balances geared towards compliance with international sustainability certifications (e.g., LEED, GBI, Mostadam). • Parametric simulation of stormwater water balance based on roof geometry and consumption profiles. • Dynamic modeling and coordination of greywater systems linked to building occupancy matrices.	• Predictive modeling of hourly domestic hot water (DHW) demand using neural networks (ANN/LSTM). • Application of hybrid CNN-LSTM networks for simulating operational behavior in greywater treatment plants. • Model-based predictive control (MPC) algorithms to optimize energy consumption in DHW systems (with savings of 19% to 35%).	• Microstructural optimization of the water/binder ratio (experimental range: 0.35–0.50) for hygrothermal control of cementitious mixtures. • Optimization of efficiency in water reuse systems using low-absorption cementitious matrices (≤1.33%) and hydrophobic coatings. • Development of controlled-porosity materials for passive filtration systems intended for greywater and rainwater regeneration.
	Loss prevention and system integrity assurance	• BIM-SA parametric optimization of hydraulic networks for pressure control and prevention of operational failures. • Algorithmic programming of pumping cycles to mitigate peak energy demand (achieving up to 69% efficiency). • Automated detection of spatial clashes in the design of complex water and sanitation networks.	• Intelligent diagnostics based on neural networks for early detection and real-time leak location. • Residual chlorine forecasting (Random Forest/LSTM) to optimize water network purging and renewal cycles. • Time series modeling of pressure and flow rate to identify anomalies and assess network operational integrity.	• Low-permeability materials (dense microstructure) that prevent infiltration. • Nanometric hydrophobicization treatments (silanization) to drastically reduce capillary absorption (from 5.12 to 0.75 g/g). • Low-roughness fiber-reinforced polymer (FRP) pipes to mitigate corrosion failure and preserve structural integrity.
ENV4	Quantification, characterization and environmental assessment of waste and materials	• Automatic estimation of waste volumes per building element. • Integration with Life Cycle Assessment (LCA) databases to evaluate the environmental impact of waste management. • Generation of as-built models using Scan-to-BIM workflows and UAV photogrammetry for accurate material inventory quantification.	• Predictive modeling (SVR/XGBoost) of the mechanical strength of concrete with incorporated byproducts (rubber, glass, slag). • Real-time automated waste sorting using machine vision (YOLOv8) coupled with unmanned aerial vehicles (UAVs). • Estimation of costs and emissions associated with waste transport using artificial neural networks.	• Development of advanced geopolymers through the characterization and valorization of construction and demolition waste (CDW), slag, and sludge to optimize their environmental performance. • Substitution of natural aggregates with recycled plastics (PET) or crushed glass in cementitious matrices. • Characterization and environmental assessment of sludge and ash as active cementitious admixtures.
	Optimizing circularity (reduction, reuse, recycling)	• Development of digital twins for deconstruction and the planning of selective on-site demolition strategies. • Parametric optimization of building elements to minimize material waste (optimal panel cutting).	• Use of reinforcement learning (Q-learning) to determine optimal waste management policies (-42.9% in GWP and -29.6% in waste mass). • Algorithmic optimization and integration of geographic information systems (GIS) for the efficient management of	• Manufacturing cross-laminated timber (CLT) and laminated timber (GLT) from reclaimed wood, reducing global warming potential (GWP) by 72%. • Development of aerogels based on cellulosic waste functionalized with phase-

• Automated decision-making based on BIM and multi-criteria analysis (BIM-MCDM) to optimize circular economy flows.	construction and demolition waste (CDW) collection routes. • Implementation of machine vision (YOLO) for purity control and automated sorting of recycling streams.	change materials (PCMs) for passive thermal insulation. • Reuse of recovered aluminum composite panels (ACMs) in architectural cladding and secondary substructures.	

Table S5. Cross matrix of technological solutions: Application cases of BIM, AIML and AMatC in the economic dimension.

Code	Practical application	Applications in BIM	Applications in AIML	Applications in AMatC
ECO1	Reduction of direct material and construction costs	• BIM-supported value engineering (VE) assessment for optimizing design and material alternatives (achieving estimated cost reductions of 35%). • Automatic quantity takeoff (QTO) to mitigate quantity takeoff errors and over-purchases on site. • Integration of commercial or custom modules for automated supplier selection and comparison within the BIM model.	• Early cost estimation using backpropagation artificial neural networks (ANN-BP) with error margins of less than 2.5%. • Predictive modeling of financial overruns using Random Forest (RF) and Support Vector Machine (SVM) algorithms. • Multi-objective optimization using genetic algorithms for the design of efficient mix design ratios (balancing cost against mechanical strength).	• Use of concrete with industrial byproducts (recycled aggregates and fly ash), reducing direct costs by 35% to 43%. • Implementation of reclaimed or residual wood components with mechanical connections as a low-cost structural alternative. • Replacement of virgin fibers with recycled fibers for the sustainable reinforcement of cementitious matrices.
	Life cycle cost (LCC) optimization and maintenance cost reduction	• Implementation of specialized plugins for automated LCC analysis during investment, operation, and maintenance phases. • Simulation of intervention scenarios for predictive planning of building system rehabilitation and replacement. • Integration of BIM models with computer-aided maintenance management systems (CMMS).	• Deep learning modeling (DBN, LSTM) for predicting annual maintenance costs. • Application of SHAP (Shapley Additive Explanations) analysis to identify the critical variables with the greatest impact on LCC. • Probabilistic reliability models for estimating the remaining useful life (RUL) of equipment and active infrastructure.	• Incorporation of nano-silica and recycled steel fibers to extend service life and reduce the need for corrective interventions. • Use of highly durable ultra-high-performance concrete (UHPC) to minimize long-term maintenance costs. • Development of self-healing materials with encapsulated bacteria for the autonomous sealing of microcracks.
	Accelerating the schedule and minimizing delays	• Integrated 4D planning with virtual and augmented reality (VR/AR) technologies to optimize usability (+10.3%), accuracy (+89.1%), and control speed (+30%). • Automated detection of space-time interferences and conflicts between critical construction activities. • Synchronization of 4D models with the Last Planner System (LPS) and Agile frameworks for dynamic production control.	• Project timeline prediction using deep neural networks (DNN) and support vector regression (SVR). • Real-time monitoring and identification of construction disruptions (weather-related factors or supply shortages) using computer vision algorithms. • Optimization of construction scheduling under environmental and resource constraints using evolutionary and genetic algorithms.	• Use of fast-setting materials and in-situ 3D printing technologies based on high early strength concrete. • Use of lightweight, precast fiber-reinforced polymer (FRP) components to accelerate assembly times. • Implementation of reusable polymer formwork systems to optimize concrete curing and pouring cycles.
ECO2	Preventive quality assurance	• Automated multidisciplinary collision detection for predictive mitigation of geometric interferences during the design phase. • Automated verification of regulatory compliance in the BIM model.	• Predictive modeling of concrete's mechanical strength using deep learning architectures (DNN) and gradient-driven algorithms (XGBoost). • Forecasting of seismic response and lateral displacements using	• Non-destructive testing using terahertz (THz) waves to ensure uniform fiber distribution and mitigate the formation of critical structural points. • Use of micronized fly ash to optimize setting homogeneity

		• Geometric and informational quality control of as-built models through tolerance validation and statistical analysis.	coupled hybrid LSTM and PSO-LSTM models. • Automated classification of design anomalies and inconsistencies using computer vision applied to the processing of technical documentation.	and prevent segregation in the cementitious mix. • Incorporation of specific additives in the fresh state to eliminate bleeding and prevent surface cracking.
	Inspection, monitoring and early detection of defects and clashes	• BIM-IoT integration using maturity sensors for dynamic monitoring and real-time estimation of concrete strength. • Augmented Reality (AR) application for recording, tracking, and managing construction defects during building handover. • Dimensional quality control of prefabricated elements assisted by 4D simulations and immersive Virtual Reality (VR) environments.	• Automated inspection using unmanned aerial vehicles (UAVs) and neural networks (YOLOv5, Knet) for structural defect detection. • Identification of structural damage from vibration signals using ConvLSTM-type spatiotemporal neural networks. • Precise location of anomalies and leaks in hydraulic networks using accelerometer fusion and artificial neural networks (ANNs).	• Evaluation of the electrical resistivity of concrete as a non-destructive indicator of curing status, durability, and strength gain. • Incorporation of smart chromogenic additives for visual alerts in the presence of moisture or excessive stress/force. • Development of conductive nanocomposites with self-sensing capabilities integrated into the matrix for continuous deformation monitoring.
ECO3	Evacuation simulation and emergency planning	• Integration of BIM models with fire dynamics simulators (FDS) and pedestrian analysis tools (MassMotion) for accurate simulation of smoke propagation and evacuation flows. • Semi-automated assessment of compliance with fire safety regulations, assisted by specialized design tools (e.g., CYPEFIRE). • Dynamic, real-time planning of evacuation routes using ontologies and sensor networks.	• Predictive modeling of fire development, temperature gradients, and carbon monoxide (CO) concentrations using hybrid CNN-LSTM architectures and Transformers-based models. • Estimation of critical evacuation time in stairwells using machine learning algorithms. • Probabilistic quantification of material losses due to fire and prioritization of mitigation measures using XGBoost algorithms and SHAP explainability analysis.	• Use of polymers and reinforced concretes (HPFRCC, CFRP, and FRP) to prevent structural collapse in evacuation routes. • Application of heat-expanding (intumescent) coatings to create an insulating barrier and preserve the load-bearing capacity of the steel. • Implementation of smart aerogels for ultra-early detection of heat sources and activation of alarms in <1.3 seconds.
	Risk monitoring, early detection and real-time response	• Integration of IoT sensors, ontologies, and 4D BIM models for dynamic updating of emergency routes. • Parametric mapping in BIM of structural damage detected using UAVs and deep learning for digital image processing. • Monte Carlo simulation integrated into 4D BIM models for visualization, analysis, and control of temporary risks on construction sites.	• Real-time detection and classification of structural pathologies and damage using YOLOv5 and ConvLSTM models. • Predictive reconstruction of missing sensor data with PSO-DNN to ensure continuous monitoring. • Assessment and classification of structural collision risk between adjacent buildings using convolutional neural networks (e.g., Adjacent Net).	• Development of self-sensing geopolymers with a high gauge factor (GF > 3800) for ultrasensitive monitoring of real structural deformations. • Implementation of three-dimensional conductive networks (nanoparticles and metallic fibers) to ensure signal transmission under high load demands. • Integration of cementitious sensors based on CNT/NCB for continuous structural monitoring without degradation of the load-bearing section.
	Assessment and mitigation of structural risks and natural phenomena	• Geotechnical modeling and evaluation of ground settlements induced by tunneling processes using interoperability protocols based on IFC and MATLAB schemes. • Application of stochastic methods to quantify the probability of structural failure due to seismic activity or corrosion.	• Automated derivation of seismic fragility curves using ANN, Random Forest, and SVM algorithms. • Predictive modeling and impact assessment of natural hazards (e.g., hurricanes and floods) using XGBoost and DFNN. • Forecasting and stochastic modeling of direct economic losses	• Structural reinforcement systems based on advanced cementitious composites (HPFRCC) and fiber-reinforced polymers (FRP) designed to mitigate progressive collapse. • Use of highly durable ultra-high-performance concrete (UHPC) to mitigate long-term risks of corrosion and fatigue.

		• Visualization and mapping of vulnerabilities in non-structural components (e.g., suspended ceilings, HVAC systems, and piping networks) under extreme risk events.	resulting from disasters or extreme weather events.	• Implementation of advanced viscoelastic materials for energy dissipation and damping of structural seismic response.
ECO4	Structural health inspection and monitoring	• Automated generation of as-built models using terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) data fusion. • Integration of structural sensor data (vibration, deformation, and temperature) into the BIM model for continuous, real-time monitoring. • Dynamic monitoring of structural integrity during the transport and installation of prefabricated modules.	• Identification and characterization of cracks and displacements through vibration signal analysis using LSTM and ConvLSTM networks. • Detection of critical load states in timber structural elements using acoustic emission combined with GRNN and GPR. • Monitoring of crack propagation under thermal gradients using RFID systems coupled to artificial neural networks (ANNs).	• Development of intelligent self-restraining cementitious matrices based on carbon nanotubes (CNTs) and carbon black (CB). • Formulation of geopolymer composites with copper-coated steel fibers for self-sensing capabilities. • Implementation of three-dimensional conductive networks in cement-based composites for continuous structural monitoring without external sensors.
	Early detection and predictive maintenance	• Planning and scheduling of preventive maintenance using BIM (7D) information models. • Integration of BIM models and augmented reality (AR) for on-site overlay of technical specifications and intervention history on the asset. • Visualization of pathologies using automated color coding in the BIM model for managing the level of degradation.	• Predictive maintenance and lifecycle management (RUL) forecasting of HVAC systems and rotating equipment using LSTM and CNN models. • Assessment of building condition and repair time forecasting using hybrid ANN and CBR systems. • Stochastic optimization of repair and component replacement policies based on reinforcement learning (Q-learning).	• Implementation of materials with a high gauge factor (3853.4) for the ultra-early detection of micro-deformations. • Incorporation of recycled fibers to mitigate premature structural failures due to thermal fatigue. • Application of surface treatments with nano-silica to extend the durability and lifespan of concrete with recycled aggregates.
ECO5	4D planning, flow simulation and coordination	• Automated spatiotemporal detection of geometric clashes and work area saturation using 4D BIM models. • Integration of BIM with Lean Construction methodologies (LPS, JIT, VSM) to increase operational productivity. • Integration of BIM models with virtual reality (VR) to optimize usability and accuracy in workflow coordination.	• Predictive modeling of labor performance using multilayer perceptron (MLP) networks. • Multifactorial analysis of exogenous variables (weather, altitude, and crew composition) on productivity using neural networks. • Prediction of manufacturing lead times in the plant using RFID systems and Random Forest algorithms.	• Implementation of low-density fiber-reinforced polymers (FRP) to simplify handling and reduce assembly times. • Use of high-precision prefabricated components through digitized design-to-manufacturing (BIM-to-Fabrication) workflows. • Adoption of reusable modular polymer formwork systems to optimize concrete pouring cycles.
	Optimization of prefabrication and off-site production	• BIM-CAM integration for digital manufacturing automation, increasing productivity by up to 57% compared to traditional CAD workflows. • Parametric coordination and simulation of the assembly of three-dimensional modules and their structural beam-column connections. • Quality control and assurance in prefabrication environments assisted by 4D dynamic simulations and virtual reality (VR).	• Cycle time prediction in industrialized prefabrication using RFID data fusion and Random Forest. • Early estimation of concrete compressive strength using DNN and XGBoost to accelerate formwork removal and dispatch cycles. • Performance monitoring and optimization in prefabrication plants using sensor networks and k-NN algorithms.	• Automation of FRP component production using robotic filament winding without molds or formwork (RCFW). • Implementation of cyber-physical systems (CPS) with sensor-enabled feedback loops for autonomous production line control. • Additive manufacturing of concrete (3D printing) through the formulation of mixes with fast-setting accelerators.

	Real-time monitoring and control of on-site productivity	• Component traceability and cloud-based updates of the construction schedule using RFID, UWB, and BIM positioning technologies. • Quantification of on-site performance by directly linking parametric elements of the BIM model with productivity rates. • Monitoring of the project's physical progress (planned vs. actual) through common data environments (CDEs) based on BIM web platforms.	• Automated monitoring using machine vision to detect bottlenecks and logistical delays at the construction site (e.g., material shortages or blocked access). • Automated classification of operational personnel work cycles using deep learning supported by wearable devices. • Continuous diagnosis of the mechanical condition of heavy machinery through vibration analysis and k-NN classification.	• Reduced logistical burden and accelerated on-site assembly through the use of lightweight FRP structural components. • Integration of passive RFID tags into advanced cementitious components for inventory and supply chain automation. • Application of high-reflectance surface coatings to optimize operational visibility and mitigate delays caused by low light.
ECO6	Selection and evaluation of suppliers and materials	• Centralization of technical requirements and supplier profiles within the parameterized BIM information model. • Integration of the Analytic Hierarchy Process (AHP) into BIM environments for multi-criteria evaluation and supplier selection. • Interoperable linking of the model with cloud-based catalogs of materials with technical and environmental certifications.	• Hybrid modeling using neural networks and multi-criteria decision-making (MCDM) for optimal material selection based on cost, lead time, and performance. • Application of semi-supervised learning algorithms (k-means and decision trees) to estimate the project's material intensity. • Predictive time series analysis to model price volatility and lead times in the construction market.	• Incorporation of standardized Environmental Product Declarations (EPDs) for the sustainable validation of geopolymers and biocomposites. • Evaluation and validation of advanced materials under international sustainability certification schemes.
	Flow optimization, monitoring, and disruption response	• Real-time traceability of components (factory-to-construction site) through the integration of RFID/UWB identification technologies and cloud-based BIM platforms. • BIM-WMS (Web Map Service) integration for geospatial optimization of critical paths and minimization of logistics distribution times. • Configuration of digital twins for stochastic simulation and resilience against supply chain variability.	• Automated identification of supply chain disruptions (e.g., component shortages or access restrictions) using computer vision. • Dynamic routing through the hybridization of Geographic Information Systems (GIS) and Machine Learning to mitigate distances and carbon emissions. • Predictive modeling and forecasting of logistics delays in supply based on historical data mining.	• Implementation of smart, sensor-equipped packaging for continuous hygrothermal monitoring of advanced materials susceptible to degradation. • Automated monitoring and inventory management through the integration of RFID tags embedded in prefabricated components. • Use of high-tenacity fiber-reinforced polymers (FRP) to mitigate shrinkage and structural damage during logistics transport.

Table S6. Cross matrix of technological solutions: Application cases of BIM, AIML and AMatC in the social dimension.

Code	Practical application	Applications in BIM	Applications in AIML	Applications in AMatC
SOC1	Centralized digital platforms for information exchange	• Cloud-BIM ecosystems and Common Data Environments (CDEs) for real-time information exchange and synchronization. • Information governance and responsibility allocation through BIM Execution Plans (BEPs). • Semantic environments based on ontologies and SWRL rules	• Collaborative AI-assisted design (CAD-AI) systems for optimizing metal structures. • Collaborative maintenance management using case-based reasoning (CBR) and natural language processing (NLP). • Generative AI for accelerated rendering and democratizing participatory design.	• Eco-materials and by-products characterized as commercial assets that enable digital exchange platforms. • Performance profiles and multi-scale properties of advanced materials as standardized datasets for open repositories. • Digital passports and sustainability attributes of advanced materials as units of

		for interactive stakeholder communication.		information for validation on secure platforms.
	Multidisciplinary coordination and collaborative conflict resolution	• Federated BIM modeling (architecture, structure, MEP) with automated clash detection. • Integration of BIM models with immersive technologies (VR/AR) for spatial validation and proactive rework mitigation. • Collaborative workflows based on federated models for continuous technical conflict resolution.	• AI-powered generative modeling for consensus-based decision-making and community validation of facades. • Augmented Reality-AI-based cognitive assistance for operational support through predictive and historical asset visualization. • NLP-based recommendation systems for decision support in resolving technical conflicts.	• Certified circular materials as standardized assets that mitigate technical uncertainty and market friction. • Materials with smart labeling (QR/RFID) for traceability and technical coordination on site.
SOC2	Accident and incident prevention (physical security)	• Automatic planning of collective protections with 4D BIM. • BIM as databases for automated auditing of safety regulations (OSHA) and fire protection. • BIM spatial and geometric modeling as data infrastructure for dynamic evacuation simulations and VR environments.	• Deep learning models (CNN-LSTM, Transformers) for fire spread forecasting and evacuation dynamics. • Safety monitoring and fall detection based on Wi-Fi signal analysis (CSI) and deep learning. • Automation of safety reports with LLMs.	• Functional aerogels with ultra-fast response for early fire warning systems. • Flame-retardant biocomposites that slow the spread of flames. • Advanced pavements with controlled microtexture for optimized friction coefficient and active fall prevention.
	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	• Parametric BIM modeling for simulating and controlling hygiene risks from contaminants on construction sites. • Pre-construction BIM models for configuring virtual reality (VR) scenarios for occupational safety and health. • Integration of air quality sensors into the BIM model.	• Predictive modeling using deep learning (LSTM/GRU/CNN) for dynamic monitoring and early warning of air quality (CO_2, PM2.5, VOCs). • Hybrid decision support systems (ANN, evidential reasoning, LLMs) for proactive and predictive management of occupational risks. • Detection of noise and vibration levels using machine learning.	• Biocomposites based on low-emissivity natural fibers for passive and high-efficiency (>50%) attenuation of volatile organic compounds (VOCs). • Purifying materials with activated carbon that absorb hazardous chemical gases to clean construction site air. • Nanomaterials developed using a safe design approach to mitigate occupational exposure and toxicity risks.
SOC3	Protecting the health and safety of the community	• Optimization of social housing using a Life Cycle Sustainability Analysis (LCSA) approach. • Georeferenced BIM models for integrating macro-scale urban data and assessing the building's surroundings. • Parametric BIM models as visual and informative assets to support citizen consultation platforms.	• Automated facade inspection using UAVs and neural networks (KNet) for public safety risk prevention. • Supervised learning models (XGBoost, Random Forest) for predictive fire risk mapping and urban safety planning. • Intelligent pollutant dispersion modeling (VOCs, PM) for air quality forecasting and public health protection.	• Ultra-low VOC biocomposites for preserving air quality. • Photocatalytic materials in building envelopes for active air purification on construction sites and reduced worker exposure to toxic gases. • High-density recycled composites for mitigating ambient noise and improving community well-being.
	Promotion of local social, cultural and economic development	• Development of citizen consultation environments based on Virtual Reality (VR) solutions integrated with the BIM model for the immersive evaluation of the urban and visual impact of different design options. • BIM infrastructure modeling for parametric connectivity analysis and optimization of social impact.	• AI-powered generative design models for the morphological integration of building envelopes in accordance with local architectural identity. • Mask R CNNs for identifying and classifying informal extensions in historic districts. • Deep learning algorithms (Mask R-CNNs) for protecting urban heritage from informal extensions.	• Locally sourced bio-based materials (plant fibers, agricultural waste) generate employment in collection and processing. • Valorization of local agricultural waste for the development of circular building materials. • Modular systems using residual wood for the self-

• Parametric attribution in BIM models for the integration of sociopolitical criteria in component selection.	• Neural models for the ethical governance and transparent management of smart urban infrastructure.	construction of affordable social housing.

2. SEARCH STRATEGY

Table S7. Boolean search strategy in Web of Science (WoS) for selected key technologies.

Construction 4.0	Code	Búsqueda WoS
Building Information Modeling	BIM	"BIM" OR "Building Information Modeling" OR "Building Information Modelling"
Artificial intelligence and machine learning	AIML	"Artificial intelligence" OR "machine learning" OR "deep learning" OR "neural networks" OR "reinforcement learning" OR "artificial neural network" OR "Long Short-Term Memory" OR "Genetic Algorithms" OR "Swarm Intelligence" OR "Large Language Models" OR "Cognitive Computing" OR "Computational Intelligence" OR "computer vision"
Advanced materials for construction	AMatC	"smart materials" OR "intelligent materials" OR "self-healing materials" OR "nanomaterials" OR "high-performance concrete" OR "ultra-high performance concrete" OR "fiber-reinforced polymers" OR "carbon-sequestering materials" OR "self-sensing materials" OR "aerogels" OR "3D printable concrete" OR "graphene-reinforced composites" OR "carbon nanotubes" OR "geopolymers" OR "smart coatings" OR "micro-encapsulation" OR "engineered cementitious composites" OR "transparent wood" OR "super-insulating materials" OR "biocomposites" OR "ecological material" OR "sustainable material" OR "green material" OR "recycled material" OR "thermochromic materials" OR "bio-based materials"

Table S8. Boolean search strategy in Web of Science (WoS) for the identification of key sustainability factors.

Key sustainability factor	Code	Boolean agents for searching in WoS
Energy management	ENV1	"energy management" OR "energy optimization" OR "energy optimisation" OR "energy monitoring" OR "energy control systems" OR "energy efficiency strategies" OR "energy consumption" OR "energy simulation" OR "smart energy management"
Environmental protection and decarbonization	ENV2	"carbon footprint" OR "CO2 emissions" OR "decarbonization" OR "environmental protection" OR "ecosystem preservation" OR "biodiversity conservation" OR "natural resource conservation" OR "habitat protection" OR "ecological impact" OR "CO2 control" OR "carbon emission reduction" OR "pollution control" OR "low-carbon construction" OR "greenhouse gas mitigation" OR "pollution prevention"
Water consumption efficiency	ENV3	"water consumption" OR "water consumption efficiency" OR "water efficiency" OR "water use minimization" OR "water saving" OR "water conservation" OR "water management" OR "water footprint" OR "water reuse" OR "on-site water treatment" OR "greywater reuse" OR "water monitoring" OR "smart water management" OR "automated water control" OR "hydrological efficiency" OR "water circularity" OR "wastewater management" OR "stormwater management" OR "water efficiency" OR "water assessment" OR "stormwater assessment" OR "wastewater assessment" OR "Water-use efficiency" OR "leakage detection" OR "water leak" OR "indoor water use" OR "Conserving water" OR "leak detection" OR "water metering"
Management of construction materials and waste	ENV4	"construction and demolition waste" OR "CDW management" OR "waste minimization" OR "waste recycling" OR "waste recovery" OR "construction materials management" OR "construction waste management" OR "material tracking" OR "waste management" OR "materials management" OR "waste estimation" OR "materials management" OR "resource management" OR "volume calculation" OR "quantity take-off" OR "quantification of materials" OR "QTO" OR "quantity takeoff" OR "Quantity Take-Offs" OR "Quantity Take-Off" OR "material circularity" OR "Life Cycle Assessment of construction materials" OR "LCA of materials" OR "Life Cycle Assessment (LCA) assessments of building materials" OR "Life Cycle Assessment of building materials" OR "material quantities" OR " building materials" OR "material passports" OR "resource efficiency" OR "passports for materials"
Cost and schedule management	ECO1	"cost management" OR "cost control" OR "financial optimization" OR "financial optimisation" OR "budget control" OR "cost estimation" OR "project financing" OR "economic viability" OR "cost overrun prevention" OR "schedule management" OR "construction scheduling" OR "delay prevention" OR "schedule control"

Quality management	ECO2	"quality management" OR "quality assurance" OR "quality control" OR "total quality management" OR "structural reliability" OR "defect minimization" OR "rework reduction" OR "ISO9001" OR "ISO 9001" OR "quality performance" OR "durability assessment" OR "service life prediction" OR "automated inspection" OR "real-time monitoring" OR "computer vision for quality" OR "image-based inspection" OR "technical inspection" OR "Clash Detection" OR "Smart construction inspection" OR "BIM clashes" OR "BIM clash" OR "Construction Conflicts" OR "Infrastructure durability" OR "structural quality" OR "crack prevention" OR "structural quality" OR "Clash Triage" OR "structural monitoring" OR "construction inspection" OR "structural health" OR "infrastructure maintenance" OR "infrastructure safety" OR "health monitoring" OR "failure risk" OR "infrastructure inspection" OR "image-based inspection"
Comprehensive risk management	ECO3	"risk management" OR "risk identification" OR "risk assessment" OR "risk mitigation" OR "comprehensive risk management" OR "probabilistic risk analysis" OR "contingency planning" OR "disaster risk reduction" OR "Safety Risk" OR "risk analysis" OR "cost contingency" OR "technical risk" OR "contractual risk" OR "performance risk" OR "risk modeling" OR "safety monitoring"
Preventive maintenance	ECO4	"preventive maintenance" OR "planned maintenance" OR "proactive maintenance" OR "systematic maintenance" OR "scheduled maintenance" OR "maintenance planning" OR "predictive maintenance" OR "deterioration prevention" OR "failure prevention" OR "structural health monitoring" OR "condition monitoring" OR "remote monitoring" OR "non-destructive evaluation" OR "sensor-based maintenance" OR "real-time diagnostics" OR "vibration analysis" OR "thermal imaging inspection" OR "reliability-centered maintenance" OR "maintenance optimization" OR "total productive maintenance" OR "structural monitoring" OR "structural maintenance" OR "building maintenance" OR "structural maintenance" OR "construction maintenance" OR "automatic maintenance"
Productivity	ECO5	"productivity" OR "productivity improvement" OR "construction productivity" OR "labor productivity" OR "production efficiency" OR "workforce productivity" OR "labor performance" OR "equipment productivity" OR "machinery efficiency" OR "Machinery productivity" OR "Schedule optimization" OR "automated progress monitoring" OR "real-time tracking" OR "improvement in the schedule" OR "increased production"
Supply chain management	ECO6	"construction supply chain" OR "supply chain management" OR "logistics management" OR "supply chain optimi*ation" OR "integrated supply chain" OR "supplier reliability" OR "inventory control" OR "stock management" OR "on-site inventory" OR "supply chain monitoring" OR "supply chain control" OR "real-time traceability" OR "supply chain resilience" OR "supply chain agility" OR "economic order quantity" OR "inventory accuracy" OR "stockout prevention" OR "inventory turnover" OR "on-hand inventory" OR "digital inventory" OR "sensor-based tracking" OR "RFID" OR "barcode scanning" OR "GPS tracking" OR "Just-in-Time Supply" OR "supply chain*" OR "logistics management" OR "value chain*" OR "Distribution Management" OR "real-time inventory" OR "automated warehousing" OR "consignment stock"
Participation and collaboration	SOC1	"stakeholder engagement" OR "stakeholder participation" OR "collaborative working" OR "multi-stakeholder collaboration" OR "community engagement" OR "public participation" OR "project communication" OR "organizational transparency" OR "collaborative culture" OR "collaborative decision-making" OR "informed decision-making" OR "participatory planning" OR "collaborative work" OR "transparent communication" OR "Relational Contracting" OR "Alliance Contracting" OR "Early Contractor Involvement" OR "Shared Governance" OR "Project Partnering" OR "Conflict Resolution" OR "Cloud-based Collaboration" OR "Common Data Environment" OR "Real-time Collaboration" OR "Community Relations" OR "efficient communication" OR "effective communication"
Occupational health and safety	SOC2	"occupational safety" OR "occupational health and safety" OR "workplace safety" OR "accident prevention" OR "safety management systems" OR "physical well-being" OR "mental health" OR "worker health" OR "occupational stress" OR "hazard mitigation" OR "safety monitoring" OR "occupational hazards" OR "occupational health" OR "computer vision for safety" OR "safety climate" OR "safety culture" OR "work-life balance" OR "safety risk" OR "psychological safety" OR "worker engagement" OR "ergonomics" OR "occupational hygiene" OR "worker training" OR "smart safety" OR "automated safety inspection"
Impact on the community	SOC3	"community benefit*" OR "social impact" OR "quality of life" OR "inclusive public spaces" OR "social sustainability" OR "urban regeneration" OR "local employment" OR "job creation" OR "community development" OR "social welfare" OR "worker welfare" OR "impact on the community" OR "sociocultural" OR "community wealth building" OR "community resilience" OR "social inclusion" OR "equity in construction" OR "corporate social responsibility" OR "social life cycle assessment" OR "well-being of individuals" OR "well-being of the community" OR "Workers' welfare" OR "local employment" OR "user welfare" or "occupant welfare" OR "occupant well-being" OR "social sustainability" OR "social benefit" OR "social benefits" OR "inclusive spaces" OR "heritage protection" OR "organizational culture" OR "local communities" OR "community well-being" OR "local well-being" OR "neighborhood well-being" OR "neighborhood comfort" OR "community engagement" OR "citizen participation" OR "community benefit" OR "community impact"

3. SELECTED ARTICLES

Table S9. Quantification and percentage distribution of selected items by technology and key sustainability factor.

Key sustainable factors	BIM		AIML		AMatC		Total	%
	No.	%	No.	%	No.	%		
ENV1	114	22%	171	35%	16	17%	301	28%
ENV2	46	9%	58	12%	20	22%	124	11%
ENV3	15	3%	13	3%	6	7%	34	3%
ENV4	75	15%	21	4%	10	11%	106	10%
ECO1	74	14%	41	8%	6	7%	121	11%
ECO2	17	3%	35	7%	4	4%	56	5%
ECO3	38	7%	40	8%	9	10%	87	8%
ECO4	18	4%	39	8%	2	2%	59	5%
ECO5	37	7%	36	7%	4	4%	77	7%
ECO6	8	2%	3	1%	1	1%	12	1%
SOC1	37	7%	3	1%	1	1%	41	4%
SOC2	27	5%	19	4%	10	11%	56	5%
SOC3	5	1%	5	1%	3	3%	13	1%
Total number of articles by factor [1]	*511*	*100%*	*484*	*100%*	*92*	*100%*	*1087*	*100%*
Total number of articles [2]	*386*	*76%*	*399*	*82%*	*86*	*93%*	*871*	*80%*
Environmental	250	49%	263	54%	52	57%	565	52%
Economic	192	38%	194	40%	26	28%	412	38%
Social	69	14%	27	6%	14	15%	110	10%

[1] Counting the total number of selected articles, considering that there are repeated articles among the key factors (ENV1-ENV4; ECO1-ECO6; SOC1-SOC3).

[2] Consider the total number of articles, eliminating duplicate articles between factors.

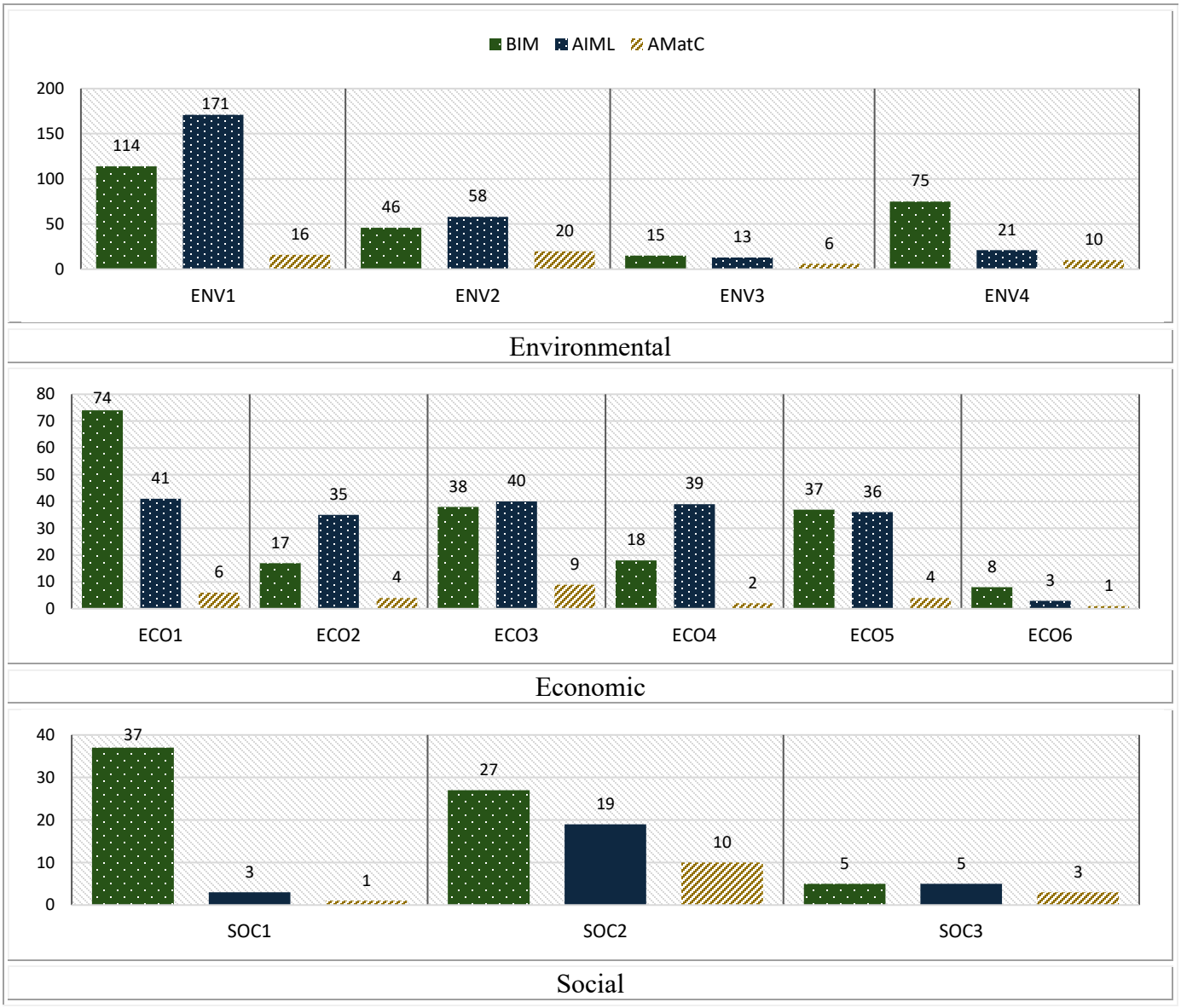


Figure S1. Frequency of articles associated with the Key Factors of environmental, economic and social sustainability for BIM, AIML and AMatC.

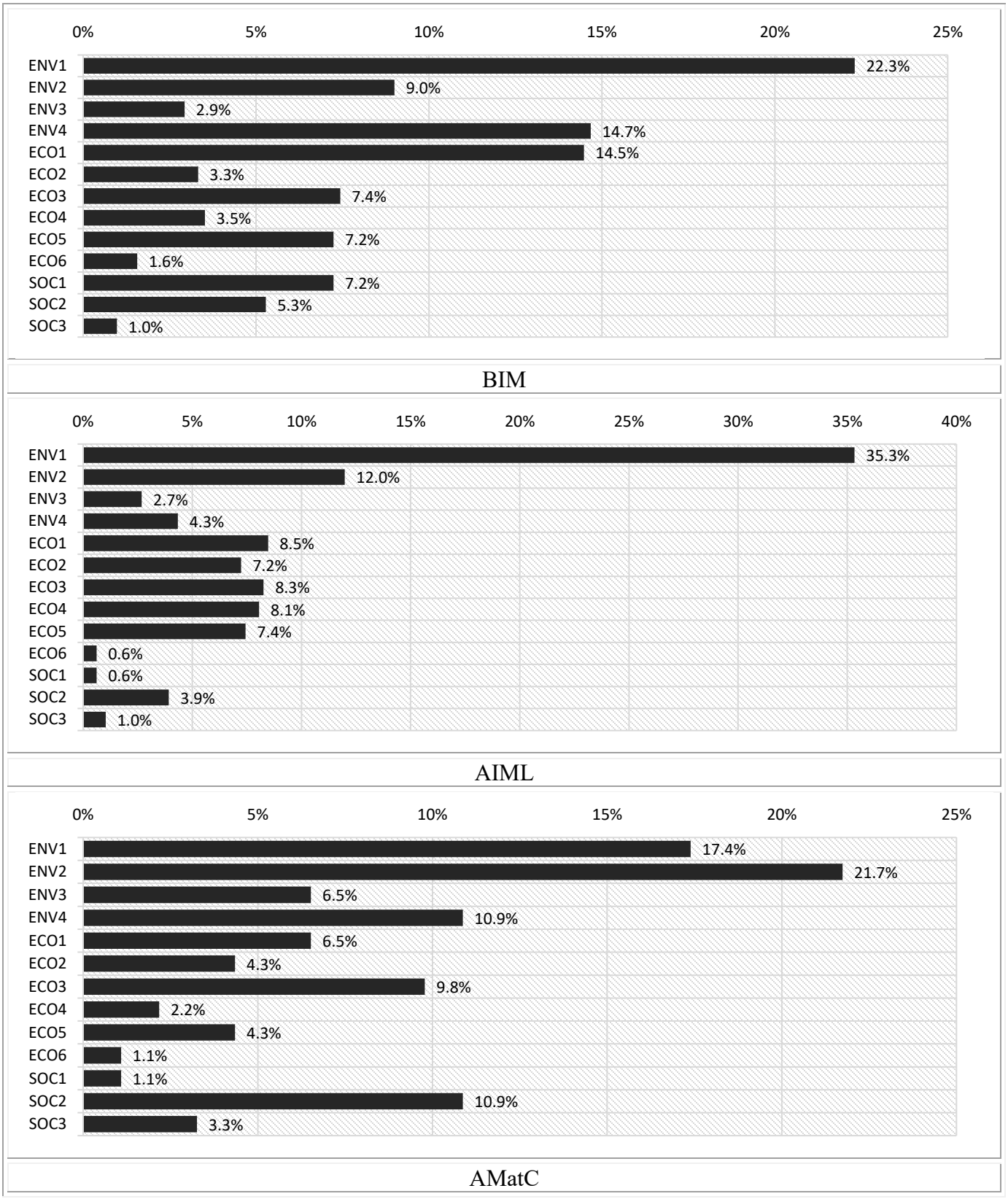


Figure S2. Percentage distribution of selected items by technology based on key factors of the environmental, economic and social dimensions.

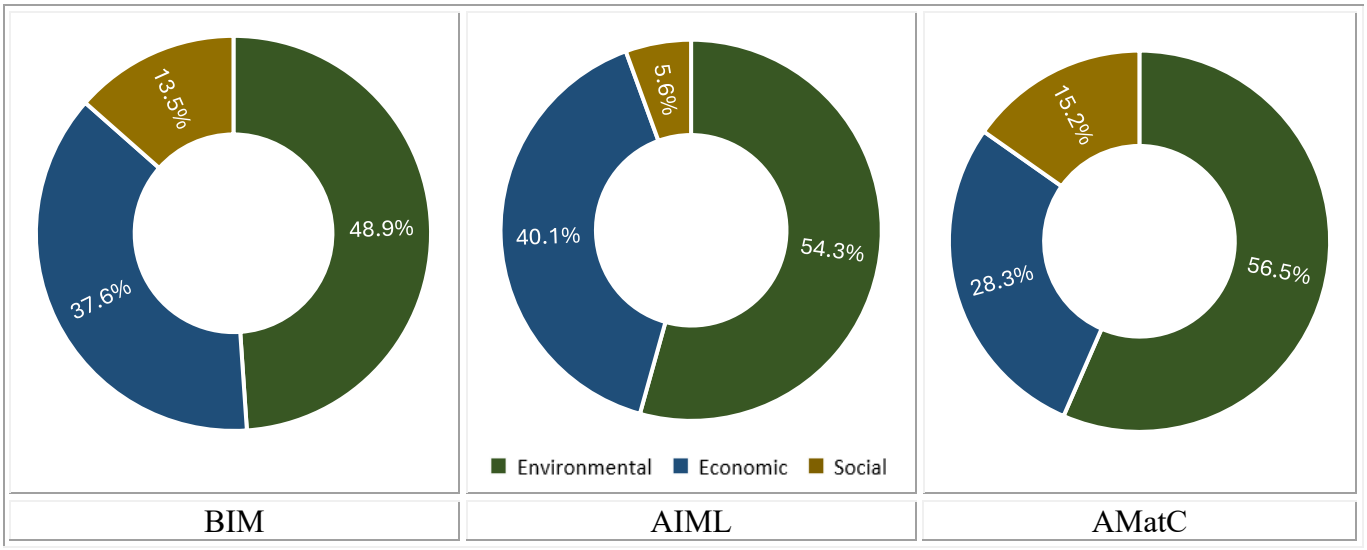


Figure S3. Percentage distribution of sustainability dimensions in the BIM, AIML and AMatC literature.

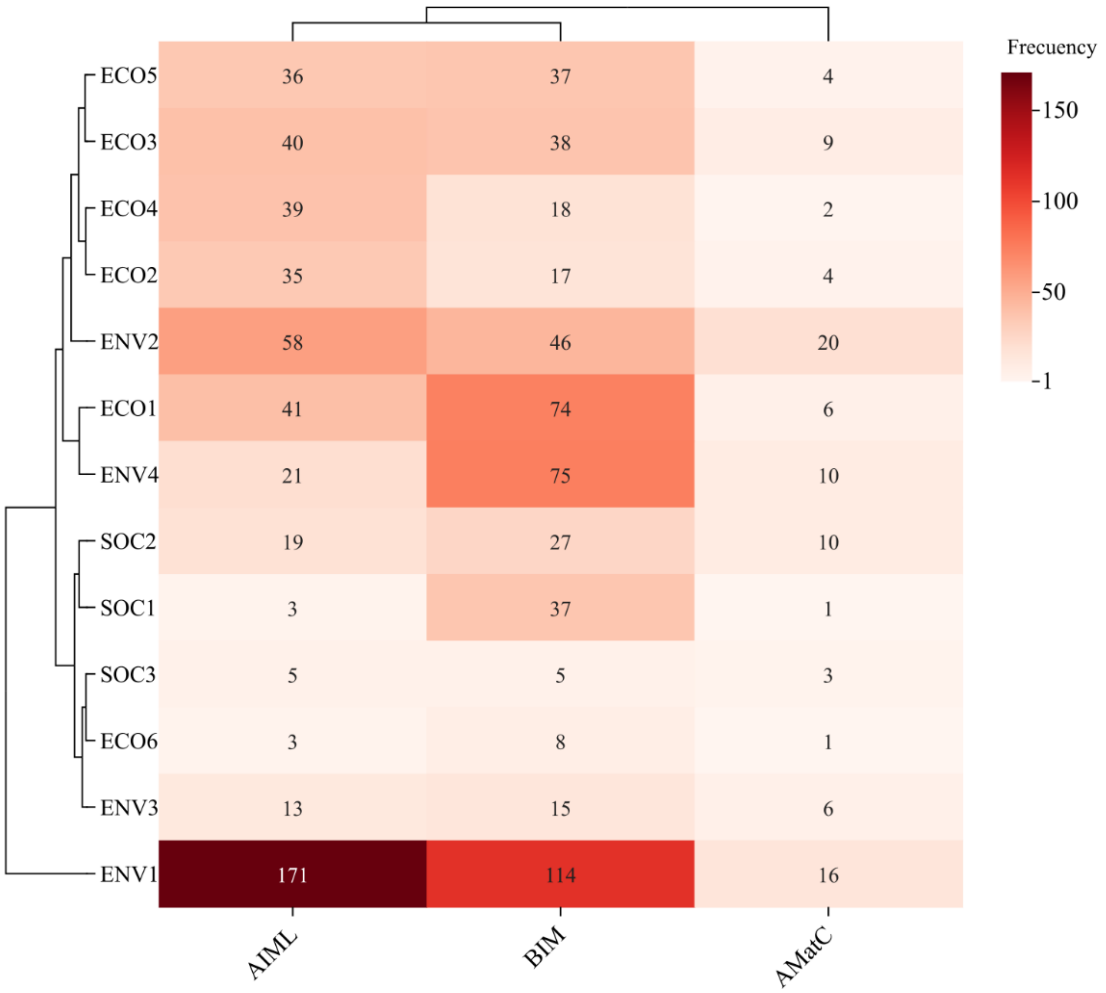


Figure S4. Heat map of selected articles by key factor (*the dendrograms along the axes represent hierarchical clustering of the rows and columns based on profile similarity, computed using Euclidean distance and complete linkage*).

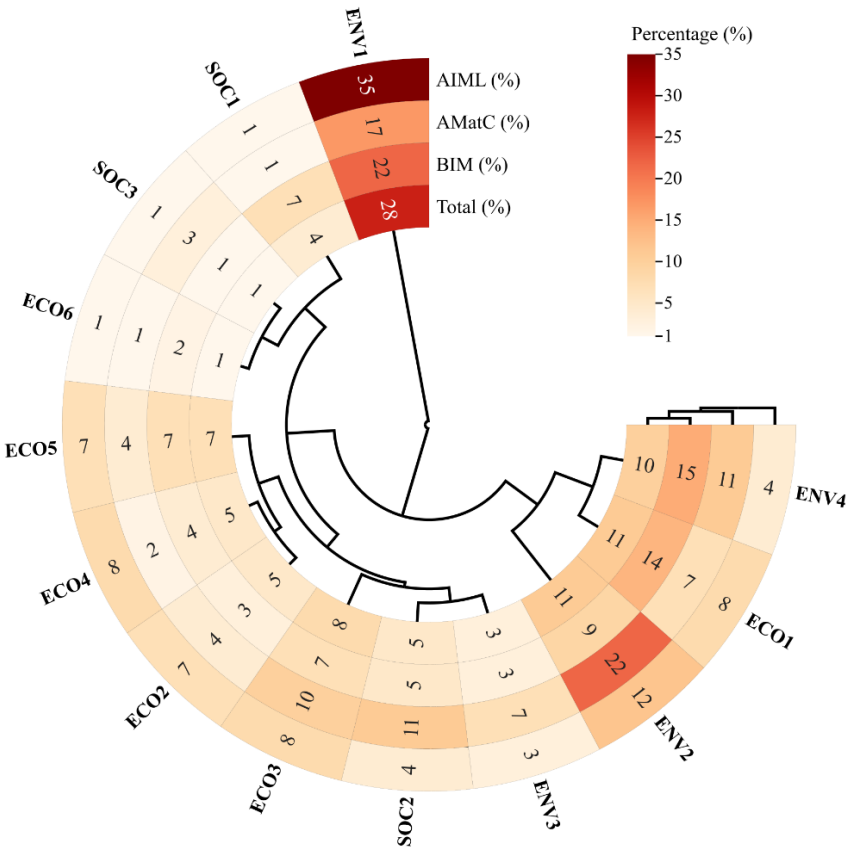


Figure S5. Heat map of the percentage distribution of selected items by key factor (*the dendrograms along the axes represent hierarchical clustering of the rows and columns based on profile similarity, computed using Euclidean distance and complete linkage*).

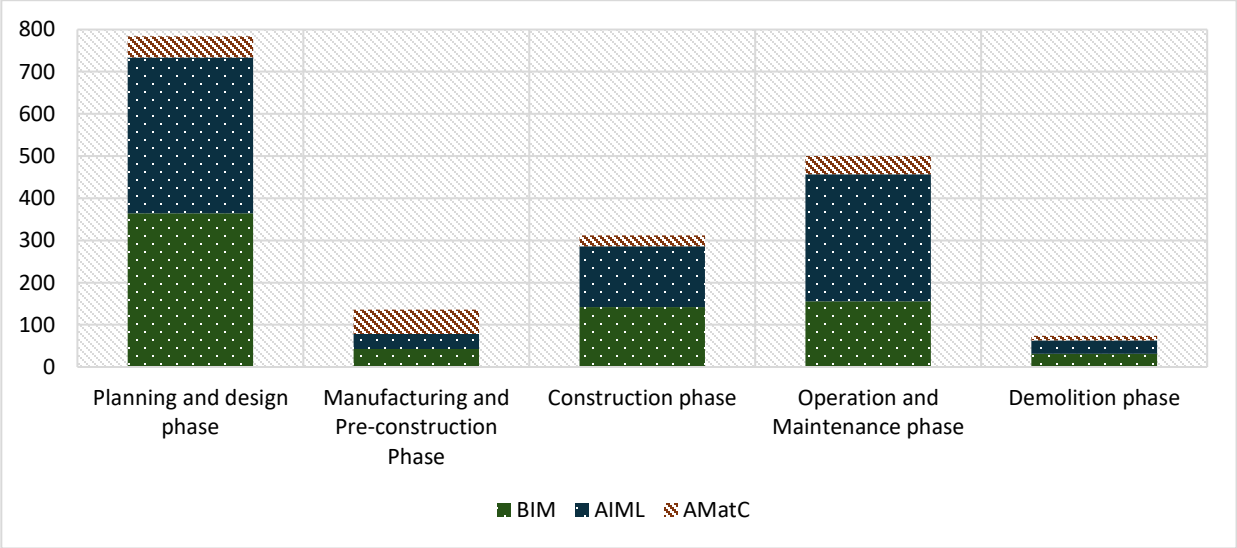


Figure S6. Frequency of articles selected by technology (BIM, AIML, and AMatC) according to project phase.

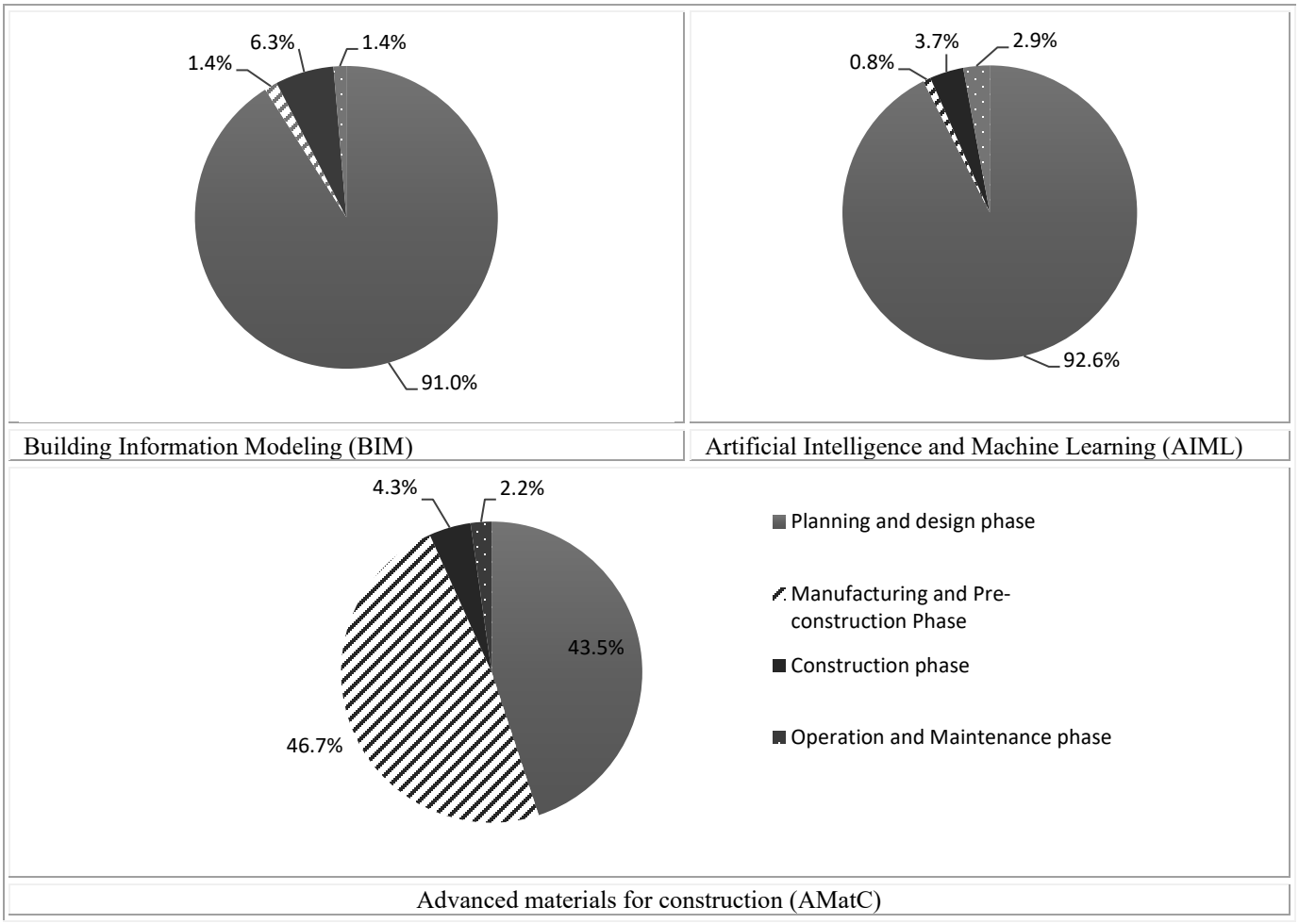
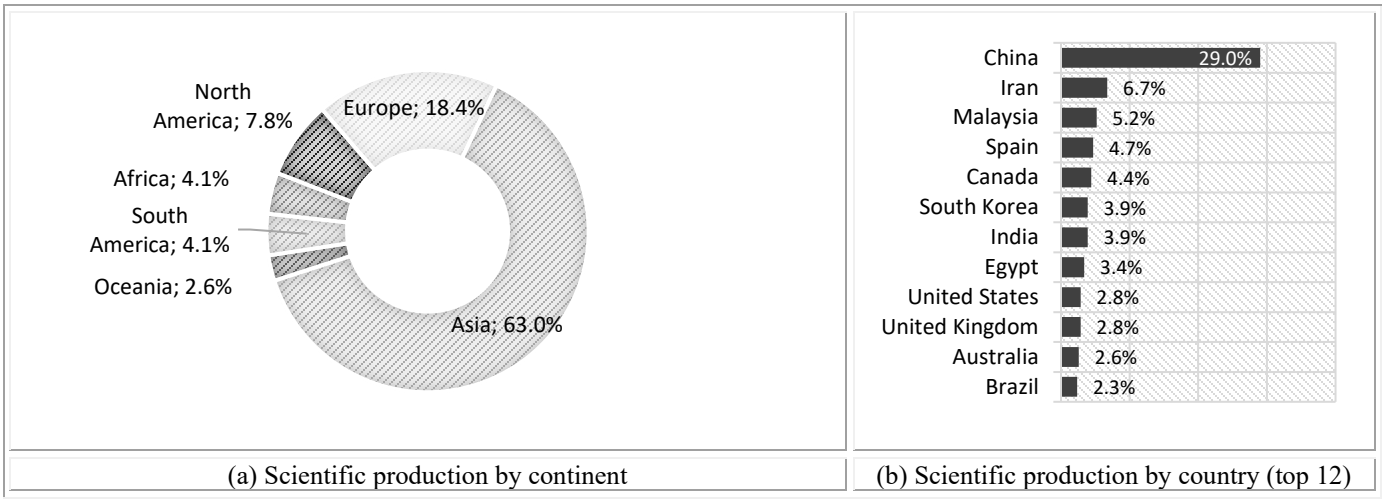
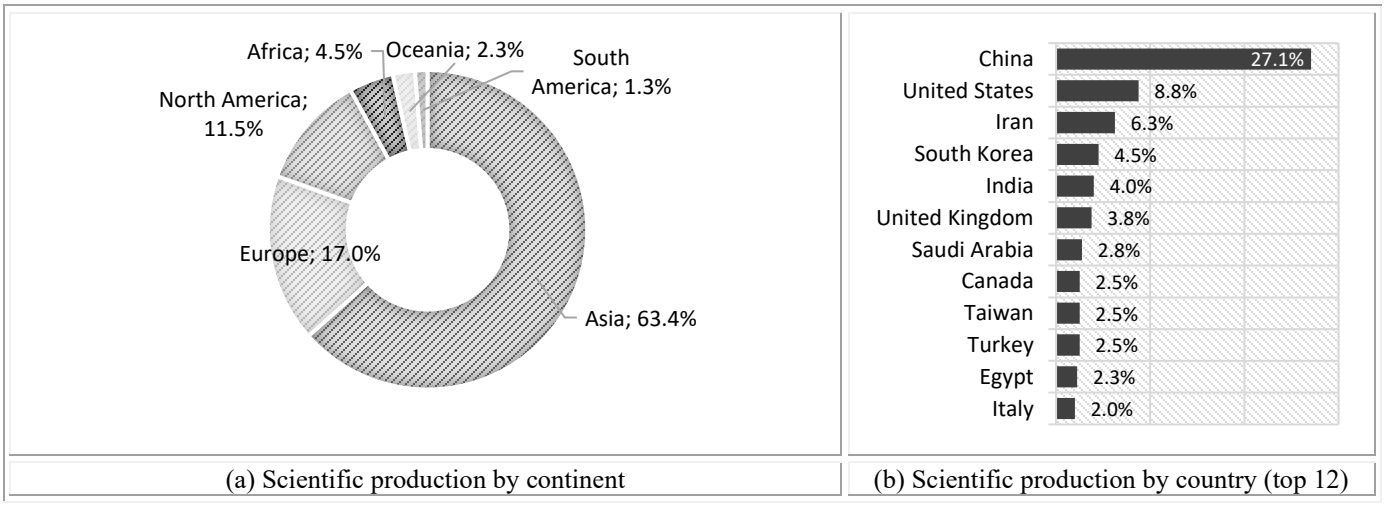


Figure S7. Percentage distribution of selected articles by technology (BIM, AIML and AMatC) according to the main phase of the project.



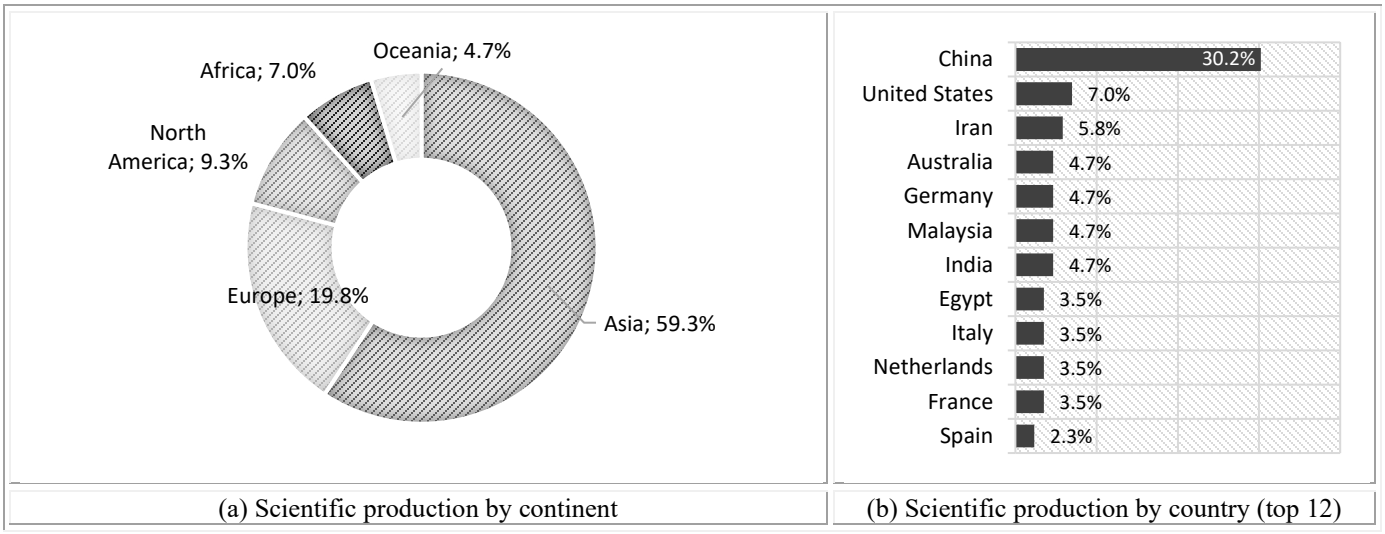
(a) Scientific production by continent (b) Scientific production by country (top 12)

Figure S8. BIM: Geographical distribution of the selected publications by continent and country.



(a) Scientific production by continent (b) Scientific production by country (top 12)

Figure S9. AIML: Geographical distribution of the selected publications by continent and country.



(a) Scientific production by continent (b) Scientific production by country (top 12)

Figure S10. AMatC: Geographical distribution of the selected publications by continent and country.

4. RESULTS OF THE SANKEY DIAGRAM: according to technology, key factors, practical applications and main construction phases.

Table S10. Ranking of the most frequent combinations (Top 20) of technologies, applications and project phases in the environmental dimension.

C4.0	Code	Application	Main phase of the project	Frecuency (Total=565)	%
AIML	ENV1	Simulation and modeling of energy demand	Planning and design phase	89	15.8%
BIM	ENV4	Quantification, characterization and environmental assessment	Planning and design phase	58	10.3%
BIM	ENV1	Simulation and modeling of energy demand	Planning and design phase	58	10.3%
BIM	ENV1	Multi-objective and life cycle assessment	Planning and design phase	48	8.5%
AIML	ENV1	Active optimization and real-time energy control	Planning and design phase	46	8.1%
BIM	ENV2	Carbon assessment and reduction	Planning and design phase	37	6.5%
AIML	ENV2	Carbon assessment and reduction	Planning and design phase	31	5.5%
AIML	ENV2	Optimization and active control of emissions	Planning and design phase	24	4.2%
AIML	ENV1	Multi-objective and life cycle assessment	Planning and design phase	19	3.4%
AMatC	ENV2	Carbon assessment and reduction	Manufacturing and Pre-construction Phase	15	2.7%
BIM	ENV3	Reducing demand, reusing and optimizing water use	Planning and design phase	14	2.5%
AIML	ENV4	Optimizing circularity (reduction, reuse, recycling)	Planning and design phase	11	1.9%
BIM	ENV4	Optimizing circularity (reduction, reuse, recycling)	Planning and design phase	10	1.8%
AIML	ENV4	Quantification, characterization and environmental assessment	Planning and design phase	9	1.6%
AIML	ENV1	Active optimization and real-time energy control	Operation and Maintenance phase	8	1.4%
AIML	ENV3	Reducing demand, reusing and optimizing water use	Planning and design phase	8	1.4%
AMatC	ENV1	Simulation and modeling of energy demand	Manufacturing and Pre-construction Phase	7	1.2%
AMatC	ENV1	Simulation and modeling of energy demand	Planning and design phase	7	1.2%
AMatC	ENV2	Carbon assessment and reduction	Planning and design phase	5	0.9%

Table S11. Ranking of the most frequent combinations (Top 20) of technologies, applications and project phases in the economic dimension.

C4.0	Code	Application	Main phase of the project	Frecuency (Total=412)	%
BIM	ECO1	Life cycle cost (LCC) optimization and maintenance cost reduction	Planning and design phase	30	7.3%
AIML	ECO3	Assessment and mitigation of structural risks and natural phenomena	Planning and design phase	28	6.8%
AIML	ECO2	Inspection, monitoring and early detection of defects and clashes	Planning and design phase	25	6.1%
AIML	ECO4	Early detection and predictive maintenance	Planning and design phase	21	5.1%
BIM	ECO5	4D planning, flow simulation and coordination	Planning and design phase	21	5.1%
BIM	ECO1	Reduction of direct material and construction costs	Planning and design phase	20	4.9%
AIML	ECO1	Reduction of direct material and construction costs	Planning and design phase	19	4.6%
AIML	ECO4	Structural health inspection and monitoring	Planning and design phase	18	4.4%
BIM	ECO3	Assessment and mitigation of structural risks and natural phenomena	Planning and design phase	18	4.4%
BIM	ECO1	Accelerating the schedule and minimizing delays	Planning and design phase	17	4.1%
AIML	ECO1	Life cycle cost (LCC) optimization and maintenance cost reduction	Planning and design phase	16	3.9%
AIML	ECO5	Real-time monitoring and control of on-site productivity	Planning and design phase	15	3.6%
BIM	ECO4	Structural health inspection and monitoring	Planning and design phase	12	2.9%
AIML	ECO5	4D planning, flow simulation and coordination	Planning and design phase	10	2.4%
BIM	ECO2	Preventive quality assurance	Planning and design phase	10	2.4%
BIM	ECO3	Evacuation simulation and emergency planning	Planning and design phase	10	2.4%
AIML	ECO3	Risk monitoring, early detection and real-time response	Planning and design phase	9	2.2%
AMatC	ECO3	Assessment and mitigation of structural risks and natural phenomena	Planning and design phase	9	2.2%
AIML	ECO2	Preventive quality assurance	Planning and design phase	8	1.9%
BIM	ECO3	Risk monitoring, early detection and real-time response	Planning and design phase	8	1.9%

Table S12. Ranking of the most frequent combinations (Top 20) of technologies, applications and project phases in the social dimension.

C4.0	Code	Application	Main phase of the project	Frecuency (Total=110)	%
BIM	SOC2	Accident and incident prevention (physical security)	Planning and design phase	26	23.6%
BIM	SOC1	Multidisciplinary coordination and collaborative conflict resolution	Planning and design phase	20	18.2%
AIML	SOC2	Accident and incident prevention (physical security)	Planning and design phase	13	11.8%
BIM	SOC1	Centralized digital platforms for information exchange	Planning and design phase	13	11.8%
BIM	SOC3	Promotion of local social, cultural and economic development	Planning and design phase	5	4.5%
AIML	SOC2	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	Planning and design phase	4	3.6%
AMatC	SOC2	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	Planning and design phase	4	3.6%
AIML	SOC1	Centralized digital platforms for information exchange	Planning and design phase	3	2.7%
AIML	SOC3	Promotion of local social, cultural and economic development	Planning and design phase	3	2.7%
AMatC	SOC2	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	Manufacturing and Pre-construction Phase	3	2.7%
BIM	SOC1	Multidisciplinary coordination and collaborative conflict resolution	Construction phase	3	2.7%
AIML	SOC2	Accident and incident prevention (physical security)	Construction phase	2	1.8%
AIML	SOC3	Protecting the health and safety of the community	Planning and design phase	2	1.8%
AMatC	SOC3	Protecting the health and safety of the community	Planning and design phase	2	1.8%
AMatC	SOC1	Centralized digital platforms for information exchange	Demolition phase	1	0.9%
AMatC	SOC2	Accident and incident prevention (physical security)	Manufacturing and Pre-construction Phase	1	0.9%
AMatC	SOC2	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	Construction phase	1	0.9%
AMatC	SOC2	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	Operation and Maintenance phase	1	0.9%
AMatC	SOC3	Promotion of local social, cultural and economic development	Planning and design phase	1	0.9%
BIM	SOC1	Centralized digital platforms for information exchange	Operation and Maintenance phase	1	0.9%

5. MAPPING THE SCIENTIFIC LITERATURE: practical applications of BIM, AIML and AMatC

- **ENVIRONMENTAL DIMENSION**

Table S13. Mapping of the scientific literature on the individual applications and synergies of BIM, AIML and AMatC in relation to key environmental sustainability factors.

Key sustainability factor	Code	Practical application	Article code[1]					
			BIM	AIML	AMatC	BIM-AIML	BIM-AMatC	AIML-AMatC
Energy management	ENV1	Simulation and modeling of energy demand	[1–3]	[4–6]	[7–9]	[10–14]	[12,15–17]	[15,18]
		Active optimization and real-time energy control	[19]	[20–22]	-	[23–27]	-	[28–30]
		Multi-objective and life cycle assessment	[31–34]	[35–37]	[38]	[26,39–42]	[43,44]	[45–47]
Environmental protection and decarbonization	ENV2	Carbon assessment and reduction	[3,33,48]	[49–51]	[52–54]	[55–60]	[16,61]	[45,62–64]
		Optimization and active control of emissions	[34]	[65–67]	-	[26,68,69]	-	-
Water consumption efficiency	ENV3	Reducing demand, reusing and optimizing water use	[70,71]	[72–74]		[75,76]	-	-
		Loss prevention and system integrity assurance	-	[77–79]	[80,81]	-	-	-
Management of construction materials and waste	ENV4	Quantification, characterization and environmental assessment of waste and materials	[82–85]	[86,87]	-	[45,60]	[45,61,88,89]	[90–92]
		Optimizing circularity (reduction, reuse, recycling)	[93–95]	[96–98]	[99,100]	[94,97]	[101]	-

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Table S14. Mapping of the scientific literature on the application of BIM, AIML and AMatC in the phases of the life cycle of a construction project according to environmental sustainability factors.

Key sustainability factor	Code	Planning and design			Manufacturing and preconstruction			Construction			Operation and maintenance			Demolition		
		BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC
Energy management	ENV1	[1–11]	[12–20]	[21–25]	[3,6,7,9]	[26]	[21,23,25,27]	[8–11,28]	[13,16,17]	[22–25]	[2,4,5,7–11,28–30]	[12–19,26,31,32]	[22–25]	[9,28]	[20]	[25]
Environmental protection and decarbonization	ENV2	[2,33–39]	[20,40–44]	[45–47]	[34,35,37–39]	[48]	[45,47,49,50]	[34–39,51]	[43,44]	[45,49]	[2,35,36,38,39,51]	[41,43,44,48,52]	[45,46]	[35,39]	[20,40]	[45,46]
Water consumption efficiency	ENV3	[53–59]	[60–63]	-	-	-	[64–66]	[55,57,59]	[60]	[64]	[53,54,56,57]	[60–63,67]	[64,65]	-	-	-
Management of construction materials and waste	ENV4	[9,68–75]	[43,76–79]	[80,81]	[68,73]	[78,82]	[80–83]	[9,68,72,73]	[43,84]	[80]	[9,85]	[43,77,79,82,84]	[82]	[70,86,87]	[76,84]	[80]

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- **ECONOMIC DIMENSION**

Table S15. Mapping of the scientific literature on the individual applications and synergies of BIM, AIML and AMatC in relation to key economic sustainability factors.

Key sustainability factor	Code	Practical application	Article code[1]					
			BIM	AIML	AMatC	BIM-AIML	BIM-AMatC	AIML-AMatC
Cost and schedule management	ECO1	Reduction of direct material and construction costs	[1–4]	[5–9]	[10,11]	[12–15]	-	[15–19]
		Life cycle cost (LCC) optimization and maintenance cost reduction	[20–22]	[23–26]	[27–29]	[30,31]	[32]	[33–35]
		Accelerating the schedule and minimizing delays	[36–38]	[39–41]	-	[42–48]	-	[49]
Quality management	ECO2	Preventive quality assurance	[50–53]	[54,55]	[29,56,57]	[58–60]	-	[17,61–63]
		Inspection, monitoring and early detection of defects and clashes	[64–66]	[67–73]	-	[74–78]	-	[79,80]
		Evacuation simulation and emergency planning	[81–83]	[84,85]	-	[86,87]	-	-
Comprehensive risk management	ECO3	Risk monitoring, early detection and real-time response	[88–91]	[70,92–95]	-	[96,97]	-	[79]
		Assessment and mitigation of structural risks and natural phenomena	[98–100]	[71,72,101–106]	[29,107–109]	[110–113]	-	-
Preventive maintenance	ECO4	Structural health inspection and monitoring	[114–117]	[67,71,72,94,118]	[119,120]	[121]	-	[122]
		Early detection and predictive maintenance	[123–125]	[74,75,126,127]	-	[75,128,129]	-	[61]
Productivity	ECO5	4D planning, flow simulation and coordination	[37,38,130]	[54,131–133]	-	[43,46,48,134]	-	[61]
		Optimization of prefabrication and off-site production	[135–138]	[44,139]	[140,141]	[142,143]	[144]	[17]
		Real-time monitoring and control of on-site productivity	[145–147]	[40,148–150]	-	[45,47,74,151]	-	[49]
Supply chain management	ECO6	Selection and evaluation of suppliers and materials	[152–154]	[155]	[29]	[156]	[157]	-
		Flow optimization, monitoring, and disruption response	[147,158]	[40]	-	[159]	[160]	-

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Table S16. Mapping of the scientific literature on the application of BIM, AIML and AMatC in the phases of the life cycle of a construction project according to economic sustainability factors.

Key sustainability factor	Code	Planning and design			Manufacturing and preconstruction			Construction			Operation and maintenance			Demolition		
		BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC
Cost and schedule management	ECO1	[1–9]	[10–16]	[17–19]	[3,4]	[13,20]	[18]	[2,5,21, 22]	[11,20, 23]	[19]	[7–9]	[10,12, 14,17]	[17,18]	[3,7]	[14]	[19]
Quality management	ECO2	[24–34]	[35–37]	[37,38]	[29,32]	[37]	[37,39–42]	[24,25, 29,31,43]	[38,44, 45]	[40,42]	[33,34, 46]	[36,44, 47–50]	[39]	[34]	-	-
Comprehensive risk management	ECO3	[51–58]	[35,59–61]	[62,63]	-	[64]	[63]	[54,58, 65]	[59,61, 66]	[62–64]	[52,53, 56,67,68]	[35,60, 69–71]	[62,63]	-	-	[64]
Preventive maintenance	ECO4	[53,72–75]	[35,74]	[76]	[72]	-	[76,77]	[72,74, 75,78]	[74,78]	-	[53,72–75,78–80]	[35,44, 47,74,78,81–84]	[76,77, 84]	-	-	-
Productivity	ECO5	[1,32,85–90]	[11]	[91,92]	[32,85, 87,89,93]	[94,95]	[91,92, 96]	[22,85–90,93]	[11,20, 66,97]	[91,92]	[90]	[36,49, 98,99]	[96]	[93]	[97]	-
Supply chain management	ECO6	[100–103]	[104]	[105]	[93,100–103]	[20]	[105]	[32,93, 101,103]	[20]	-	-	-	-	[93]	-	-

Table S16 References

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- **SOCIAL DIMENSION**

Table S17. Mapping of the scientific literature on the individual applications and synergies of BIM, AIML and AMatC in relation to key social sustainability factors.

Key sustainability factor	Code	No.	Practical application	Article code[1]					
				BIM	AIML	AMatC	BIM-AIML	BIM-AMatC	AIML-AMatC
Participation and collaboration	SOC1	1	Centralized digital platforms for information exchange	[1–4]	[5]	[6]	[7–9]	-	-
		2	Multidisciplinary coordination and collaborative conflict resolution	[10–13]	-	-	[14]	-	-
Occupational health and safety	SOC2	3	Accident and incident prevention (physical security)	[15–17]	[18–20]	[21]	[22–26]	-	-
		4	Protection of occupational health (environmental quality, exposure to toxins, mental well-being)	[27]	[28–30]	[31–35]	-	-	-
Impact on the community	SOC3	5	Protecting the health and safety of the community	-	[36,37]	[34,38]	[39,40]	-	-
		6	Promotion of local social, cultural and economic development	[41–43]	[44–46]	[47]	[48,49]	-	-

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Table S18. Mapping of the scientific literature on the application of BIM, AIML and AMatC in the phases of the life cycle of a construction project according to social sustainability factors.

Key sustainability factor	Code	Planning and design			Manufacturing and preconstruction			Construction			Operation and maintenance			Demolition		
		BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC	BIM	AIML	AMatC
Participation and collaboration	SOC1	[1–10]	[11]	[12]	[9]	-	-	[3,5–7,9,13]	[11,13]	[12]	[4–6,8,10,13]	[11,13]	-	-	-	[12]
Occupational health and safety	SOC2	[14–26]	[26–35]	[36–40]	-	-	[37,38,40,41]	[14,17,19,22,24]	[26,28,30,32–35,39,42]	[37]	[16,17,20,21,23,24]	[28,34,42]	[36–38,41,43]	[25]	[35]	-
Impact on the community	SOC3	[44–47]	[48–51]	[36,37,52]	-	-	[52]	-	[50,51]	-	[44–46]	[51]	[52]	-	[48]	-

Note: The numerical codes cited in this Table are bibliographic references found in the Appendix.

Table S18 References

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6. PREFERRED REPORTING ITEMS FOR SYSTEMATIC REVIEWS AND META-ANALYSES EXTENSION FOR SCOPING REVIEWS (PRISMA-SCR) CHECKLIST

Table S19. PRISMA methodology checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2-4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	4
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	3-5
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	7-8
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	7-8
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	8-9
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	9-10
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	9-10
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	5-8
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	8
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	9-10

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	9-10
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	10-16
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	10-16
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	10-16
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	10-11
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	34
Limitations	20	Discuss the limitations of the scoping review process.	32
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	35-36
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	36

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.
* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.
† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).
‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.
§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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