A Distributed Simulation Framework Using HLA for Circular Economy Modeling in Road Construction

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Abstract – Road construction consumes large quantities of virgin aggregates and asphalt, while circular-economy (CE) strategies, such as using reclaimed asphalt pavement (RAP) and recycled aggregates, remain underutilized due to quality uncertainties, logistical constraints, and limited digital integration. Existing simulation tools are predominantly linear and single-site, which prevents the realistic evaluation of CE strategies across demolition (DEM), mixing (MIX), and construction (CON) operations. This paper introduces a distributed simulation framework based on the High-Level Architecture (HLA) that links DEM, MIX, and CON federates to model dynamic, multi-site and closed-loop material flows. A conceptual CE framework, a set of simulation requirements, and a literature-based gap analysis are developed. A proof-of-concept implementation demonstrates federate connectivity and quantifies CE effects: recycled flows supply 544 t of RAP and 7,500 t of mineral recyclates, reducing virgin-material demand by roughly 25 %. The results demonstrate that distributed simulation offers a feasible and extensible framework for analyzing CE strategies under realistic operational constraints, thereby supporting sustainable, smart, and lean road-construction planning through network-level logistics, environmental indicators, and scenario-based optimization.

Keywords – circular economy; road construction; distributed simulation; high level architecture; material flow

1 Introduction

Road construction is a highly material-intensive sector that relies on large quantities of aggregates, asphalt, and concrete, among other materials [1], [2]. At the same time, the industry faces increasing pressure to reconcile traditional project objectives – cost, quality, and time – with growing ecological requirements and resource scarcity [3]. Achieving an economically viable, specification-compliant pavement while simultaneously reducing environmental impacts creates an inherent conflict of goals for contractors, agencies, and material suppliers [4]. These competing objectives intensify the need for more resource-efficient, data-driven, and operationally integrated methods capable of supporting future-ready road-construction workflows. Circular Economy (CE) principles offer substantial potential for addressing these challenges [5], [6]. Strategies such as incorporating reclaimed materials demonstrate clear potential [1], [2], [7]. However, CE adoption in practice remains limited. Key barriers include uncertainties in the properties of reclaimed materials [2], [8], logistical constraints across demolition, production, and paving operations [9], [10], restrictive specifications, and limited digital integration among stakeholders [8], [9]. Despite increasing political attention to circular construction, practical operational models for implementing CE principles in road construction are still lacking [10]. Existing modeling tools offer limited support for CE integration. Most simulation approaches remain linear, isolated, and focused on single sites [11], [12]. Road-construction networks involve dynamic material exchanges among demolition (DEM) sites, mixing plants (MIX), and construction (CON) sites that are spatially separated and temporal in nature [12], [13], [14]. Current models cannot represent multi-site material availability, quality-dependent blending, or the temporal coordination required to evaluate recycling feasibility [13], [15]. As a result, they cannot generate system-level CE indicators such as recycled content or virgin-material substitution [16], [17]. To address these limitations, this paper proposes a distributed simulation framework based on the High-Level Architecture (HLA). The framework links three federates – DEM, MIX, and CON – to represent multi-site interactions and circular material flows, with the option to add and remove more sites to ensure fidelity with real-world project schedules. The aim is to demonstrate that distributed modeling enables detailed site-specific process representation, realistic and scalable multi-site material exchange, and explicit closed-loop modeling (DEM-MIX-CON). The main contributions of this paper are:

1. A conceptual and technical framework combining CE principles with distributed simulation.
2. Integration of discrete process simulation with material-flow and Sankey-based CE visualization.
3. A requirement set (R1–R7) for CE-oriented simulation in road construction.
4. A systematic literature comparison covering simulation in construction and their relevance to CE in road construction.
5. A proof-of-concept federated HLA implementation linking DEM, MIX, and CON.

The remainder of the paper is structured as follows: Section 2 reviews related work across CE, material-flow modeling, construction simulation, and distributed simulation. Section 3 introduces the conceptual framework and federation design. Section 4 presents the implementation and proof-of-concept demonstration. Section 5 discusses implications and challenges, and Section 6 concludes with an outlook for future research.

2 Background and Related Work

This section presents a review of CE concepts, material flow modeling techniques, and construction simulation methods, with the aim of specifying requirements and identifying knowledge gaps for creating realistic and scalable simulations of road construction circularity. Together, these perspectives highlight the need for more integrated and digitally coordinated approaches to support future resource-efficient construction workflows.

2.1 Circular Economy in Road Construction

CE principles, such as reduce, reuse, recycle, provide a strategic foundation for improving resource efficiency and reducing environmental impacts in pavement engineering [18]. Strategies such as substituting virgin materials with reclaimed ones, using rejuvenators, or improving end-of-life recovery can substantially reduce material extraction and emissions [1], [2], [7], [16]. However, CE implementation remains limited due to quality variability of reclaimed materials, aging effects, and contamination that complicate mix design [2], [19]. Logistical issues, such as transport distances and timing mismatches between demolition and production, further constrain practical feasibility [20], [21]. Standards often restrict the use of recycled content, and digital tools for coordinating material flows across organizations are still scarce [8], [9], [22]. Despite increasing policy attention, most CE studies in pavement engineering remain material-centric and do not address the dynamic, process-level, and network-level considerations required for operational CE integration [13], [17].

2.2 Material Flow Modeling

Material Flow Analysis (MFA) provides a quantitative framework for assessing inputs, outputs, and stocks of materials within a defined system boundary [15]. In road construction, MFA is used to represent material requirements for pavement layers and the material flows [1], [22]. MFA enables transparent reporting of circularity indicators such as recycled content, virgin substitution, and diversion rates [16]. Sankey diagrams are widely used to visualize these flows, offering an intuitive representation of how materials move through the system and where losses or inefficiencies occur [23]. Such visualizations are effective communication tools, particularly for comparing linear and circular system configurations. However, MFA is inherently static. It does not account for temporal aspects such as scheduling, process durations, capacity constraints, or quality-dependent blending decisions [15]. For road construction, these temporal dynamics are crucial: DEM output may not align with MIX demand; materials may degrade during storage; and transport times may disrupt planned operations [7], [13], [19]. Consequently, MFA alone cannot determine whether CE strategies are operationally feasible or economically beneficial under realistic process conditions. A dynamic model is needed that can integrate temporal, spatial, and operational constraints across the network. This motivates the development of CE-oriented dynamic simulation approaches.

2.3 Simulation in Construction Processes

In contrast to the static nature of Sankey diagrams, discrete event simulation (DES) offers a convenient method to analyze the dynamics of construction operations through explicit modeling of activity sequencing logic, resource flows, and uncertainties in duration and quantities involved. These properties enable simulation to overcome the limitations of real-world experimentation (expensive and unfeasible) and static analytical modeling (which make overly simplifying assumptions about the underlying system) to provide an objective means of analyzing and optimizing construction operations [11], [24]. Prior work that showcases the applicability and generalizability of DES to construction operations in general include tunnel boring [25], pipe-spool module assembly [26], modular construction ([27], disaster recovery [28], and asphalt paving operations [29]. However, despite these strengths of DES for modeling construction operations, it has some significant limitations that hinder its ability to model circularity in roadway construction: (1) the DES current focuses on modeling only single sites, which makes it unsuitable to model multiple sites in a region; (2) it is difficult to model the temporariness of projects as they would occur in the real world, as DES tends to focus on modeling operations from start to finish for a single operation on a single site; (3) current DES methods do not enable the transfer of resources between models in a time-synchronized manner, which is necessary to model material transfer between sites for circular roadway construction. These limitations are overcome in this research by adopting the HLA for distributed simulations using the ConStrobe simulation engine, as will be described in Section 3.

2.4 Requirements for CE-oriented simulation in road construction

Based on the gaps identified in the previous sections, a simulation framework intended to support CE in road construction must satisfy several functional requirements that exceed the capabilities of traditional MFA or isolated discrete-event models.

1. R1 – Scalable Multi-Site System Representation: Road construction CE requires modeling interactions among multiple DEM, MIX, and CON sites operating concurrently within a distributed network [12], [20], [21].
2. R2 – Dynamic Material Flow Tracking: The simulation must track material batches over time, including their quantities, origins, and quality attributes, since recycling feasibility depends on temporal and compositional alignment [13], [15].
3. R3 – Circular Material Feedback Loops: Closed-loop flows must be modelled to quantify circularity indicators such as recycled content, virgin-material reduction, and diversion rates [16], [18].
4. R4 – Process-Level Operational Detail: The model must capture operational constraints (e.g., queueing, capacity limits, availability, and process times at DEM, MIX, and CON sites) [11], [12].
5. R5 – Inter-Model Communication and Modularity: Given the heterogeneity of DEM, MIX, and CON processes, the simulation must support independent models that communicate through standardized interfaces, as enabled by the HLA [30], [31].
6. R6 – Scalability to Network-Level Decisions: To evaluate CE strategies at the project or regional level, the simulation must scale to multiple sites and varying process configurations [14], [21].
7. R7 – CE Indicators and Visualization: The framework must generate CE-relevant metrics and support visualization through flow diagrams such as Sankey charts [16], [23].

Together, these requirements form the basis for a CE-capable simulation architecture, demonstrating the need for a distributed modeling approach that integrates multi-site material flows and operational dynamics.

2.5 Requirement-Based Evaluation of Existing Simulation Approaches

To assess the suitability of existing construction-simulation research for CE-oriented modeling, the requirements defined in Section 2.4 (R1–R7) were used as evaluation criteria. The DES-focused literature discussed in Section 2.3 represents the dominant modeling approaches in construction operations and offers mature capabilities in activity sequencing, equipment modeling, and queue-based resource interaction. However, these studies remain fundamentally constrained by their single-site scope and linear process assumptions. Table 1 summarizes the comparison between representative DES studies and the CE-oriented requirements. Conventional DES models generally satisfy process-detail requirements (R4) but lack mechanisms for multi-site coordination (R1, R6), dynamic material-quality tracking (R2), circular flow modeling (R3), inter-model communication (R5), and CE indicator generation (R7). All reviewed works are limited to single-site, linear processes and do not represent interdependent DEM–MIX–CON systems, circular material feedback loops, or closed-loop mass tracking.

Overall, no existing DES study fulfills more than two CE-relevant requirements. No prior work combines multi-site process modeling, dynamic material-flow tracking, and circularity assessment, highlighting a clear research gap that directly motivates the distributed HLA-based simulation framework presented in Section 3.

Table 1: Assessment of existing studies

	R1	R2	R3	R4	R5	R6	R7
[11] AbouRizk (2010) Role of Simulation in CEM	○	○	○	●	○	○	○
[24] Martinez (1996) StroboScope	○	○	○	●	○	○	○
[25] Ruwanpura et al. (2001) Tunnel Simulation	○	◔	○	●	○	○	○
[26] ElMenshawy et al. (2025) Pipe Spool Scheduling	○	◔	○	◕	○	○	○
[27] Abiri et al. (2019) Modular Construction	◔	◔	○	◕	○	◔	○
[28] Louis & Dunston (2018) IoT-enabled Operations	○	◑	○	●	◔	○	○
[29] Mostafavi et al. (2012) Asphalt Paving	○	◔	○	●	○	○	○

3 Conceptual Framework and System Design

This section presents the conceptual foundation for modeling circular material flows across demolition, mixing, and construction activities, as modeled by the corresponding federates. The framework integrates CE principles with a distributed, multi-site simulation perspective, directly operationalizing the requirements derived in Section 2.4. The framework enables transparent tracking of material origins, quality-dependent transformation steps, and batch-level allocation across the distributed DEM–MIX–CON system. The modeling approach mirrors the physical organization of road-construction processes and provides the basis for evaluating recycling and substitution effects under realistic operational constraints.

3.1 System Boundary and Material Loop

The framework encompasses the entire material cycle associated with demolishing and constructing a 1 km-long and 7 m-wide road section. All materials extracted during demolition, as well as those required for constructing the surface, base, and frost layers, are included. The process is decomposed into three domains:

- **DEM** – milling and excavating surface, base, and frost layers; asphalt-bound and mineral materials.
- **MIX** – classification, crushing, screening, and production of asphalt and granular mixes.
- **CON** – placement and compaction of the new road.

The analysis encompasses all materials generated from DEM and all materials necessary for CON. While this models a single life-cycle iteration, the structure supports multi-cycle CE assessments by allowing CON outputs to re-enter future DEM processes or even introduce maintenance activities as a combination of the DEM and CON federates.

3.2 Pavement Structure, Material Composition and Machinery

The pavement consists of three layers: surface, base, and frost, each with distinct material compositions and recycling potentials.

Table 2: Pavement layers, material composition, and machinery

	Primary Materials	DEM Machines	CON Machines
Sur-face	Asphalt(1)/RAP(2), Bitumen(3), Crushed Stone(4), Filler(5)	Milling Machine	Asphalt Paver, Roller
Base	Asphalt(1)/RAP(2), Concrete(6), Crushed Stone(4), Gravel(7)	Excavator, Wheel Loader	Grader, Roller, Wheel Loader
Frost	Concrete(6), Crushed Rock(8), Gravel(7)		

3.3 Reference Material Flows and Sankey-Based CE Representation

The Sankey diagram in Figure 1 forms the quantitative backbone of the conceptual framework. It depicts the complete flow of materials from DEM to MIX for all pavement layers, identifying the recoverable asphalt components, the mineral fractions suitable for reuse, and the unavoidable losses resulting from fines, contamination, or mechanical degradation. The recyclable materials are depicted in light green.

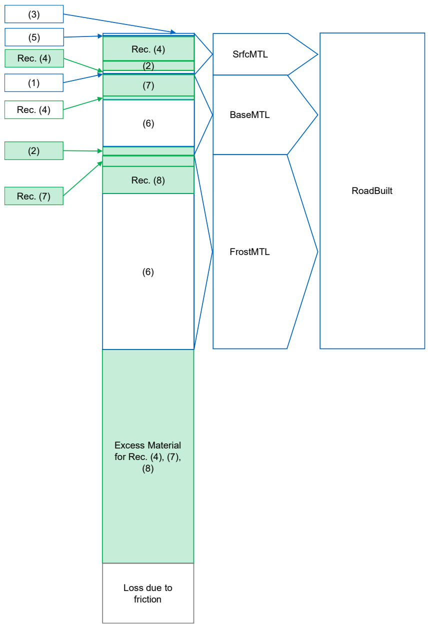

Figure 1: Sankey diagram of material flows across DEM-MIX-CON

The underlying values are derived from an estimation model calibrated using real project data and validated through expert interviews. DEM generates three primary material streams corresponding to the original pavement structure: approximately 1,314 t from the surface layer, 2,533 t from the base layer, and 6,131 t from the frost/sub-base layer. These streams sum to 9,979 t and are decomposed into asphalt-bound components, recoverable granular fractions, and non-recoverable losses. In the surface layer stream, 308 t of material are recovered as high-quality RAP (approximately 90 % of the asphalt content), 777 t are recycled as mineral fractions (around 80 % of the unbound portion), and 229 t are lost due to processing-related degradation. The base layer yields 236 t of RAP, 1,818 t of recycled mineral aggregates, and 462 t of losses. The frost/sub-base layer, containing no asphalt binder, contributes the largest volume of mineral recyclate, with 4,905 t recovered and 1,226 t lost. In total, the CE potential amounts to 544 t of RAP and 7,500 t of reusable mineral aggregates, whereas 1,916 t of material must be virgin inputs. These flows define the theoretical upper bound of substitution in the CON process and establish quality and mass constraints governing decisions in MIX.

3.4 Material Transformation Logic from DEM to MIX to CON

The transformation logic governs how materials move through the DEM–MIX–CON chain, ensuring that the simulation reflects realistic process behavior and CE constraints. DEM produces heterogeneous batches characterized by material type, grain-size distribution, asphalt content, binder ageing (for RAP), moisture, and contamination. These properties determine their eligibility for high-quality RAP production or mineral recycling pathways. Once transferred to MIX, the batches undergo screening, crushing, composition analysis, and RAP-quality evaluation before being sorted into dedicated stockpiles. MIX thus transforms DEM output into three categories: RAP suitable for asphalt mixtures in surface or base layers, recycled aggregates for base and frost layers, and reject fines, representing the loss streams in the Sankey diagram. CON consumes the processed materials according to the structural requirements of each layer. The surface layer relies on bitumen, high-quality aggregates, filler, and a controlled RAP share. The base layer accommodates a wider mix of RAP and recycled minerals, while the frost/sub-base layer can incorporate nearly all available mineral recyclates. When recycled supply is insufficient or fails to meet quality requirements, virgin materials are introduced to maintain mass balance and ensure layer specifications are met. In this way, the simulation can evaluate both the theoretical CE potential and the operational feasibility of recycling outcomes.

3.5 Distributed Simulation and HLA

Given the limitations of conventional DES to model multiple spatially and temporally distributed demolition sites, construction sites, and mixing plants that form the dynamic system for which circularity is being considered, this research proposes the use of distributed simulations that is enabled through the IEEE 1516 HLA standard for creating distributed, time-synchronized simulations. In this framework, individual simulation models are referred to as federates, and they join a federation through a Runtime Infrastructure (RTI), which facilitates time synchronization and data exchange between the individual federates. AbouRizk (2010) has previously identified HLA as a promising direction for construction simulation and has developed the Construction Synthetic Environment (COSYE) for the Simphony simulation system. This research utilizes the CERTI HLA framework [32] for the RTI and the ConStrobe simulation system [33] to provide individual federates for the various demolition, construction, and mix plant sites within the road network. A schema of this distributed simulation framework is shown in Figure 2.

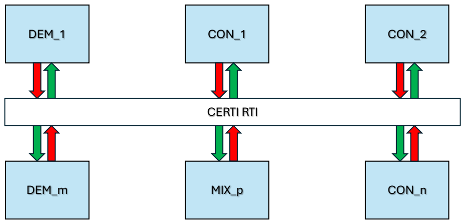

Figure 2: HLA Architecture

The light blue boxes represent HLA-compliant ConStrobe models that represent any of the different DEM, CON, or MIX sites, which act as federates and publish and subscribe to data from other federates through the CERTI RTI. They interact through a shared Federation Object Model that defines material batches using attributes such as mass, material type, RAP fraction, binder properties, grain-size class, timestamp, and federate origin. Time management services coordinate the execution order and ensure synchronized access to material stocks and process events. The modularity of the architecture enables the integration of extended scenarios, such as additional recycling facilities, alternative pavement designs, or network-level simulations, without requiring modifications to existing federates.

3.6 Circularity Indicators and Model Outputs

The distributed simulation generates CE-relevant performance measures, including RAP utilization in asphalt production, mineral substitution rates across all layers, total recycled versus virgin material, and mass balance consistency across federates. Temporal indicators, such as synchronization between DEM supply and CON demand, further support the evaluation of CE strategies under realistic scheduling and capacity constraints. Together, the outputs translate static Sankey-derived potentials into dynamic operational CE metrics.

4 Implementation and Demonstration

This section presents the prototype implementation of the distributed simulation framework and demonstrates the feasibility of linking DEM, MIX, and CON through HLA. The implementation follows a modular design, in which each federate operates as an independent simulation unit, utilizing a simplified DES logic.

4.1 Model Description

Each federate is implemented with DES-like process logic, supporting queueing, batching, and resource-driven processing. DEM generates material batches corresponding to the layer-specific flows defined in the Sankey diagram, assigning attributes such as mass, material type, RAP fraction, and binder quality. MIX applies simplified processing steps, mapping DEM outputs to the recycling categories defined in Section 3.4. Figure 3 depicts DEM as an exemplary federate.

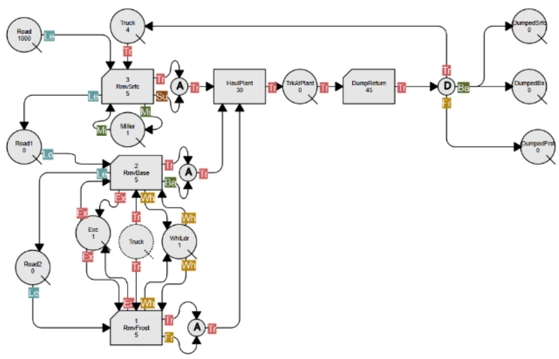

Figure 3: DEM federate in ConStrobe

CON receives processed materials and allocates them to surface, base, or frost layers according to their specification requirements. Several simplifying assumptions enable a clear proof-of-concept demonstration without overburdening the model:

- Machinery resources are represented through processing-time proxies rather than detailed equipment behavior.
- Transport between DEM–MIX–CON is modelled using deterministic travel times.
- MIX capacity is assumed sufficient for the given scenario, avoiding queue overflow.

These assumptions preserve focus on inter-federate communication, CE mass flows, and model extensibility.

4.2 Federate Connections and HLA Synchronization

The three federates communicate through the RTI using object and interaction classes defined in the Federation Object Model. DEM publishes MaterialBatch objects, which include mass, type, timestamp, and origin. MIX subscribes to these objects and publishes corresponding ProcessedBatch objects after transformation. CON then consumes these batches through MaterialRequest and MaterialDelivery interactions. Time-stepped HLA time management is used to ensure logical causality. All federates advance simulation time in synchronized increments. This mechanism ensures that the distributed model remains consistent with the temporal dynamics of real-world construction operations, where material availability constrains production and placement.

4.3 Demonstration Scenario

The demonstration uses the case introduced in Section 3. The DEM federate generates batches totalling 9,979 t, decomposed by layer origin. MIX processes these batches into RAP, recycled mineral aggregates, and residual losses, applying the CE transformation logic defined in Section 3.4. CON then sequentially constructs the frost, base, and surface layers by requesting and receiving materials in accordance with their layer-specific specifications. Through the demonstration run, the federates successfully exchange materials, update inventories, and maintain time-synchronized execution. The resulting simulation logs capture all material transformations and serve as the basis for deriving a dynamic Sankey diagram that mirrors Figure 1.

4.4 Results: Connectivity and Material-Substitution Effects

The proof-of-concept implementation confirms that DEM, MIX, and CON federates can be reliably linked through HLA. All federates exchanged material batches without message loss, and synchronized time advancement preserved correct causal ordering of production, processing, and consumption events. This demonstrates the technical feasibility of distributed, multi-site simulation for road construction processes.

Table 3: Material substitution results for linear vs. circular scenarios

	Linear scenario	CE-enabled scenario
Total material [t]	9,979	9,979
Virgin material [t]	9,979	7,519
RAP used [t]	-	544
Recycled mineral aggregates used [t]	-	7,500
Virgin material reduction [t]	-	2,460

Beyond connectivity, the simulation quantifies the impact of circular material flows on demand for virgin materials. In a linear reconstruction scenario, the full 9,979 t of pavement material is supplied from virgin sources. When CE pathways are enabled, recycled outputs from DEM and MIX provide 544 t of RAP and 7,500 t of recycled mineral aggregates, reducing virgin material demand by approximately 2,460 t (~25 %). Substitution effects are strongest in the frost and base layers, while surface-layer reductions are limited by RAP quality requirements. These results show that CE performance depends not only on theoretical recycling potential but also on the operational synchronization of DEM–MIX–CON federates.

5 Discussion

The proof-of-concept demonstrates that distributed simulation is a viable approach for modeling CE-oriented material flows across DEM, MIX, and CON operations. Using HLA enables modularity and interoperability, allowing heterogeneous process models to exchange material batches through a shared, synchronized representation and to dynamically generate CE metrics (e.g., RAP utilization and virgin-material substitution), rather than relying on aggregate assumptions. Key implementation challenges remain. Consistent data structures across federates require careful FOM design, particularly when introducing additional material types or quality attributes. Interoperability issues may arise when federates operated by different organizations use incompatible internal models. Differences in temporal and spatial granularity between DEM, MIX, and CON also require harmonization strategies to maintain causal consistency. Overall, the framework provides a basis for extending the federation to multi-site networks, comparing recycling configurations (e.g., mobile vs. stationary), and integrating additional indicators such as CO_2 emissions or energy use.

6 Conclusion and Outlook

This study presented a distributed simulation framework that links DEM, MIX, and CON processes through HLA to evaluate CE-oriented material flows in road construction. The proof-of-concept demonstrated reliable federate synchronization and batch exchange, enabling dynamic assessment of recycling and substitution effects under operational constraints. A key result is that synchronized DEM–MIX–CON interactions reduced virgin material demand by ~25 % compared with a linear scenario. Future work can enhance model fidelity by integrating spatial data (BIM/GIS) to account for transport and network effects and coupling the simulation with environmental and economic assessment modules to support informed decision-making for circular infrastructure planning. By enabling digitally connected, resource-efficient, and operationally synchronized construction processes, the proposed framework contributes to constructing the future of road infrastructure that is sustainable, smart, and lean.

References

[1] Y. Huang, R. N. Bird, and O. Heidrich, “A review of the use of recycled solid waste materials in asphalt pavements,” Resour. Conserv. Recycl., vol. 52, no. 1, pp. 58–73, Nov. 2007, doi: 10.1016/j.resconrec.2007.02.002.

[2] M. Zaumanis and R. B. Mallick, “Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art,” Int. J. Pavement Eng., vol. 16, no. 1, pp. 39–55, Jan. 2015, doi: 10.1080/10298436.2014.893331.

[3] A. Böckel, I. Weissbrod, and J. Böhm, Eds., *Mythen der Circular Economy*. Leuphana Universität Lüneburg, 2022. doi: 10.25368/2022.163.

[4] T. Baumgärtel et al., “Bauen heute und morgen,” in Digitale Baustelle- innovativer Planen, effizienter Ausführen, W. Günthner and A. Borrmann, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 1–21. doi: 10.1007/978-3-642-16486-6_1.

[5] F. Pichlmeier et al., “Tiefbau-Fachsymposium ‘Ressourceneffizienz im Straßenbau,’” Nov. 2017.

[6] European Environment Agency., Circular economy in Europe: developing the knowledge base. LU: Publications Office, 2016. https://data.europa.eu/doi/10.2800/51444

[7] H. Ali and A. Rojali, “Recycling Asphalt Pavements: The State of Practice,” in Recycling Strategy and Challenges Associated with Waste Management Towards Sustaining the World, H. M. Saleh and A. I. Hassan, Eds., IntechOpen, 2023. doi: 10.5772/intechopen.106235.

[8] R. Karlsson and U. Isacsson, “Material-Related Aspects of Asphalt Recycling—State-of-the-Art,” J. Mater. Civ. Eng., vol. 18, no. 1, pp. 81–92, Feb. 2006, doi: 10.1061/(ASCE)0899-1561(2006)18:1(81).

[9] S. Choudhari and A. Tindwani, “Logistics optimisation in road construction project,” Constr. Innov., vol. 17, no. 2, pp. 158–179, Apr. 2017, doi: 10.1108/CI-03-2016-0014.

[10] A. Fredriksson and M. Huge-Brodin, “Green construction logistics – a multi-actor challenge,” Res. Transp. Bus. Manag., vol. 45, p. 100830, Dec. 2022, doi: 10.1016/j.rtbm.2022.100830.

[11] R. Berbner, C. Elsholz, M. Nicklis, and J. Hagenschulte, “Die Bauindustrie weiter im Umbruch: Fehlendes Know-how und Bürokratie bremsen.” Feb. 01, 2025. [Online]. Available: https://www.pwc.de/de

[12] M. J. Riberinho et al., “The next normal in construction; How disruption is reshaping the

world's largest ecosystem." June 01, 2020. [Online]. Available: https://www.mckinsey.com
[13] F. Naz, Improving Transport Efficiency in the Construction Supply Chain, vol. 2396. in Linköping Studies in Science and Technology. Dissertations, vol. 2396. Linköping: Linköping University Electronic Press, 2024. doi: 10.3384/9789180757010.
[14] S. AbouRizk, "Role of Simulation in Construction Engineering and Management," J. Constr. Eng. Manag., vol. 136, no. 10, pp. 1140–1153, Oct. 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000220.
[15] K. Jaafar, "Construction logistics: a simulation case study to improve performance processes," Int. J. Simul. Process Model., vol. 17, no. 1, p. 16, 2021, doi: 10.1504/IJSPM.2021.120840.
[16] Z. Liu and N. Kringos, "Transition from linear to circular economy in pavement engineering: A historical review," J. Clean. Prod., vol. 449, p. 141809, Apr. 2024, doi: 10.1016/j.jclepro.2024.141809.
[17] A. G. Vetnes and R. O'Born, "Bridging the Shift from Linear to Circular Economy in Road Infrastructure: The Norwegian Stakeholders' Perspectives on Challenges and Opportunities," in The 1st International Conference on Net-Zero Built Environment, vol. 237, M. Kioumarsi and B. Shafei, Eds., in Lecture Notes in Civil Engineering, vol. 237. , Cham: Springer Nature Switzerland, 2025, pp. 1573–1583. doi: 10.1007/978-3-031-69626-8_131.
[18] P. H. Brunner and H. Rechberger, Handbook of Material Flow Analysis, 0 ed. CRC Press, 2016. doi: 10.1201/9781315313450.
[19] W. Haas, F. Krausmann, D. Wiedenhofer, and M. Heinz, "How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005," J. Ind. Ecol., vol. 19, no. 5, pp. 765–777, Oct. 2015, doi: 10.1111/jiec.12244.
[20] F. Pomponi and A. Moncaster, "Circular economy for the built environment: A research framework," J. Clean. Prod., vol. 143, pp. 710–718, Feb. 2017, doi: 10.1016/j.jclepro.2016.12.055.
[21] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," Resour. Conserv. Recycl., vol. 127, pp. 221–232, Dec. 2017, doi: 10.1016/j.resconrec.2017.09.005.
[22] T. Bergmann, D. Bleher, and W. Jenseit, "Ressourceneffizienzpotenziale im Tiefbau: Materialaufwendungen und technische Lösungen." Nov. 01, 2025.
[23] M. Schmidt, "The Sankey Diagram in Energy and Material Flow Management: Part I: History," J. Ind. Ecol., vol. 12, no. 1, pp. 82–94, Feb. 2008, doi: 10.1111/j.1530-9290.2008.00004.x.
[24] J. C. Martinez, "STROBOSCOPE: State and Resource Based Simulation of Construction Processes," The University of Michigan, Ann Arbor, 1996.
[25] J. Y. Ruwanpura, S. M. AbouRizk, K. C. Er, and S. Fernando, "Special purpose simulation templates for tunnel construction operations," Can. J. Civ. Eng., vol. 28, no. 2, pp. 222–237, Apr. 2001, doi: 10.1139/l00-101.
[26] M. ElMenshawy, L. Wu, B. Gue, and S. AbouRizk, "Automating Pipe Spool Fabrication Shop Scheduling for Modularized Industrial Construction Projects Using Reinforcement Learning," J. Comput. Civ. Eng., vol. 39, no. 3, p. 04025013, May 2025, doi: 10.1061/JCCEE5.CPENG-6042.
[27] B. Abiri, J. Louis, and M. Riggio, "Decision-making for Cross-Laminated Timber Modular Construction Logistics Using Discrete Event Simulation," Modul. Offsite Constr. MOC Summit Proc., pp. 381–388, May 2019, doi: 10.29173/mocs117.
[28] J. Louis and P. S. Dunston, "Integrating IoT into operational workflows for real-time and automated decision-making in repetitive construction operations," Autom. Constr., vol. 94, pp. 317–327, Oct. 2018, doi: 10.1016/j.autcon.2018.07.005.
[29] A. Mostafavi, V. Valentin, D. M. Abraham, and J. Louis, "Assessment of the Productivity of Nighttime Asphalt Paving Operations," J. Constr. Eng. Manag., vol. 138, no. 12, pp. 1421–1432, Dec. 2012, doi: 10.1061/(ASCE)CO.1943-7862.0000531.
[30] R. M. Fujimoto, "Distributed simulation systems," in Proceedings of the 2003 International Conference on Machine Learning and Cybernetics, New Orleans, LA, USA: IEEE, 2003, pp. 124–134. doi: 10.1109/WSC.2003.1261415.
[31] H. Taghaddos, S. M. AbouRizk, Y. Mohamed, and I. Ourdev, "Distributed agent-based simulation of construction projects with HLA," in 2008 Winter Simulation Conference, Miami, FL, USA: IEEE, Dec. 2008, pp. 2413–2420. doi: 10.1109/WSC.2008.4736349.
[32] E. Noulard, J.-Y. Rousselot, and P. Siron, "CERTI, an Open Source RTI, why and how," presented at the Spring Simulation Interoperability Workshop, San Diego, Jan. 2009.
[33] J. Louis, "ConStrobe - Construction Operations Simulation for Time and Resource Based Evaluations," presented at the Winter Simulation Conference (WSC), 2025.