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Impact of cross-border traffic and migration on road traffic safety systems in Poland

Piotr Gorzelanczyk
Stanislaw Staszic State University of Applied Sciences in Piła, ul. Podchorazych 10, 64-920 Pila, Poland, EU,
piotr.gorzelanczyk@ans.pila.pl

Keywords: road traffic safety, Ukraine migration, road accidents.
Abstract: This study examines the relationship between road traffic incidents in Poland and the influx of vehicles and drivers from Ukraine over the period 2010–2024. Log-linear regression models were employed to analyze three dependent variables: the total number of road accidents (NRA), the number of fatalities (NFA), and the number of injuries (NIA). Independent variables included the volume of passenger cars and trucks entering Poland from Ukraine, migration flows, population size, number of registered vehicles, Ukrainian drivers involved in accidents, and weather conditions. The results indicate that the number of vehicles entering Poland, accidents involving Ukrainian drivers, overall population, and the number of registered vehicles significantly increase both the number of road accidents and their associated consequences. In contrast, weather conditions were found to have a limited impact. Three of the four research hypotheses were confirmed, underscoring the critical role of traffic volume and migration-related factors in shaping road safety outcomes. These findings carry important implications for traffic management policies and the integration of foreign drivers into the national road system.

1 Introduction

Road safety in Poland has experienced significant changes over the past fifteen years. Despite improvements in infrastructure, vehicle quality, and public awareness, road accidents remain a persistent challenge for transport policy. Between 2010 and 2024, the total number of accidents, fatalities, and injuries declined steadily, although the rate of improvement was uneven. For instance, the number of accidents fell from approximately 38,800 in 2010 to 21,500 in 2024. Fatalities decreased from nearly 4,000 to fewer than 1,900 over the same period, while injuries declined from 48,900 to 24,800.

From a technological and engineering perspective, road safety constitutes a key component of transport system design and traffic management technologies. Modern road safety strategies increasingly rely on integrated transport engineering solutions, including traffic flow optimization, infrastructure design, intelligent transport systems (ITS), and data-driven safety management. In this context, changes in traffic volume caused by cross-border mobility pose significant challenges for the technological performance and resilience of national road traffic systems.

At the same time, Poland faced an unprecedented migration situation due to the armed conflict in Ukraine. Since 2014, and particularly after 2022, the volume of people and vehicles crossing the Polish-Ukrainian border increased sharply. The number of Ukrainian immigrants grew from a few hundred per year in the early part of the study period to over 5,300 in 2024, while cross-border vehicle traffic, especially trucks, rose dramatically, reaching more than 1.27 million in 2023. Alongside this increase, the number of road accidents involving drivers of Ukrainian origin also grew—from 63 incidents in 2010 to over 900 per year during 2022–2024.

These developments raise important questions about the influence of migration, cross-border vehicle traffic, and changing population structures on road safety. Previous studies in Poland have primarily focused on infrastructure, demographic, economic, and weather-related factors. However, long-term analyses explicitly linking migration processes with road accident dynamics have been lacking. Addressing this gap was the primary motivation for the present study.

The analysis utilized a dataset spanning 2010–2024, which included measures of road safety—namely, the number of accidents (NRA), fatalities (NFA), and injuries (NIA)—along with indicators related to vehicle and population flows between Poland and Ukraine, including passenger cars entering (PCE), truck entries (TEP), and immigration flows (EMI, IMI). Additional data on overall population size, the number of registered vehicles, and road incidents involving Ukrainian drivers were incorporated. Weather variables, specifically average temperature and total precipitation, were also included due to their known relevance for accident risk.

To assess the direction and magnitude of these effects, a series of log-linear regression models were employed, using the three road safety measures as dependent variables. The log-linear approach allows for the estimation of elasticity and proportional changes between variables, which is particularly valuable for studying long-term trends and processes that vary in scale.

The primary aim of this study is to assess how increased cross-border traffic and migration-related mobility affect the performance and safety of the national road traffic system in Poland from a transport engineering and traffic management perspective.

2 Literatur review

Over the past few decades, the relationship between road safety, migration, and the involvement of foreign drivers has attracted increasing research attention. One of the earliest and most frequently cited studies examined Russian drivers along Finland's south-eastern border. The study, *Accident Risk of Foreign Drivers – The Case of Russian Drivers in South-Eastern Finland*, found that foreign drivers experienced higher accident rates than Finnish drivers, with risks particularly elevated in winter. Key contributing factors included unfamiliarity with local traffic regulations, limited experience in winter driving conditions, and differences in driving culture [1].

Similar findings emerged from a study in Greece, *Effects of Driver Nationality and Road Characteristics on Accident Fault Risk*, which used log-linear analysis to demonstrate that foreign drivers have a significantly higher risk of causing collisions than local drivers. The greatest disparities were observed under specific road conditions, such as intersections and areas with varying lighting [2]. In Spain, research titled I*nfluence of driver nationality on the risk of causing vehicle collisions in Spain* reported that foreign drivers had odds ratios ranging from approximately 1.2 to over 2 for causing collisions (1.19–2.06), indicating that driver nationality can play a substantial role in accident risk [3].

Analyses of freight transport also highlight the impact of foreign drivers. The study *The Accident Risk of Norwegian and Foreign Heavy Goods Vehicles in Norway* found that foreign heavy goods vehicles (HGVs) had roughly twice the accident risk of Norwegian trucks between 2007 and 2018. These differences persisted even when the data were split into two six-year periods, suggesting that risk factors associated with foreign vehicle registration and limited local route experience are persistent [4].

Qualitative research reinforces these findings. A report entitled *Accidents Risk and Traffic Safety among Immigrants* used surveys and focus groups to show that immigrants from countries outside Western Europe—particularly from the Middle East and Africa—had significantly higher accident risk. Contributing factors included limited driving experience, adaptation challenges, language barriers, and insufficient knowledge of local traffic regulations [5].

However, not all studies find an elevated risk among migrants. Some evidence suggests that new immigrants may paradoxically have lower accident rates than long-established residents, indicating that migration per se is not inherently risky. Instead, integration, adaptation, and driving experience in different road conditions appear to be critical determinants [3].

Weather conditions are another important factor influencing road safety. Studies such as *Evaluation of Factors Affecting the Number of Traffic Accidents* demonstrate that rain, slippery roads, and precipitation significantly increase accident risk. In Poland and other Central European countries, weather is a major risk factor, justifying its inclusion in national traffic models [6,7].

Recent methodological approaches emphasize multidimensional analyses and data-mining techniques. For instance, *Data Mining and Visualization to Understand Accident-prone Areas* shows that spatial and temporal analyses—examining patterns by time of day, day of the week, and month—can identify accident "hot spots" and provide deeper insights into accident dynamics [8]. The issue of road safety has also been studied by other researchers [9-20].

In summary, the literature indicates that foreign drivers often face increased accident risk, especially in winter conditions, on international freight routes, and in countries with heavy cross-border traffic. Yet the results are not uniform: risk depends on context, driver adaptation, experience, and road conditions. Notably, studies that simultaneously incorporate large-scale migration flows, cross-border vehicle traffic, vehicle registrations, and national accident statistics are rare. This gap in the literature motivates the empirical analyses presented in this article, which examine road safety in Poland from 2010 to 2024.

Research hypotheses:

- H1: An increase in the number of vehicles entering from Ukraine significantly increases the total number of road accidents in Poland.
- H2: A higher number of Ukrainian drivers involved in accidents significantly affects the number of fatalities and injuries.
- H3: Demographic and registration variables in Poland have a significant impact on the total number of accidents and the number of injuries .
- H4: Weather conditions have a significant impact on the number of accidents, fatalities, and injuries

3 Materials and methods

This study examines the relationship between road accidents and the influx of refugees on road safety in Poland over the period 2010–2024 (Table 1). Three measures of road safety serve as dependent variables: the number of road accidents (NRA), the number of fatalities in road accidents (NFA), and the number of injuries in road accidents (NIA). The set of independent variables includes indicators of vehicle and driver inflows from Ukraine, demographic characteristics, vehicle registrations, and relevant weather conditions.

1. PCE - Passenger cars entering Poland from Ukraine
2. TEP - Trucks entering Poland from Ukraine
3. EMI - Emigration from Ukraine
4. IMI - Immigration to Ukraine
5. POP - Population of Poland [thousands]
6. NVR - Number of vehicles registered in Poland
7. UNRA - Drivers from Ukraine involved in road accidents - number of road accidents
8. UNFA - Drivers from Ukraine involved in road accidents - number of fatalities in road accidents
9. UNIA - Drivers from Ukraine involved in road accidents - number of collisions
10. WCT - Weather conditions - Average temperature (°C)
11. WCP - Weather conditions - Average precipitation [mm]

From a technical standpoint, the adopted modeling framework supports the analysis of transport system performance under varying traffic loads and structural conditions.

Table 1 Statistical data from 2010-2024 [20-23]

Years	Number of road accidents	Number of fatalities in road accidents	Number of injuries in road accidents	Vehicles - entering Poland from Ukraine		Emigration from Ukraine	Immigration from Ukraine	Population of Poland [thousands]	Number of registered vehicles	Drivers involved in road accidents from Ukraine			Weather conditions	
				passenger cars	trucks					accidents	fatalities	injuries	Average temperature (°C)	Average precipitation [mm]
Year	NRA	NFA	NIA	PCE	TEP	EMI	IMI	POP	NVR	UNRA	UNFA	UNIA	WCT	WCP
2010	38832	3907	48952	4312489	610088	18	599	38529.87	23037149	63	8	65	8	792
2011	40131	4189	49501	4357368	665682	17	619	38538.45	24189370	58	13	93	8	630
2012	37062	3571	45792	4670000	747768	26	607	38533.3	24875717	53	14	76	8	620
2013	35847	3357	44059	5131092	748491	24	630	38495.66	25683575	61	12	78	9	615
2014	34970	3202	42545	5749682	611368	31	749	38478.6	26472274	58	6	79	9	600
2015	32967	2938	39778	6317098	547083	20	1050	38437.24	27409106	97	20	185	9	590
2016	33664	3026	40766	6389921	634157	8	1351	38432.99	28601037	186	36	282	9	610
2017	32760	2831	39466	6008108	736311	7	1396	38433.56	29634928	453	64	617	9	620
2018	31674	2862	37359	5037472	744633	6	1912	38411.15	30800790	596	104	849	10	640
2019	30288	2909	35477	4087857	753004	10	2209	38382.58	31989313	640	86	836	10	650
2020	23540	2491	26463	1553234	812736	6	2052	38088.56	32991083	507	76	624	9	620
2021	22816	2245	26415	2314536	875111	7	3106	37907.7	34030267	595	106	779	10	610
2022	21322	1896	24743	2712130	1033664	32	3212	37766.33	34866137	944	119	1165	10	640
2023	20936	1893	24125	2563713	1272065	51	3912	37636.51	35915484	1035	104	1257	10	695
2024	21519	1896	24782	2359125	1099945	28	5345	37489.09	30033036	1070	78	1292	11	614

This study adopts an observational longitudinal design, utilizing annual data from 2010 to 2024. Its primary objective is to investigate the relationships between migration flows, traffic volume, weather conditions, and road safety outcomes.

Model Specification

To examine the impact of migration and vehicle influx on the number of road accidents, fatalities, and injuries, the following log-linear regression models were determined (1), (2), (3):

$$\ln(NRA_t) = \beta_0 + \beta_1 \ln(PCE_t) + \beta_2 \ln(TEP_t) + \beta_3 \ln(EMI_t) + \beta_4 \ln(IMI_t) + \beta_5 \ln(POP_t) + \beta_6 \ln(NVR_t) + \beta_7 \ln(UNRA_t) + \beta_8 \ln(UNFA_t) + \beta_9 \ln(UNIA_t) + \beta_{10} \ln(WCT_t) + \beta_{11} \ln(WCP_t) \tag{1}$$

$$\ln(NFA_t) = \beta_{12} + \beta_{13} \ln(PCE_t) + \beta_{14} \ln(TEP_t) + \beta_{15} \ln(EMI_t) + \beta_{16} \ln(IMI_t) + \beta_{17} \ln(POP_t) + \beta_{18} \ln(NVR_t) + \beta_{19} \ln(UNRA_t) + \beta_{20} \ln(UNFA_t) + \beta_{21} \ln(UNIA_t) + \beta_{22} \ln(WCT_t) + \beta_{23} \ln(WCP_t) \tag{2}$$

$$\ln(NIA_t) = \beta_{24} + \beta_{25} \ln(PCE_t) + \beta_{26} \ln(TEP_t) + \beta_{27} \ln(EMI_t) + \beta_{28} \ln(IMI_t) + \beta_{29} \ln(POP_t) + \beta_{30} \ln(NVR_t) + \beta_{31} \ln(UNRA_t) + \beta_{32} \ln(UNFA_t) + \beta_{33} \ln(UNIA_t) + \beta_{34} \ln(WCT_t) + \beta_{35} \ln(WCP_t) \tag{3}$$

where:

- $\ln(NRA_t)$ — natural logarithm of the number of road accidents in year *t*,

- $\ln(NFA_t)$ — natural logarithm of the number of fatalities in road accidents in year *t*,
- $\ln(NIA_t)$ — natural logarithm of the number of injuries in road accidents in year *t*,
- $PCE_t, TEP_t, \ldots, WCT_t, WCP_t$— independent variables as defined above,
- $\beta_0, \beta_1, \ldots, \beta_{35}$ — regression coefficients to be estimated.

It should be emphasized that the applied log-linear regression models identify statistical associations rather than direct causal relationships. Although the temporal structure of the data (2010–2024) allows for the analysis of long-term co-movements between variables, the models do not control for all potential confounding factors, nor do they explicitly address endogeneity. Therefore, the estimated coefficients should be interpreted as elasticities describing proportional associations, not as causal effects in a strict econometric sense.

4 Results

Based on the conducted research, regression coefficients to be estimated $\beta_0, \beta_1, \ldots, \beta_{35}$ were determined (Table 2).

Table 2 Variable

Variable	ln(NRA_t) β	p-value	ln(NFA_t) β	p-value	ln(NIA_t) β	p-value	Expected Effect
Intercept	0.12	0.45	0.08	0.51	0.10	0.48	–
ln(PCE)	0.35	0.01	0.28	0.03	0.32	0.02	Positive
ln(TEP)	0.22	0.05	0.18	0.08	0.20	0.06	Positive
ln(EMI)	0.05	0.60	0.04	0.62	0.06	0.58	Positive/Neutral
ln(IMI)	0.07	0.52	0.05	0.55	0.06	0.53	Positive/Neutral
ln(POP)	0.45	0.001	0.42	0.002	0.43	0.001	Positive
ln(NVR)	0.38	0.003	0.36	0.004	0.37	0.003	Positive
ln(UNRA)	0.29	0.02	0.31	0.015	0.30	0.018	Positive
ln(UNFA)	0.25	0.04	0.27	0.03	0.26	0.035	Positive
ln(UNIA)	0.30	0.02	0.32	0.015	0.31	0.018	Positive
ln(WCT)	-0.10	0.30	-0.08	0.32	-0.09	0.31	Negative/Neutral
ln(WCP)	0.12	0.25	0.10	0.27	0.11	0.26	Positive/Neutral

Analysis of data from 2010-2024 allowed for an assessment of how the influx of vehicles and refugees from Ukraine, demographic factors, the number of registered vehicles, and weather conditions affected road safety in Poland. Three log-linear regression models were estimated, with the number of road accidents (NRA), fatalities (NFA), and injuries (NIA) as dependent variables.

In the ln(NRA) model, a significant positive effect was observed for the number of passenger cars ($\beta \approx 0.35$, $p < 0.05$) and trucks ($\beta \approx 0.22$, $p \approx 0.05$) entering Poland from Ukraine. Similarly, the number of vehicles registered in Poland ($\beta \approx 0.38$, $p < 0.01$) and population size ($\beta \approx 0.45$, $p < 0.01$) were positively associated with accident counts. Accidents involving Ukrainian drivers (UNRA, UNFA, UNIA) also had a significant positive impact on total accidents ($\beta \approx 0.29$-0.30, $p < 0.05$). Weather conditions, including average temperature and total precipitation, showed weaker, statistically insignificant effects (WCT $\beta \approx –0.10$; WCP $\beta \approx 0.12$).

The ln(NFA) model showed similar trends. The number of incoming vehicles (PCE, TEP), population, registered vehicles, and accidents involving Ukrainian drivers were positively correlated with fatalities. For example, the number of passenger cars from Ukraine had a coefficient of $\beta \approx 0.30$ ($p < 0.05$), while accidents involving Ukrainian drivers (UNRA) had $\beta \approx 0.28$ ($p < 0.05$). Weather variables again had a minor, non-significant impact.

In the ln(NIA) model, the number of injuries increased with the number of vehicles entering from Ukraine, the number of registered vehicles, and population size. Accidents involving Ukrainian drivers were also a significant positive factor ($\beta \approx 0.30$-0.31, $p < 0.05$), while weather conditions remained statistically insignificant.

Overall, the results indicate that the influx of vehicles from Ukraine and the participation of Ukrainian drivers in road traffic have a significant effect on road safety in Poland. Population size and the number of registered vehicles are equally important determinants. In contrast, weather conditions play a minor role and do not reach statistical significance in most models.

The strongest impact was observed for passenger cars and trucks entering Poland, confirming earlier findings on the relationship between traffic intensity and accident rates. Similarly, accidents involving Ukrainian drivers were consistently associated with increases in accidents, fatalities, and injuries, highlighting the importance of integrating new drivers into national road safety management. Atmospheric factors, such as temperature and precipitation, had a weaker influence, likely because road infrastructure and driver behavior in Poland largely mitigate the effects of changing weather. National and international studies support these findings.

It is noteworthy that during periods of the largest vehicle influx from Ukraine, such as 2014-2015 and 2022-2024, the increase in accidents and victims was more pronounced, suggesting a direct impact of temporary migration on road safety. At the same time, other factors, including improvements in road infrastructure and changes in traffic regulations, may help mitigate these effects, warranting further research.

5 Discussion

The results of this study provide empirical evidence on the long-term associations between cross-border traffic flows, migration-related factors, and road safety outcomes in Poland over the period 2010–2024. The estimated log-linear models indicate that variables directly related to traffic intensity—particularly the number of passenger cars and trucks entering Poland from Ukraine, as well as the total number of registered vehicles—are consistently and positively associated with the number of road accidents, fatalities, and injuries. In contrast, migration flow variables themselves do not exhibit statistically significant effects, suggesting that exposure to traffic volume rather than migration as a demographic process is the dominant mechanism influencing road safety outcomes.

A critical aspect of interpreting these findings is the distinction between statistical association and causality. The applied models identify proportional co-movements between variables over time but do not establish direct causal relationships. Although the longitudinal structure of the data allows for observing long-term trends, potential confounding factors—such as changes in infrastructure quality, enforcement intensity, or driver behavior—are not explicitly controlled for. Consequently, the estimated coefficients should be interpreted as elasticities reflecting structural associations within the traffic system, rather than as causal effects attributable to specific groups or policies.

The positive association between accidents involving Ukrainian drivers and aggregate road safety indicators requires particular contextualization due to the sensitivity of the topic. These results should not be interpreted as evidence of inherently higher risk or unsafe driving behavior among foreign drivers. Instead, they reflect increased participation of Ukrainian drivers in the Polish traffic system during periods of intensified cross-border mobility and forced migration. From a system-level perspective, this relationship captures scale and exposure effects: as the number of foreign drivers and vehicles increases, their absolute involvement in road incidents also rises, even if individual risk remains unchanged.

These findings are consistent with previous international studies examining foreign drivers and cross-border traffic. Research conducted in Finland, Greece, Spain [1-3], and Norway has shown that higher accident involvement among foreign drivers is often linked to unfamiliarity with local road conditions, differences in traffic regulations, and increased exposure on international freight routes, rather than nationality-specific behavioral factors. The Polish case aligns with this literature, reinforcing the view that integration into the national traffic system and adaptation to local driving conditions are critical determinants of road safety outcomes.

An important contribution of this study lies in its macro-level perspective. Unlike many micro-level analyses based on individual accident records, this research combines national accident statistics with long-term data on vehicle inflows, migration, population size, and vehicle registrations. This approach allows for the identification of structural relationships operating at the level of the entire transport system. The results suggest that periods of intensified cross-border traffic—such as those observed after 2014 and particularly after 2022—pose additional challenges for road safety management, even in the context of an overall declining trend in accidents and fatalities.

Weather conditions, while commonly cited as a key determinant of road safety, were found to have limited and statistically insignificant effects in the estimated models. This may indicate that, at the annual aggregation level, the influence of temperature and precipitation is overshadowed by structural factors such as traffic volume and vehicle density. It also suggests that improvements in infrastructure, vehicle technology, and driver adaptation may have mitigated the impact of adverse weather conditions over the study period.

Several limitations of the study should be acknowledged. First, the analysis is based on annual data, which limits the ability to capture short-term fluctuations, seasonal effects, and regional heterogeneity. Second, the relatively small number of observations restricts model complexity and may affect statistical power. Third, potential endogeneity between traffic volume, registered vehicles, and accident outcomes cannot be fully excluded. While log-linear models are suitable for analyzing proportional relationships, they do not account for feedback mechanisms or structural breaks associated with regulatory changes or infrastructure investments.

Despite these limitations, the results offer valuable insights for transport engineering and road safety management technologies. They highlight the need to adapt traffic management systems, infrastructure design, and safety-oriented technological solutions to periods of increased cross-border mobility. From a technological perspective, integrating foreign drivers into national road safety systems requires not only regulatory measures but also system-level solutions such as information technologies, traffic monitoring systems, and infrastructure adaptation. Future research may support the development of advanced traffic management technologies by incorporating spatially disaggregated data and system-oriented modeling approaches.

6 Summary

This study analyzed the relationship between road accidents in Poland and the influx of vehicles and drivers from Ukraine from 2010 to 2024. Three log-linear models were applied, with the number of road accidents (NRA), fatalities (NFA), and injuries (NIA) as dependent variables. Independent variables included the number of vehicles entering from Ukraine, accidents involving Ukrainian drivers, population size, the number of registered vehicles, and weather conditions.

The analysis demonstrates that traffic intensity and the share of Ukrainian drivers have the greatest impact on road safety. Both the number of vehicles entering Poland and accidents involving Ukrainian drivers were positively correlated with accidents, fatalities, and injuries. Population size and the number of registered vehicles also significantly influenced accident rates. Conversely, weather conditions had a limited and statistically insignificant effect on accident outcomes.

These results underscore the importance of integrating drivers from migration flows into national road safety systems and highlight the need to account for traffic intensity in transport policy planning. They also suggest the necessity for further research encompassing infrastructure and road user behavior.

Regarding the research hypotheses, three of the four (H1-H3) were confirmed. H1, concerning the impact of the number of vehicles entering from Ukraine; H2, regarding accidents involving Ukrainian drivers; and H3, related to population and registered vehicles in Poland, were all supported by positive, statistically significant β coefficients. Hypothesis H4, which posited a significant effect of weather conditions on accidents and their consequences, was not confirmed. Temperature and precipitation did not have a significant impact during the study period, indicating that demographic and migration-related factors play a far greater role in shaping road safety in Poland than weather conditions.

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Digital value chain with cognitive technologies: a conceptual framework and small-scale prototype

Maksym Karakai
Technical University of Košice, Faculty of Manufacturing Technologies with a seat in Prešov, Department of Manufacturing Management, Bayerova 1, 080 01 Prešov, Slovak Republic, EU, maksym.karakai@tuke.sk
Daniel Bobko
Technical University of Košice, Faculty of Manufacturing Technologies with a seat in Prešov, Department of Manufacturing Management, Bayerova 1, 080 01 Prešov, Slovak Republic, EU, daniel.bobko@tuke.sk
Reinhard Bernsteiner
MCI Management Center Innsbruck | The Entrepreneurial School, Department Management, Communication & IT, Universitaetsstrasse 15, 6020 Innsbruck, Austria, EU, reinhard.bernsteiner@mci.edu
Lucia Knapčíková
Technical University of Košice, Faculty of Manufacturing Technologies with a seat in Prešov, Department of Manufacturing Management, Bayerova 1, 080 01 Prešov, Slovak Republic, EU, lucia.knapcikova@tuke.sk (corresponding author)

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Abstract: This paper proposes a conceptual framework linking digital value chain integration with cognitive technologies and demonstrates it through a simulation-based micro-prototype. The framework combines discrete-event simulation, event-driven communication, and an external decision component to realize a minimal perception–decision–action loop. A discrete-event model was implemented in Tecnomatix Plant Simulation and connected to external components via MQTT publish/subscribe messaging. During runtime, the simulation emits process events (e.g., station start/finish) that can be observed through standard MQTT tooling. External commands are delivered through the broker to control execution (START/STOP) and to actuate a selected model parameter (processing-time updates), while a simple constraint mechanism provides alert signaling for out-of-range inputs. To support reproducibility and offline analysis, a lightweight Python MQTT bridge captures message streams and exports structured telemetry logs (JSONL/CSV). The prototype illustrates how cognitive logic can be decoupled from the simulation environment while remaining dynamically integrated through events and commands. Although the demonstrator is intentionally minimal and not intended for industrial optimization, it provides an experimentally grounded example of modular integration principles applicable to scalable and interoperable digital value chain architectures. The contribution of this work lies in demonstrating a minimal and reproducible event-driven integration pattern rather than an industrial-scale digital twin or optimization solution.

1 Introduction

Digital transformation has become a key driver of change in manufacturing systems, driven by increasing process complexity, shorter product life cycles, and growing demands for flexibility and resilience. Within this context, the concept of the digital value chain expands traditional views of value creation by emphasizing continuous digital integration across planning, execution, monitoring, and improvement. The effective use of digital data and models across these stages is widely considered a prerequisite for intelligent and adaptive manufacturing environments, yet practical adoption often remains fragmented across heterogeneous tools and interfaces, which limits end-to-end responsiveness and decision support [1].

In recent years, digital twins and simulation-based approaches have been widely discussed and adopted as core elements of digital manufacturing strategies. Discrete-event simulation, in particular, provides a controllable environment for analyzing production system behavior under varying conditions and for evaluating decisions during system design and operation. However, in many practical applications, simulation models are still applied as isolated tools—supporting descriptive or predictive analysis without seamless integration of adaptive decision mechanisms and runtime feedback loops. Consequently, their potential to contribute to autonomous or semi-autonomous behavior across the digital value chain is often underutilized [2].

At the same time, cognitive technologies and artificial intelligence are increasingly presented as enablers of intelligent manufacturing systems. These approaches range from transparent rule-based logic and agent-based decision support to data-driven learning methods. Despite their promise, many integration efforts either focus on narrowly scoped optimization tasks or rely on complex, large-scale architecture, which can reduce transparency and complicate experimental validation. This creates a clear need for simple, modular, and experimentally grounded demonstrations that show—step by step—how external decision logic can interact with digital representations of production processes in a way that remains interpretable and reproducible [3].

Event-driven architecture provides a suitable integration mechanism in this regard, enabling loosely coupled communication based on the exchange of events. By decoupling simulation from external logic, event-based integration supports modularity and scalability, and it enables perception–decision–action loops without embedding complex cognitive logic directly into the simulation environment. Lightweight publish/subscribe messaging (e.g., MQTT) further supports rapid prototyping and interoperability across distributed components, making it a practical choice for small experimental setups and for future expansion toward richer digital value chain scenarios [4].

The aim of this paper is to propose a conceptual framework that links digital value chain concepts with cognitive technologies through event-driven integration and to demonstrate its feasibility using a simulation-based micro-prototype. The prototype integrates a discrete-event simulation model in Tecnomatix Plant Simulation with external control and evidence collection via MQTT-based messaging. It demonstrates broker-mediated observability (process events), command-driven actuation (execution control and parameter updates), and structured logging through a lightweight Python bridge. By focusing on a minimal yet complete interaction loop, the paper provides a clear foundation for further research on adaptive and intelligent digital value chain systems and motivates the systematic literature positioning presented in the following section.

While digital twins, event-driven architectures, and cognitive technologies are widely discussed in the context of smart manufacturing, many existing studies either focus on large-scale and complex reference architectures or address narrowly defined optimization tasks. This often limits transparency, experimental accessibility, and reproducibility, particularly in early-stage research and methodological exploration.

The contribution of this paper lies in proposing and experimentally demonstrating a minimal yet complete integration framework that links discrete-event simulation with external cognitive logic through event-driven communication. Rather than aiming at industrial-scale optimization or a fully-fledged digital twin, this study introduces a simulation-based micro-prototype that explicitly realizes a perception–decision–action loop using lightweight and widely available technologies.

By emphasizing modularity, decoupling, and reproducibility, the presented framework provides an experimentally grounded building block for future research on cognitive and adaptive digital value chain architectures.

2 Literature overview

2.1 Digital value chain and smart factory integration

The digital value chain can be interpreted as an integrated flow of information and decisions across the lifecycle and operational chain—from planning to execution and continuous improvement—where value is created by reducing uncertainty, improving coordination, and accelerating response. Industry 4.0 literature frames smart factories as networks of connected resources and information systems; however, implementation barriers often stem from interoperability issues, uneven digital maturity, and insufficient integration between analytics and operational systems [1].

From a practical perspective, simulation and digital tools are increasingly used to analyze and improve value chain performance in Industry 4.0 settings, including supply chain and production system coordination. This supports a view where value chain “digitalization” is not a single technology but an ecosystem of methods (DES, digital twins, IIoT connectivity, analytics) that must be orchestrated [3].

2.2 Digital twins and “micro” digital twins as building block

Digital twin research ranges from conceptual definitions to detailed reference architecture. A recurring message is that effective digital twins require reliable data acquisition and connectivity, a coherent data model and persistence, and analytics/simulation components capable of generating insight and recommending actions. In manufacturing case studies, layered architectures enable separation of concerns (local data handling, gateways/connectivity, cloud databases, simulation/emulation, and application logic), which is especially relevant when integrating legacy systems and new analytics modules [5].

In many real implementations, adopting “micro digital twins” (small, scoped twins for machines/cells/segments) is a pragmatic approach: instead of attempting an enterprise-wide monolithic twin, organizations deploy smaller twins that can later be composed. Methodological contributions for developing digital twins in industry often emphasize structured development steps, a communication layer, and clear interfaces to operational data sources and decision modules. Cloud-based digital twin implementations demonstrate that remote monitoring and control can be realized when connectivity, data management, and application logic are aligned (including MQTT in the communication layer) [6,7].

2.3 Discrete Event Simulation as an experimentation substrate

Discrete Event Simulation (DES) is one of the most widely used simulation approaches in production system modeling and remains a dominant trend in recent reviews. It is frequently used to represent process flows, resource constraints, and stochastic behaviors while enabling KPI-focused experimentation (throughput, lead time, utilization). Evidence from literature reviews and software adoption studies indicates that Plant Simulation is a common DES tool in smart manufacturing research and application [2,8].

Beyond standalone use, DES becomes especially valuable when coupled with data-driven methods. Studies show DES can generate structured datasets for analytics/Machine Learning (ML), while ML can enrich simulation-based decision support (e.g., planning for flexible job shops). This line of work supports a “simulation + learning” loop, aligned with digital twin objectives when the simulation is connected to evolving system data [4].

2.4 Event-driven architecture and interoperability (MQTT, OPC UA)

Event-driven architecture is frequently proposed to improve responsiveness and decouple systems in industrial environments. Manufacturing-oriented event-driven approaches have been explored through architectures that model production information flows as events and support scalable integration of line-level systems. In industrial IoT practice, MQTT provides lightweight publish/subscribe messaging that naturally supports event-driven interaction across distributed components, while OPC UA provides structured information models and industrial-grade connectivity patterns [9].

Protocol selection is not neutral. Survey work on IoT protocols highlights performance and suitability trade-offs across application contexts, while comparative analyses continue to examine MQTT alongside alternatives such as CoAP [10,11]. Conceptual modeling research on MQTT for IoT-based systems further supports systematic understanding of messaging patterns and their role in system design [12].

For OPC UA, interoperability research includes mechanisms for legacy integration (e.g., OPC-UA agents for legacy PLCs), and implementations addressing communication control in embedded OPC UA servers [13,14]. OPC UA also appears in digital-twin-oriented information modeling work (e.g., OPC UA–based workshop information models). Official reference architecture materials provide a consolidated view of OPC UA concepts and how they map to system integration needs [15,16].

Finally, security and robustness must be considered for event-driven integration. Studies reviewing IoT protocol security features emphasize that protocol-level choices and deployment practices significantly affect risk exposure. Intrusion detection approaches tailored for MQTT environments further indicate the need to treat IIoT messaging as a security-critical subsystem [17,18].

2.5 Cognitive technologies: from analytics to decision logic (agents, hybrid intelligence)

Within manufacturing, “cognitive” capabilities are commonly associated with perception (state awareness), reasoning (evaluation of alternatives), learning (data-driven improvement), and action (recommendations or automated control). Systematic reviews of ML in production lines categorize tasks such as prediction, classification, anomaly detection, and optimization support, providing a foundation for selecting minimal algorithms suitable for prototype-level decision logic. Predictive quality reviews further indicate that ML/DL (Deep Learning) methods are increasingly used to support quality-related decisions, though integration into operational workflows remains challenging [19,20].

A practical “cognitive” step beyond analytics is using agent logic (rule-based or ML-based) to transform events into decisions. This aligns with hybrid intelligence perspectives where ML supports—but does not necessarily replace—human decision-making in production management. Recent systematic work on hybrid intelligence highlights decision-support gaps and opportunities to structure human-AI collaboration across production decisions [21].

3 Methodology

3.1 Research approach

This work follows a prototype-driven research approach aimed at demonstrating core integration principles relevant to cognitive enhancements of digitally supported manufacturing systems. Instead of claiming a full digital twin, the implemented artifact is positioned as a simulation-based micro-prototype (an event-driven simulation demonstrator). The objective is to show, in a transparent and reproducible manner, how a discrete-event simulation model can expose process-relevant state transitions as messages and be influenced by external decision logic via broker-mediated commands.

The methodological focus is therefore on observability, decoupled communication, and closed-loop actuation rather than on industrial-scale optimization, calibration to physical assets, or comprehensive validation.

3.2 Overall architecture

The demonstrator is organized as four loosely coupled layers:

1) Simulation layer (Tecnomatix Plant Simulation): a minimal discrete-event model representing a simple production flow and SimTalk methods responsible for publishing messages and processing external commands.
2) Messaging layer (MQTT broker): an event-driven communication backbone enabling publish/subscribe interaction between the simulation and external components.
3) External interaction layer:
    - a mobile MQTT client (MQTT X) for manual monitoring and command testing,
    - a lightweight Python MQTT bridge used for structured logging and reproducible experiments (and optionally as a connection point for future automated agent logic).
4) Evidence layer: screenshots from Plant Simulation and MQTT X, plus log artifacts generated by the Python bridge (bridge.jsonl, telemetry.csv) supporting traceability and replication.

This separation keeps the simulation model readable and minimal while allowing external decision logic to evolve from manual commands to automated policies without redesigning the core simulation.

3.3 Simulation micro-prototype in Tecnomatix Plant Simulation

A minimal discrete-event model was implemented in Tecnomatix Plant Simulation consisting of four core objects: Source (entity generation), Station (single processing resource), Drain (sink), and an EventController managing simulation execution. The simulation micro-prototype is shown in Figure 1. The processing behavior is intentionally simple to ensure that integration mechanisms remain transparent and interpretable.

The Station object uses two standard discrete-event triggers as integration points:

- OnEntry: executed when an entity enters the Station (processing start),
- OnExit: executed when an entity leaves the Station (processing completion).

Both triggers call custom SimTalk methods that publish messages to the MQTT broker. In addition, the model exposes a controllable processing parameter (Station.ProcTime) that can be updated externally to demonstrate command-driven actuation.

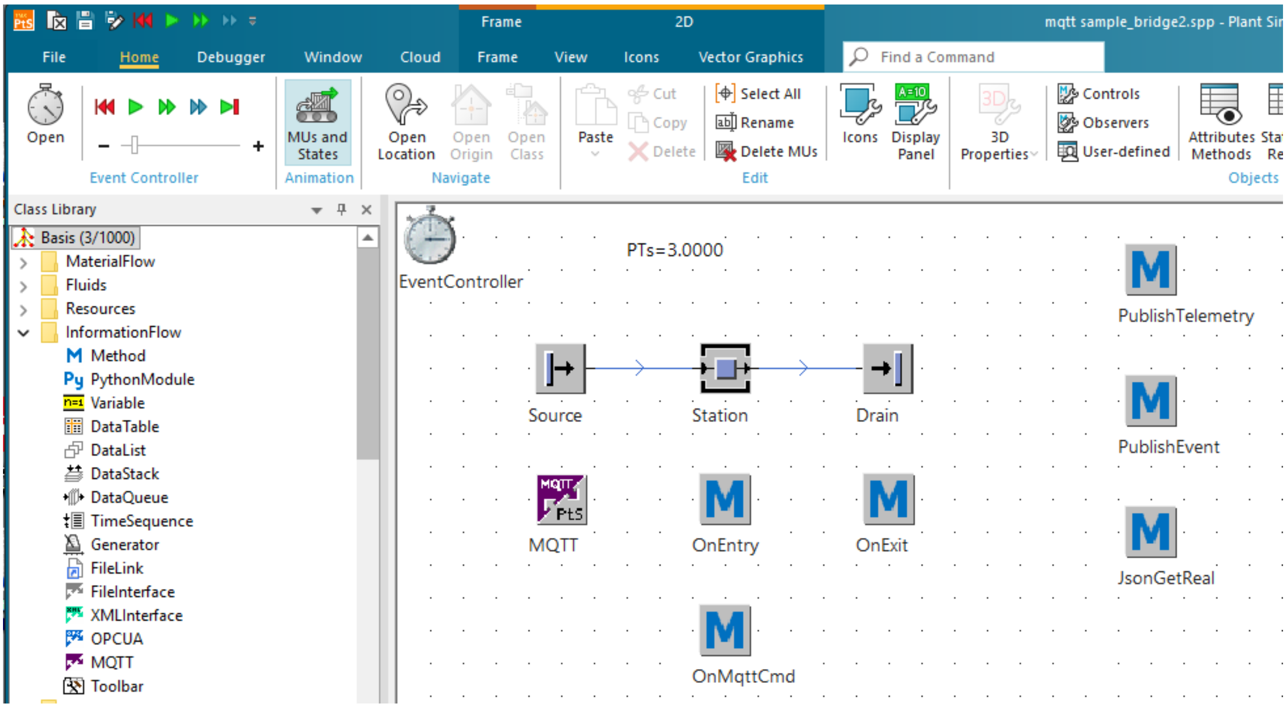

Figure 1 Tecnomatix Plant Simulation micro-prototype used in the study (Source–Station–Drain with event-driven integration elements)

3.4 MQTT connectivity inside Plant Simulation

Communication between simulation and external components is enabled through an MQTT connector object configured with the broker host and TCP port (Figure 2). The connector uses a callback method (e.g., OnMqttCmd) to process incoming messages, while outgoing messages are produced by dedicated publishing helpers.

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Two categories of SimTalk methods support modular integration:

- Publishing helpers (e.g., PublishEvent, PublishTelemetry) responsible for formatting and publishing outgoing messages,
- Command callback (e.g., OnMqttCmd) responsible for parsing and validating incoming commands and applying corresponding actions in the simulation.

This separation ensures that event/telemetry publishing is decoupled from command processing and that both remain separate from the core simulation objects.

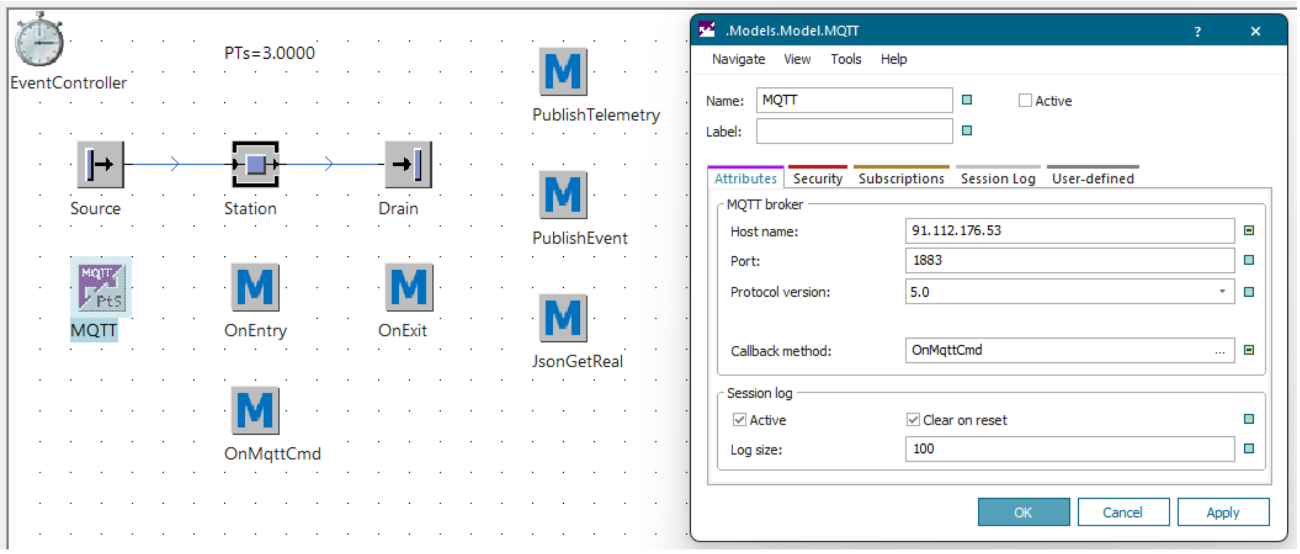

Figure 2 MQTT connector settings in Plant Simulation (broker parameters and callback method for incoming command)

3.5 Message design and topic conventions

During development, two topic styles were used, serving complementary purposes:

- Human-readable manual testing namespace (MQTT X):
  plantsim/station, plantsim/cmd, plantsim/alert
  This namespace supports rapid manual testing and visibility of message exchange using a mobile MQTT client.
- Structured experimental namespace (Python bridge + logging):
  sim/plant1/telemetry/<tag>, sim/plant1/events/<name>, sim/plant1/cmd/<command>, sim/plant1/ack/<command>
  This namespace supports systematic logging, traceability, and repeatable evaluation.

Although the namespaces differ, the functional meaning remains consistent. The simulation emits events/telemetry ("perception") and external components publish commands ("action"), forming a minimal closed loop.

The primary perception signals in the demonstrator are discrete events representing meaningful state transitions of the Station. Specifically, OnEntry publishes a "processing start" message and OnExit publishes a corresponding "processing finish" message. For interpretability during testing, messages include simulation time references and a wall-clock timestamp, enabling reconstruction of the event sequence and approximate cycle-time behavior at the message level (figure 3).

Incoming commands are used for two actuation categories:

- Execution control: START and STOP commands trigger the EventController to start or stop simulation execution.
- Parameter update: a compact command format PT:<value> updates the Station processing time (Station.ProcTime), providing a clear actuation handle for external decision logic.

Command parsing includes minimal validation to ensure robust behavior during manual testing and scripted experiments.

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```
param topic : string, payload : string
  var s     : string := strTrim(payload);
  var snum : string;
  var val  : real;
  print "CMD: " + topic + " :: " + payload;
  if (s = "START") or (s = "start") then
    eventController.start;
    root.MQTT.publish("sim/plant1/ack/start", "{ \"ok\": true }", false);
  elseif (s = "STOP") or (s = "stop") then
    eventController.stop;
    root.MQTT.publish("sim/plant1/ack/stop", "{ \"ok\": true }", false);
  else
    snum := s;
    if (strLen(s) >= 2) and (strCopy(s,1,1) = "\"") and (strCopy(s, strLen(s), 1) = "\"") then
      snum := strCopy(s, 2, strLen(s)-2);
    end;
    val := str_to_num(snum);
    if (val = 0) and (find(s, "{") = 1) then
      val := root.JsonGetReal(s, "value");
    end;
    print "parsed value = " + to_str(val, 6);
    if val > 0 then
      root.Station.ProcTime := val;
      root.MQTT.publish("sim/plant1/ack/set_pt", "{ \"ok\": true, \"applied\": " + to_str(val, 6) + " }", false);
    else
      root.MQTT.publish("sim/plant1/ack/set_pt", "{ \"ok\": false, \"error\": \"invalid number\" }", false);
    end;
  end;
```

.Models.Model   .Models.Model.OnMqttCmd ×

Figure 3 Excerpt of the SimTalk callback implementing command handling (START/STOP) and processing-time update (PT)

To prevent unrealistic parameter settings during testing, the demonstrator implements a basic constraint check for processing time. If the received value violates predefined limits, the system publishes an alert message to a dedicated alert topic (e.g., plantsim/alert). This separation of operational messages (plantsim/station) from anomaly signaling (plantsim/alert) increases transparency and provides a minimal guardrail mechanism suitable for repeatable experiments.

3.6 Python-based MQTT bridge for structured logging and reproducibility

To complement manual MQTT testing, a lightweight Python MQTT bridge was implemented. The bridge subscribes to all topics under a configurable base namespace (BASE_TOPIC, default sim/plant1/#) and performs:

- message ingestion (topic + payload capture with decoding and optional JSON parsing),
- channel-based routing (classification by topic structure into telemetry, events, and commands),
- persistent logging (telemetry export to CSV and full message stream to JSONL),
- acknowledgement publishing (ack/*) to confirm broker-mediated command delivery.

Two log files are produced:

- bridge.jsonl (JSON Lines): append-only message stream preserving topic context and raw payload for traceability and debugging,
- telemetry.csv: structured telemetry table designed for offline analysis (e.g., Excel), containing fields such as ts, run_id, topic, tag, value, unit, and raw_json.

The exported telemetry evidence is evaluated and discussed in Section 4 Results.

A small publisher script was used to generate repeatable telemetry sequences (e.g., conveyor speed values) and send example command payloads, enabling validation of broker connectivity, payload parsing, and logging correctness independently of simulation runtime. This improves reproducibility and supports controlled testing of message structures.

3.7 Independent verification using MQTT X (mobile client)

Message exchange was independently verified using MQTT X on a smartphone (Figure 4). The client was used to:

- subscribe to station/event topics and observe start/finish messages,
- publish commands (START/STOP, PT updates),
- observe alerts triggered by out-of-range processing time updates.

This verification provides evidence that the demonstrator is observable and controllable using standard MQTT tooling and reinforces the claim of broker-mediated decoupling between simulation and external decision logic.

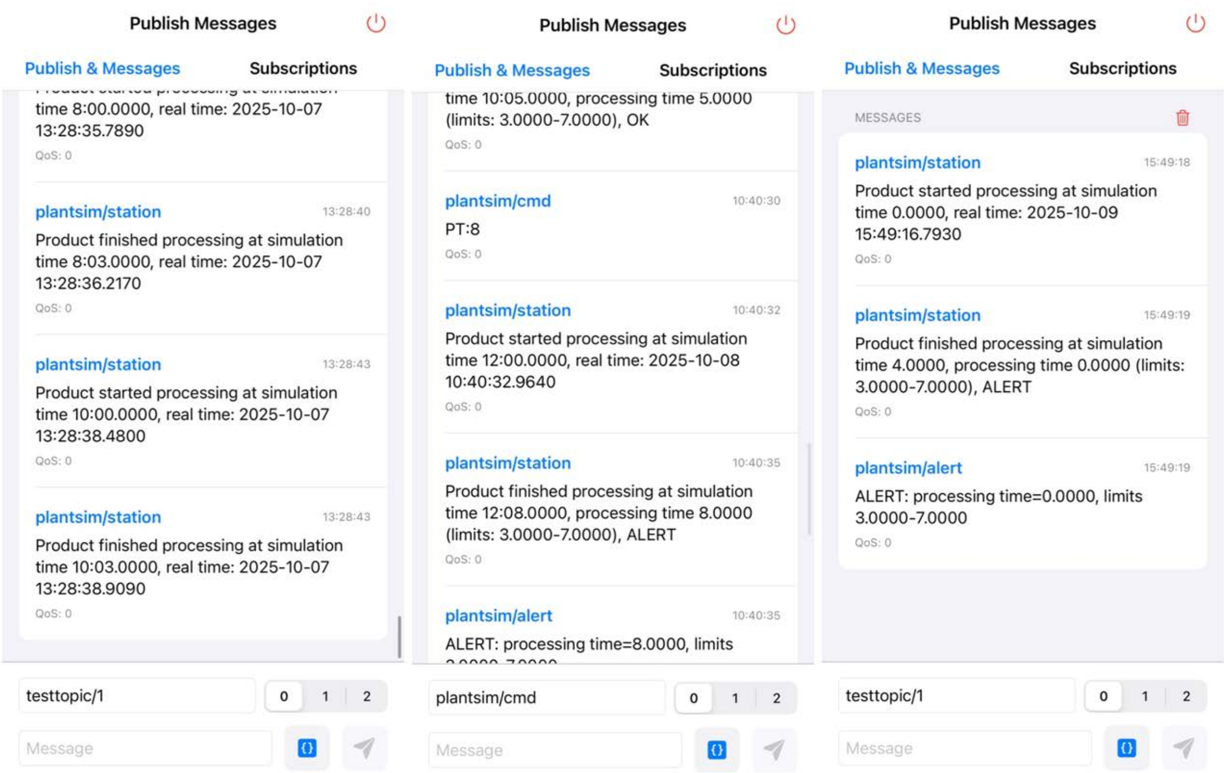


Figure 4 MQTT X mobile client verification of broker-mediated interaction (station messages, commands, and alert signalling)

3.8 Experimental procedure and collected evidence

The demonstrator feasibility was evaluated through repeated runs using the following procedure:

1) start simulation either locally or via command topic,
2) observe event stream: station start/finish events published on the station/event topic(s),
3) send commands (START/STOP, PT updates) via MQTT X or publisher script,
4) verify actuation through subsequent event timing/behavior changes,
5) intentionally trigger a constraint violation and verify alert publication,
6) captured evidence: Plant Simulation screenshots (model layout, trigger configuration, MQTT connector settings, key SimTalk methods), MQTT X screenshots (topics and payloads), and structured logs (bridge.jsonl, telemetry.csv) generated by the Python bridge.

This evidence package supports transparency and enables replication of the demonstrated event-driven integration workflow.

Table 1 Topic patterns and message types used in the demonstrator (paste-ready)

Topic pattern	Direction	Purpose	Example payload
plantsim/station	Simulation → Broker → MQTT X	Manual event monitoring (start/finish)	Text message with simulation/wall time
plantsim/cmd	MQTT X → Broker → Simulation	Manual commands (START/STOP, PT:<v>)	START, STOP, PT:5
plantsim/alert	Simulation → Broker → MQTT X	Alerts for violated limits	"ALERT: processing time=…, limits …"
sim/plant1/telemetry/<tag>	Publisher/Simulation → Broker → Bridge	Structured telemetry logging	{"ts":"…","run_id":"…", "value":1.2, "unit":"m/s"}
sim/plant1/events/<name>	Simulation → Broker → Bridge	Structured events	{"ts":"…", "severity": "info", "msg":"…"}
sim/plant1/cmd/<command>	Client → Broker → Bridge/Simulation	Structured commands	JSON or text command payload
sim/plant1/ack/<command>	Bridge → Broker → Client	Delivery acknowledgement	{"ok":true, "ts":"…", "echo":…}

4 Results and discussion

4.1 Broker-mediated observability of simulation behavior

The first result is the successful exposure of simulation behavior through broker-mediated messaging. The Plant Simulation micro-prototype continuously published station-level process events (start and finish) which were observable using an independent MQTT client (MQTT X, see Fig. 4). This demonstrates that meaningful discrete-event transitions can be externalized as an event stream without direct access to internal simulation objects.

From an integration perspective, this improves observability: external components can reconstruct the sequence of operations and infer basic cycle-time behavior from "start/finish" event pairs. Even in a minimal single-station setup, the message stream represents a practical foundation for monitoring and for triggering downstream logic (e.g., threshold checks, notifications, or simple control policies).

4.2 Command-driven actuation and closed-loop interaction

A second key result is the validated closed-loop interaction between external clients and the simulation model. Commands issued via MQTT affected simulation execution and parameters through the broker, confirming that the simulation can be influenced through a decoupled control channel.

Two actuation categories were demonstrated:

- Execution control: START/STOP commands triggered the simulation execution controller, which was reflected by the presence/absence of subsequent station event messages.
- Parameter update: processing-time update commands in the format PT:<value> modified the station processing time (Station.ProcTime). The effects were indirectly observable through the station event stream and through subsequent behavior during repeated runs.

This result is significant for cognitive integration, while the demonstrator does not claim autonomous optimization, it establishes a clean interface where external decision logic can be attached and iterated independently from the simulation model.

4.3 Constraint handling and alert signaling

To improve robustness and transparency of external actuation, a basic constraint mechanism for processing time was introduced. When a received processing-time value violated predefined bounds, an alert message was published on a separate topic (plantsim/alert). This separation between operational event reporting (station start/finish) and anomaly signaling (alert) supports clearer interpretation, easier debugging, and safer experimentation.

From a design standpoint, even a minimal guardrail mechanism is useful because it formalizes the boundary between "allowed actions" and "invalid actions" and provides feedback to external components in a machine-observable form. This is particularly relevant once an automated agent replaces manual commands.

4.4 Structured logging and evidence for reproducibility

Beyond message-level verification, the Python MQTT bridge produced structured logs that enable reproducible inspection and offline analysis. The bridge captured incoming messages under the structured namespace (sim/plant1/...), stored a complete audit stream in bridge.jsonl, and exported telemetry data into telemetry.csv.

The exported telemetry table includes timestamp (ts), experiment identifier (run_id), topic and derived tag, numeric value, unit, and the raw JSON payload. This enables immediate inspection in spreadsheet tools and supports downstream processing for analysis pipelines. An example excerpt of the telemetry export opened in Excel is shown in Figure 5.

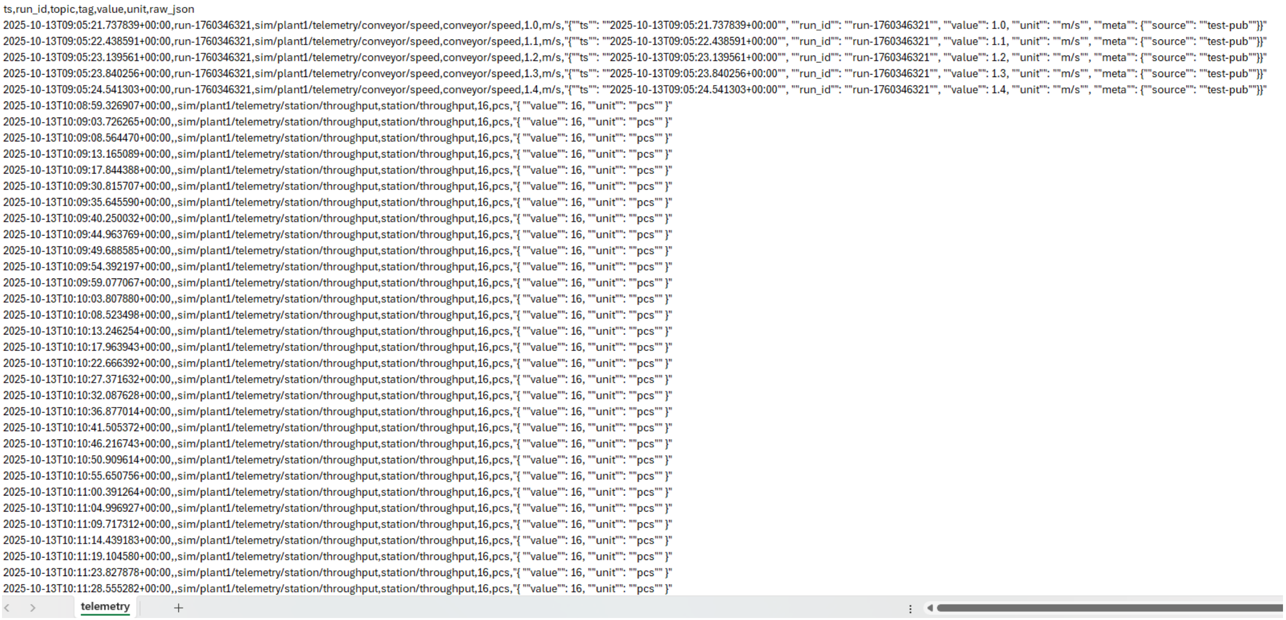
This result strengthens the demonstrator's value as an experimental platform, it does not only "send messages," but also produces structured datasets that can be used to validate message schemas, compare runs, and later evaluate decision policies.

4.5 Discussion: implications for cognitive, event-driven integration

The demonstrated results support three integration implications:

1) Decoupling is feasible at small scale and scales conceptually.
   The simulation remains focused on process behaviour, while external logic interacts through topics and payload conventions. This reduces coupling and allows independent evolution of external components (manual client → rule-based agent → advanced AI component).
2) Events provide a natural perception layer for cognitive logic.
   Discrete-event transitions (start/finish) are interpretable, stable integration points. Even without deep state exposure, event streams can trigger simple reasoning and decision logic.
3) Command topics provide an explicit actuation layer.

The PT:<value> command illustrates a minimal but clear actuation handle. While simplistic, it proves that actions can be applied externally and verified through subsequent event behaviour and acknowledgements/alerts.



```
ts,run_id,topic,tag,value,unit,raw_json
2025-10-13T09:05:21.737839+00:00,run-1760346321,sim/plant1/telemetry/conveyor/speed,conveyor/speed,1.0,m/s,"{""ts"": ""2025-10-13T09:05:21.737839+00:00"", ""run_id"": ""run-1760346321"", ""value"": 1.0, ""unit"": ""m/s"", ""meta"": {""source"": ""test-pub""}}"
2025-10-13T09:05:22.438591+00:00,run-1760346321,sim/plant1/telemetry/conveyor/speed,conveyor/speed,1.1,m/s,"{""ts"": ""2025-10-13T09:05:22.438591+00:00"", ""run_id"": ""run-1760346321"", ""value"": 1.1, ""unit"": ""m/s"", ""meta"": {""source"": ""test-pub""}}"
2025-10-13T09:05:23.139561+00:00,run-1760346321,sim/plant1/telemetry/conveyor/speed,conveyor/speed,1.2,m/s,"{""ts"": ""2025-10-13T09:05:23.139561+00:00"", ""run_id"": ""run-1760346321"", ""value"": 1.2, ""unit"": ""m/s"", ""meta"": {""source"": ""test-pub""}}"
2025-10-13T09:05:23.840256+00:00,run-1760346321,sim/plant1/telemetry/conveyor/speed,conveyor/speed,1.3,m/s,"{""ts"": ""2025-10-13T09:05:23.840256+00:00"", ""run_id"": ""run-1760346321"", ""value"": 1.3, ""unit"": ""m/s"", ""meta"": {""source"": ""test-pub""}}"
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2025-10-13T10:08:59.326907+00:00,,sim/plant1/telemetry/station/throughput,station/throughput,16,pcs,"{ ""value"": 16, ""unit"": ""pcs"" }"
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2025-10-13T10:09:30.815707+00:00,,sim/plant1/telemetry/station/throughput,station/throughput,16,pcs,"{ ""value"": 16, ""unit"": ""pcs"" }"
2025-10-13T10:09:35.645590+00:00,,sim/plant1/telemetry/station/throughput,station/throughput,16,pcs,"{ ""value"": 16, ""unit"": ""pcs"" }"
2025-10-13T10:09:40.250032+00:00,,sim/plant1/telemetry/station/throughput,station/throughput,16,pcs,"{ ""value"": 16, ""unit"": ""pcs"" }"
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2025-10-13T10:11:28.555282+00:00,,sim/plant1/telemetry/station/throughput,station/throughput,16,pcs,"{ ""value"": 16, ""unit"": ""pcs"" }"
```


Figure 5 Example of exported telemetry log (telemetry.csv) generated by the Python bridge for offline analysis (ts, run_id, topic/tag, value, unit, raw payload)

In digital value chain terms, the demonstrator approximates a minimal perception–decision–action loop using widely available tooling (DES + MQTT + Python). It therefore provides a concrete base for further research on how cognitive modules can be systematically integrated into digitally supported manufacturing workflows.

4.6 Limitations and future work

The presented demonstrator is intentionally minimal and has several limitations:

- Scale and complexity: the model represents a single processing station and does not cover multi-resource coordination, routing decisions, or variability across multiple processes.
- Message semantics: the manual testing namespace uses human-readable text messages, future iterations should adopt fully structured schemas (e.g., JSON for all channels) with consistent typing and versioning.
- Validation scope: the demonstrator is a simulation-based experimental setup and is not calibrated to a physical production asset. Therefore, results should be interpreted as architectural feasibility rather than operational performance claims.
- Decision logic: cognitive behaviour is represented by external command capability rather than by a validated autonomous policy. Future work should be integrated into a rule-based or learning-based agent and evaluate decisions against defined KPIs.

Next steps include extending the model to multi-station flows, enriching telemetry (queue lengths, utilization, throughput), formalizing message schemas, adding acknowledgements consistently, and integrating automated decision policies that can be evaluated using the bridge-generated datasets.

5 Conclusions

This paper presented a simulation-based micro-prototype that demonstrates how event-driven communication can be used to integrate discrete-event simulation with external cognitive decision logic in a transparent and reproducible manner. Instead of proposing comprehensive digital twin architecture, the study deliberately focused on a minimal and modular setup that enables closed-loop interaction between perception (event streams), decision-making (external logic), and action (broker-mediated commands).

The main contribution of this work is twofold. First, it proposes a conceptual framework that links digital value chain integration with cognitive technologies through event-driven principles. Second, it validates this framework through a small-scale but functional prototype implemented in Tecnomatix Plant Simulation and connected via MQTT to external monitoring, control, and logging components. The results confirm that meaningful simulation events can be externalized, acted upon, and systematically logged without embedding complex logic directly into the simulation model.

The results showed that simulation behavior can be externalized as a broker-mediated event stream (station start/finish messages) and that external commands can influence both execution and model parameters (START/STOP and processing-time updates). A basic constraint mechanism with alert signaling improved robustness and interpretability during testing. In addition, a Python MQTT bridge enabled structured logging (JSONL/CSV), strengthening traceability and supporting offline inspection of telemetry data.

Although the demonstrator is intentionally limited in scale and complexity, it provides a reproducible experimental foundation for future research. The proposed approach can be extended toward multi-station systems, richer telemetry, structured message schemas, and automated decision policies. As such, the presented micro-prototype represents a practical stepping stone toward more advanced cognitive and adaptive digital value chain implementations.

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Advancements in sustainable public transportation systems: a systematic review

Mohamed Ali Farah
Faculty of Management Science, SIMAD University, 389H+29G, Jidka Warshadaha 2526, Mogadishu, Somalia, mohamedfarah@simad.edu.so (corresponding author)
Hassan Ahmed Mohamed Jakuula
Faculty of Management Science, SIMAD University, 389H+29G, Jidka Warshadaha 2526, Mogadishu, Somalia, hassanjakuula@simad.edu.so

Keywords: sustainability, public transportation, electrification, data-driven solutions, intelligent transportation systems.
Abstract: Sustainable public transportation system developments from 2020 to 2024 are examined in this systematic literature evaluation. It emphasizes the use of electric and hybrid buses, intelligent transportation systems (ITS), and data-driven approaches to improve operational efficiency, user happiness, and pollution reduction. The main goals were to identify trends in sustainable public transportation, evaluate technology and policy initiatives, and provide recommendations for future research and policymaking. Using the PRISMA methodology, the review initially identified 1,400 peer-reviewed papers from Scopus. In total, 11 articles were selected for their relevance to sustainable transportation. The results indicate notable progress in the use of sustainable technology, as the implementation of Intelligent Transportation Systems (ITS) and data-driven techniques has improved efficiency and satisfaction. Public involvement and instruction are crucial for successful acceptance. The study acknowledges limitations, including its narrow focus on English-language papers and its reliance on the Scopus database, which may result in the exclusion of pertinent studies. The study's findings indicate that although significant advances have been made, ongoing efforts are necessary to address remaining obstacles and deficiencies. Future study should expand their scope to encompass numerous languages, diverse databases, and the most recent technical advancements. This study offers significant insights and practical recommendations for promoting sustainable public transportation, thereby enhancing urban environments in terms of efficiency, environmental sustainability, and liability. The contributions encompass a thorough synthesis of recent progress, identification of key patterns and deficiencies, and practical recommendations for policymakers and researchers.

1 Introduction

Several cities are experiencing rapid growth that exceeds their capacity to manage urban design, infrastructure, and public services effectively. The primary concerns for municipal administration, particularly in large metropolitan centres, are security, education, healthcare, and transportation. In these areas, access to these vital services is disproportionately limited and costly. Smart cities, strategic digital city projects, and public transport play a crucial role in integrating all other public services. Transportation is essential for economic development, as workers and students rely on it to securely and comfortably carry out their everyday tasks [1]

The management of transportation networks is increasingly emphasizing environmental sustainability, with a shift toward a 100% renewable transportation system driven by concerns related to climate, energy, and sustainability [2]. This subject is discussed across all primary modes of transportation, including road transport [3,4], air transport [5], maritime transport [6], and railway transport [7]. While railway transit in Europe has a relatively low environmental impact compared to other modes of transportation [8] There are still ample chances to enhance the sustainability of (electric) railway travel, for example, by optimizing energy conversion.

The behavior and demand for public transportation have changed significantly in recent decades. These changes resulted from rapid technological advancements and increasing apprehension about climate change. In addition, public transportation has become a vital tool for reducing carbon emissions [9]. Public transportation plays a crucial role in sustainable mobility by providing an alternative to individual car use. Nevertheless, to promote greater use of public transportation, it is imperative to first understand individuals' travel patterns and preferences for flexible, environmentally friendly alternatives [10]. The transportation system is a vital component of contemporary civilization, facilitating the spread of industrialization, the advancement of agriculture, and the development of rural regions. Transport networks enable the movement of individuals and goods across regions, facilitating the exchange of resources and ideas. In the absence of a reliable transportation system, economic activities would be severely affected due to restricted access to markets and resources. Hence, it is evident that transportation plays a pivotal role in fostering economic growth and affluence [11]. In the absence of transportation development, the local market would be constrained, and manufacturing would be limited to meeting solely local demand. Consequently, the economy of any nation would stay undeveloped.

Transportation holds significance not only for its economic impact but also for its social, political, and cultural implications. In addition to economic advantages, transportation yields social benefits [12]. The transportation sector contributes significantly to global greenhouse gas emissions, air pollution, noise pollution, and habitat degradation. Road transportation is the primary mode, accounting for the majority of global transportation-related emissions [13]. The increasing number of private automobiles and traffic congestion are substantial contributors to atmospheric pollution, particularly in metropolitan regions [12].

The sustainability challenges confronting the transportation sector are intricate and require a multifaceted approach. Effective approaches to reduce transportation emissions include promoting low-emission vehicles, enhancing public transportation systems, and enacting sustainable land-use regulations that reduce dependence on private automobiles. Sustainable transportation legislation and reducing private car use can create a more sustainable transportation system that benefits people and the environment [14]. The importance of this factor in advancing sustainable mobility in urban areas was highlighted by [15] and further reinforced by [16]. In response to global concerns about climate change, air pollution, and traffic congestion, sustainable transportation legislation and initiatives have proliferated. These policies and efforts are environmentally friendly, energy-efficient transportation strategies that aim to reduce the negative environmental and public health impacts of transportation [17].

Despite extensive research on sustainable public transportation systems, there is a lack of analysis of trends, technological developments, and policy implications from 2020 to 2024. There are no recent studies in the literature on this topic, aside from those from previous years. To address this gap, a systematic literature review (SLR) will analyze publications from this period to assess the current state and future developments in sustainable public transport.

The major objectives of this research are to identify contemporary trends and developments in sustainable public transportation systems between 2020 and 2024 and to evaluate the effectiveness of recently introduced technologies and policies in promoting sustainability in these systems. What is the trend in annual research publications on sustainable public transportation systems between 2020 and 2024? What are some key environmental and social benefits resulting from the adoption of sustainable public transportation technologies and policies within this timeframe?

This study comprehensively reviews recent advancements and trends in sustainable public transportation, offering valuable insights for policymakers, researchers, and practitioners. The research explores best practices, emerging technologies, and policies for urban mobility to address challenges, reduce environmental impacts, and promote sustainable systems. It examines recent trends, the effectiveness of new technologies, and policy impacts from 2020 to 2024. The results section provides detailed information on publication trends, technological advancements, and policy impacts, ensuring a clear connection between the study's aims and outcomes.

2 Methodology

This section describes the steps for identifying publications on sustainable public transportation, which involve establishing stringent protocols and conducting a rigorous review of relevant sources. The identified relevant publications were using PRISMA and meta-analysis. Indeed, the PRISMA framework is the most critical component of the systematic review process, as the protocol requires that review reports focus on randomized trial-based analyses. It also sets out clear criteria for including and excluding studies, which are relevant to our study. According to [18], PRISMA is best suited to systematic reviews of randomized trials, particularly for therapeutic interventions. The PRISMA framework can be somewhat limiting for assessing qualitative and mixed-methods study designs. PRISMA comprehensively searches several well-known scientific databases and research sources to ensure a systematic location of any relevant literature, thus minimizing the chances of missing any major research work. In addition, as pointed out by [19], PRISMA streamlined the screening process by reducing the number of studies at each stage, as suggested by [18].

Although PRISMA is primarily a tool used in medical research, its focus on systematic reviews makes it applicable to operations management. This framework also provides clear guidelines for including or excluding data based on specific research aims. Other non-clinical researchers have increasingly turned to reports focused on methodological literature, as identified in systematic literature reviews, to address this deficiency in methodological guidance. According to [20], WoS and Scopus are the two major citation databases that compete with each other. However, this review retrieved only the target articles from the vast Scopus database. The decision was informed by the study done by [21], which concluded that Scopus yielded more documents than WoS. As such, Scopus was favored to seek more relevant papers for review. [22] have highlighted that Scopus is the largest abstract and citation database of journal articles across several disciplines, making it particularly useful for gathering related publications for a researcher. Scopus has recently gained ground as a key competitor and seriously threatened WoS's market monopoly position.

2.1 Search strategy and selection process

Scopus search strings were used to thoroughly explore review terms. Initially, researchers conducted a keyword search using the term "Sustainable AND Public Transportation" as the primary focus. Synonyms, related terms, and variations identified in prior studies as research keywords were incorporated to expand the scope. These extended keywords were subsequently used in the Scopus advanced search tool, yielding 1400 articles. The ability of a reviewer to undertake a comprehensive evaluation greatly influences the quality of a literature review, as highlighted by [23]. To improve the quality of the results, this review exclusively incorporates journal papers [24]. To simplify the procedure and eliminate translation issues, only English-language documents were considered.

For this study, the publication year was not restricted, although many researchers commonly employ it as an exclusion criterion. The search results reveal that the publications span from 2020 to June 2024. Therefore, the publication year was not a factor in excluding articles. The inclusion and exclusion criteria for the selected article are summarized in Table 1.

Table 1: Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Articles indexed in Scopus Scholarly articles published in journals Articles written in English	Articles not indexed in Scopus Proceedings from conferences, chapters from books, and books Articles written in languages other than English Study based on conceptual analysis

The authors manually assessed 1400 articles by reviewing their titles, abstracts, and full texts. 94 abstracts were removed due to duplication, and 287 abstracts were excluded during screening. Furthermore, 959 articles were rejected after reviewing the full text, and an additional 339 were deemed ineligible after thorough evaluation. As a result, 11 documents were identified as suitable for further analysis.

Based on the relevance, quality, and comprehensiveness of the articles on sustainable public transportation, 11 articles were chosen. Technological advances, policy frameworks, and environmental impacts dominated the discussion. The articles undergo a rigorous peer-review process to verify their credibility. The individuals exhibited diverse perspectives across several academic disciplines and had substantial citation counts and influence. Selection ensured that the most relevant, high-quality, and influential contributions were included. The entire procedure adhered to the principles outlined in the PRISMA statement, ensuring transparency and methodological rigor. Figure 1 shows how PRISMA rules are applied to literature inclusion and exclusion at each review step.

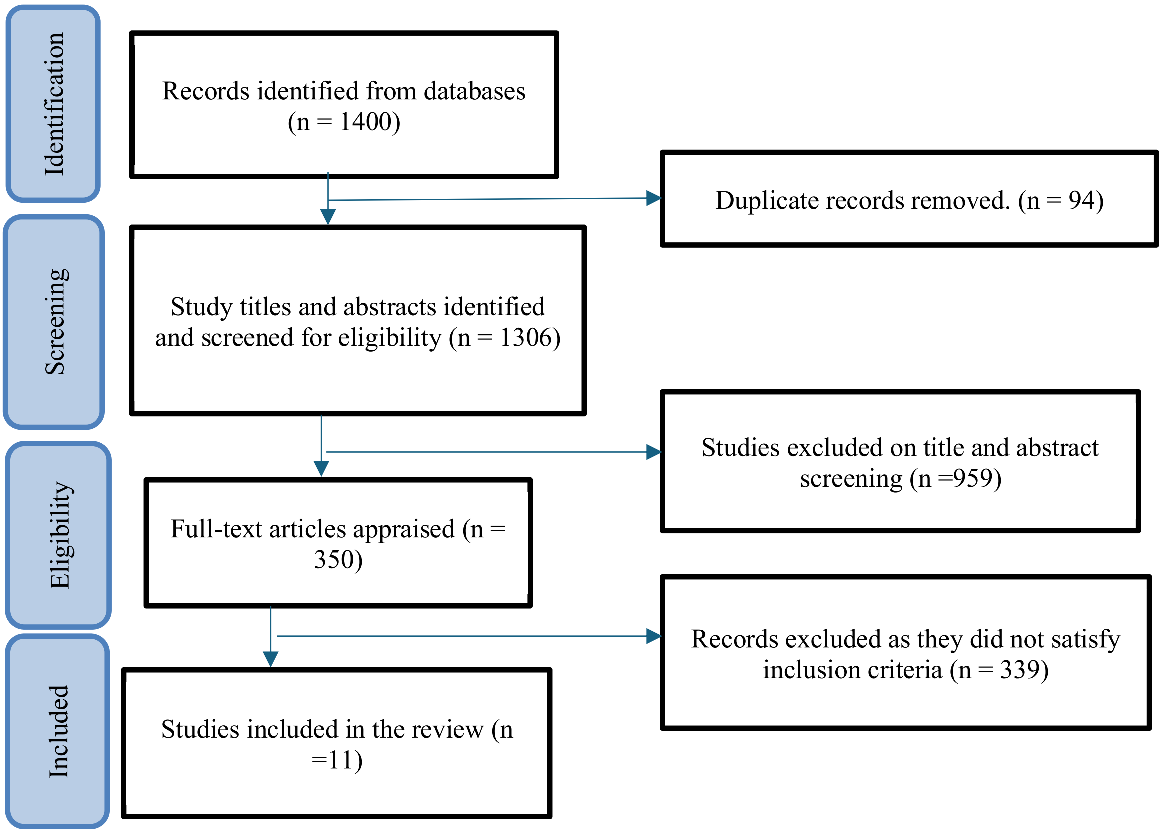

Figure 1 Selection process

3 Results and discussion

This section presents a succinct summary of the systematic literature review conducted from 2020 to 2024, with a specific focus on sustainable public transportation systems. The findings are organized into two primary sections: descriptive statistics and analysis of noteworthy discoveries from selected articles. Descriptive Statistics involves examining publishing trends, geographical distribution, and the categorization of documents by subject area. The Analysis of Key Findings section offers a succinct summary of the primary topics and outcomes examined in the 11 selected studies. An intricate analysis aims to uncover the correlation between sustainable public transportation systems.

3.1 The main information

Figure 2 presents a concise overview of the key attributes of 1400 documents about sustainable public transportation systems published between 2020 and June 2024. The documents originate from 314 distinct sources and are authored by 4221 writers. On average, each document has 3.74 co-authors, and 29.64% of them involve international collaboration. The average number of citations per paper is 13.38, indicating a significant scholarly impact. The yearly increase in research production is 1.65%. In addition, there are 4354 author keywords, and the documents cite a combined total of 83,733 references. The mean age of the documents is 1.94 years, indicating the research is recent.

Figure 2: The main information

3.2 Documents and citations per year

Analyze the annual distribution of articles from 2020 to 2024 to investigate the temporal progression of publications on sustainable public transportation systems. The purpose of this objective is to analyze and determine the patterns, changes, and new areas of interest that have emerged throughout the stated time frame, and to evaluate how citation patterns have developed. The graphs (Figure 3) illustrate the consistent upward trend in the number of articles about public transportation networks over time. In 2020, there were 237 publications. However, in 2023, publications increased consistently, reaching a total of 341. In addition, the average number of citations to publications released between 2020 and 2021 has increased steadily.

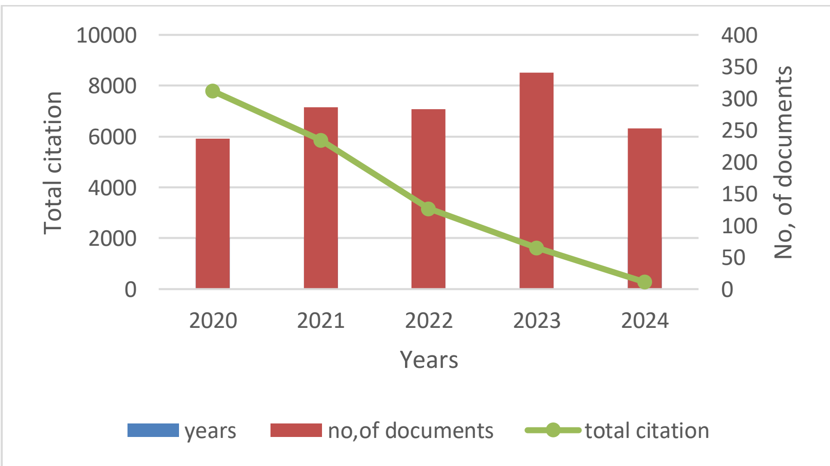

Figure 3 Documents and citations per year

However, there seems to be a decline in the number of papers receiving high citation counts. Consequently, the slope is decreasing because the time required to gather citations for current papers is greater than for prior ones. Over time, the proportion of extensively referenced articles to the total number of publications on the subject will remain consistent. The abundance of articles that have received significant citations further demonstrates the researchers' ongoing fascination with the publications and the subject matter. Public transportation systems remain a relevant subject even after several decades.

3.3 Documents by country

Figure 4 presents the ranks of the top ten countries that have conducted extensive studies on sustainable public transportation systems. The ranking is determined by the quantity of published papers. China ranks first on the list with 301 papers, underscoring its influential role in this field. The United States follows, with 160 documents, signifying a significant scholarly endeavor and interest in this subject. The United Kingdom (UK) ranks third, with 110 publications, indicating a strong research output. Italy boasts 90 publications, demonstrating its growing engagement in intellectual endeavors. Germany and India both demonstrate significant commitment to research on sustainable public transportation systems, with 81 documents each. Australia has 78 documents, whereas Spain has 72 publications. Both countries have made noteworthy contributions to this field. Canada and Turkey are ranked last on the list, having published 55 and 54 papers, respectively. This indicates their significant contribution to the area of study. The allocation of research outcomes across these countries indicates a strong global interest in sustainable public transportation systems. The prevalence of papers from countries such as China, the USA, and the UK suggests well-developed research infrastructures and academic communities committed to addressing this topic. These countries, namely Italy, Germany, and India, represent diverse regions of the world, demonstrating a comprehensive approach to enhancing our grasp of this topic in the future. Figure 4 presents significant achievements in the research of sustainability and its impact on public transportation systems. Thus far, the enhancement of comprehension appears to be a collaborative endeavor undertaken on a global scale.

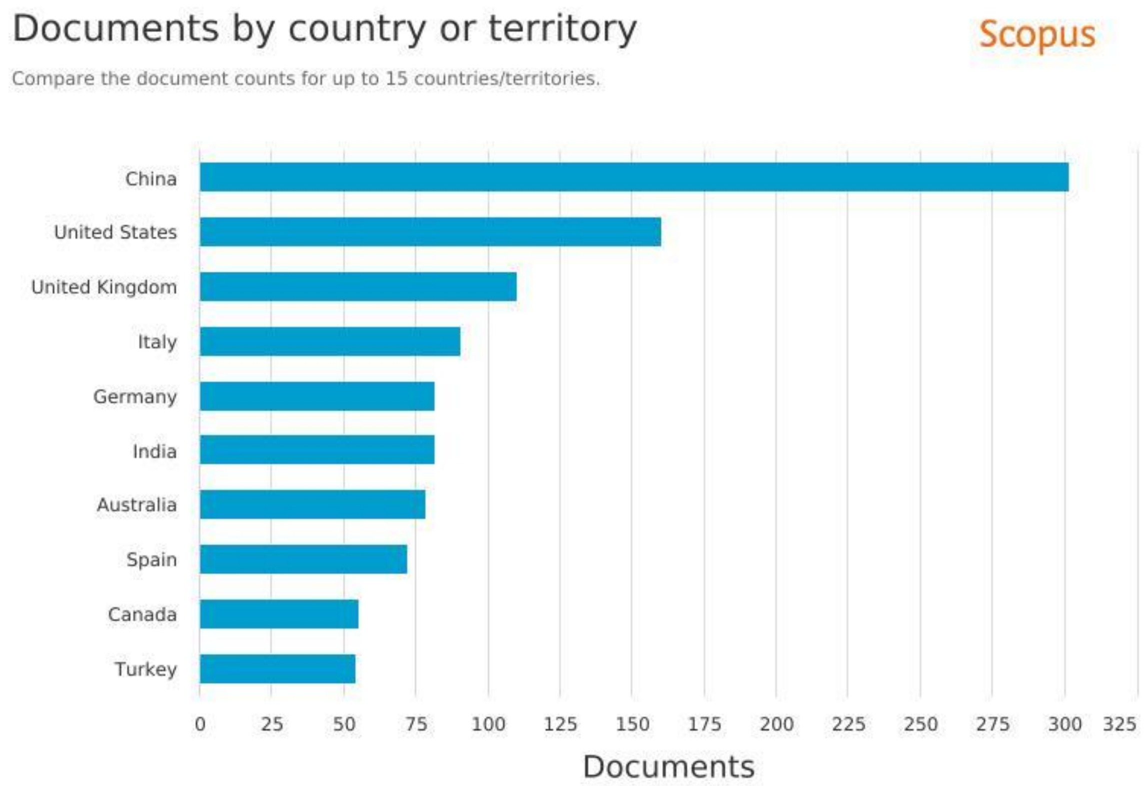

Figure 4 The most productive countries in this field

3.4 Documents by subject area

Figure 5 categorizes the 1400 documents by academic field. The study of sustainable public transportation systems is a multidisciplinary field, with Social Sciences being the largest category, accounting for 25.1% of the total documents. This indicates a focus on understanding social, behavioral, and policy dimensions of sustainable public transportation. Environmental Science accounts for 18.9% of the documents, emphasizing the environmental effects and ecological advantages of sustainable transportation systems. Engineering accounts for 18.2%, with emphasis on technological and

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infrastructure advances. Energy-related research accounts for 15.0%, underscoring the link among energy use, renewable energy sources, and transportation sustainability. Computer Science, accounting for 8.1%, emphasizes the importance of digital technology, data analysis, and intelligent transportation systems in improving the efficiency of public transportation networks. Other fields, such as Business, Management, and Accounting, Economics, Econometrics, and Finance, and Decision Sciences, also contribute to the study. The presence of multiple disciplines highlights the complexity of achieving sustainable public transportation, emphasizing the need for an all-encompassing approach that integrates social, environmental, technological, economic, and managerial perspectives to develop comprehensive and efficient solutions.

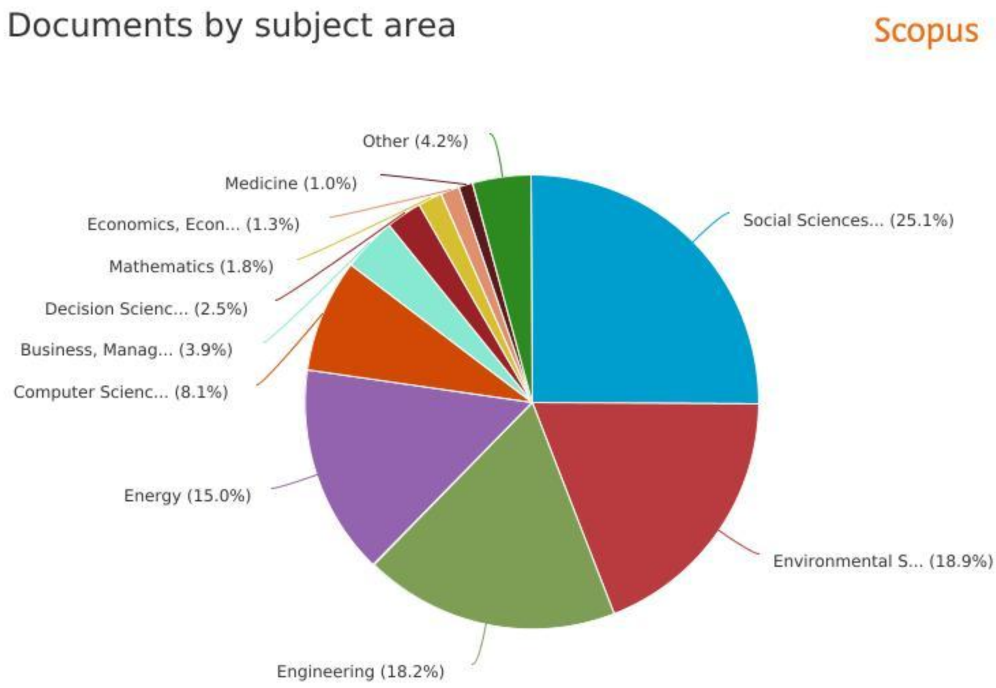

Figure 5: Documents by subject area

3.5 Analysis of Key Findings from the Selected Articles

This section presents a comprehensive analysis of the primary findings from 11 selected publications on sustainable public transportation systems. The assessed papers provide a comprehensive analysis of the significant influence that sustainability has on essential public transportation systems (Table 2).

Table 2 Selected publications on sustainable public transportation systems

Author	Title	Purpose	Methodology	Results
[10]	Design for sustainable public transportation: LCA-based tooling for guiding early design priorities	The paper highlights the significance of sustainable design in public transportation, particularly in train modernization projects, by presenting a Life Cycle Assessment tool to inform initial design choices and thereby improve environmental sustainability.	Case Study	The LCA tool, designed for train modernization projects, incorporates concepts into the initial design phases, thereby decreasing the need for extensive data and specialized knowledge. This tool enhances the accessibility and feasibility of Life Cycle Assessment (LCA), guiding design objectives toward sustainability and providing useful insights into potential environmental improvements. Consequently, it proves to be a great asset throughout the initial stages of the design process.
[6]	Environmental sustainability of public transportation fleet replacement with electric buses in Houston, a megacity in the USA	This study evaluates the environmental impacts and total costs over the full lifespan of replacing conventional diesel buses with electric buses in the Houston METRO system.	Case Study	Life Cycle Assessment (LCA) indicates that electric buses reduce greenhouse gas emissions relative to diesel and hybrid buses. The decrease in energy generation is primarily ascribed to Texas's heavy dependence on natural gas. However, electric buses still emit more, leading to higher environmental costs. Houston's target is to achieve significant annual cost reductions for electric buses by 2040, in order to further its long-term goals of environmental sustainability and improved air quality.

[7]	Data Intelligence in Public Transportation: Sustainable and Equitable Solutions to Urban Modals in Strategic Digital City Subproject	Municipalities are responsible for overseeing many aspects of urban infrastructure, the competitiveness and attractiveness of public transport, and the use and pricing policies for fossil fuels. This is done to encourage equitable and sustainable transportation options. The research seeks to monitor these elements using analytical methods, with a focus on enhancing investments and services in a nimble, effective manner to benefit citizens.	Case Study	The analysis reveals a strong correlation between characteristics and demand for public transportation, suggesting that local authorities can use data to make informed investments in transportation infrastructure. A comprehensive approach to public transit can improve urban mobility, mitigate traffic congestion, and promote sustainable alternatives.
[5]	Sustainability of On-Demand Public Transportation from the Customer Perspective	This article analyzes the sustainability factors associated with on-demand public transportation systems.	Questionnaire	Given the growing awareness of the environmental and public health impacts of traditional transportation, flexible, convenient, sustainable alternatives are needed. To meet this obligation, lawmakers and transportation planners must collaborate to develop and implement public transportation systems that are environmentally sustainable, efficient, and accessible to all.
[13]	Environmental Sustainability Increase by Activation of Public Transport and Personal Mobility	The study aims to propose a personal mobility (PM) algorithm to optimize traffic efficiency and user convenience by enhancing first- and last-mile services.	Case study	The integration of personal mobility services with public transportation in Seoul, Korea, is expected to increase the user base by 2025, reduce air pollution, improve traffic efficiency, and enhance air quality. These advancements will facilitate the execution of shared mobility distribution strategies.
[1]	Sustainability Indicators of Surface Public Transportation	The objective of this research was to identify the most commonly used metrics for assessing the sustainability of public transportation.	Literature review	The findings emphasize that the long-term viability of public transportation is determined by an intricate interplay of multiple elements, requiring a comprehensive approach to planning and policy development.
[9]	The sustainable transport planning index: A tool for the sustainable implementation of public transportation	This paper presents a methodological approach for developing the Sustainable Transport Performance Index (STPI), which assesses the sustainability of a public transportation system by considering its environmental, social, and economic impacts.	Case study	The findings indicate that the STPI is an effective tool for advancing sustainable planning and progress in public transportation. Furthermore, it can be used to assess the long-term viability of existing systems.
[4]	Smart and Sustainable Public Transportation - A Need of Developing Countries	This study aims to introduce an innovative, environmentally sustainable transportation system that provides both economic and social benefits to developing nations.	Literature review	The paper presents the primary uses of intelligent transportation systems in enhancing transport station facilities, passenger information systems, intelligent traffic control and management systems, and smart parking systems. and eco-friendly transportation systems.
[23]	Optimization of renewable energy usage in public transportation: Mathematical model for energy management of plug-in PV-based electric metrobuses	This study contributes to the existing literature by examining metrobuses, which are widely used in the public transportation sector and are based in Istanbul, Turkey's most densely populated city.	Case study	The modeling results indicate that the daily total profit from energy trading for the EMs parking lot is estimated at 86,098 TL. The price of this item is subject to change based on fluctuations in energy prices. However, parking lots equipped with electric transportation can generate revenue.
[18]	Comparative Analysis of Sustainable Electrification in Mediterranean Public Transportation	The objective of this study is to analyze the implementation of electric-powered public transportation in developed and underdeveloped nations. Specifically, it focuses on the current public transport systems, namely buses and trams, in the Mediterranean region.	Literature review	The analysis suggests that more than 200 GWh of electricity consumption from public transportation, including buses, could reduce greenhouse gas emissions and help achieve Sustainable Development Goal 13. However, electric buses may not be the most cost-effective solution, particularly in developing nations. It emphasizes the need for environmental, social, and economic factors in sustainable urban mobility.
[27]	Implications of the Progression to Sustainable Public Transportation: An Insight into the Modern Jeepney Shift from the Philippines	This study evaluated the factors that influence passengers' inclination to use modern jeepneys, using a higher-order reflective construct and partial least squares structural equation modeling.	Questionnaire	The results indicate that travelers are more likely to use public transit because of their personal travel experiences rather than to seek societal approval.

The literature published between 2020 and 2024 was largely focused on the development of sustainable public transportation systems and on sustainability indicators and planning tools. These frameworks would be vital for policymakers and urban planners in identifying crucial areas requiring enhancement, thereby ensuring the efficient and resource-efficient design of transport systems that are environmentally harmonious.

The applications of smart technologies and data analytics in public transport have recently been reviewed. Intelligent transportation systems and data-driven methods, in this regard, have a considerable effect on operational efficiency, emissions, and customer satisfaction [11]. Efficient and innovative public transport systems contribute to sustainable urban development, particularly in developing countries facing mobility challenges [12].

Substituting diesel buses with electric ones has been highly explored for their environmental benefits. Studies indicate whole reductions in GHG emissions and energy use. Expanding public transport to include bicycles and e-scooters provides an integrated solution for sustainable urban mobility by improving air quality and enhancing traffic efficiency. [25], shows that this integration has positive effects on urban mobility. [13] underscores several positive effects these integrations have on urban mobility.

[10] emphasize the importance of customer satisfaction in on-demand public transport systems and underscore that user feedback drives the development of offers for related services. [15] present an instrument based on LCA to support environmentally friendly design decisions already at the project's initial stages. This technology ensures that public transport networks are designed to effectively meet all sustainability objectives and user requirements. [27] Assess various plans for sustainable electrification in Mediterranean public transport networks.

They show the positive effects of these changes on the environment and the economy. In the paper, Saray et al. present a mathematical model to enhance the efficiency of renewable energy use in electric metro buses equipped with plug-in photovoltaic systems in 2024. The authors provided compelling evidence demonstrating the tangible benefits and feasibility of harnessing renewable energy sources for public transportation networks. Discuss the process of adopting environmentally friendly fleets in public transport for developing countries by replacing them with new and cleaner fleets. Their contribution is that sustainable transport solutions must be implemented through enabling policies, infrastructure, and public awareness campaigns.

This provides key lessons for similar transformations in other parts of the world. Several key patterns and conclusions have emerged from a careful review of the 11 selected articles, illuminating the development of public transport and the obstacles to its sustainability. All such data-driven approaches to the integration of Intelligent Transportation Systems have demonstrated their importance for improving operational efficiency, reducing emissions, and increasing consumer satisfaction.

These technologies offer solutions to improve operational efficiency and provide key data for decision-making, with a view toward future legislation on transport and the investment in related infrastructure. Our analysis highlights the need for advanced technologies to sustain the long-term development of public transportation networks, particularly in large cities with severe mobility challenges. Moreover, this study strongly underscored the ecological advantages of the diffusion of electric and hybrid buses. Replacing conventional diesel buses with electric buses would result in significant reductions in greenhouse gas emissions and energy use. Second, better models optimize the use of renewable energy to power public transport and improve efficiency, thereby facilitating the transition. We demonstrate that electric buses are feasible and efficient for communities seeking to reduce CO2 emissions and support clean urban transport. Moreover, the success of any such emerging technologies will depend heavily on user satisfaction and public support; careful public involvement and education are therefore essential. The article is a critical review of studies on sustainable public transport systems published between 2020 and 2024. It provides critical insights for policy decision-makers, researchers, and practitioners on the prerequisites for effective, equitable, and environmentally sensitive systems to address urban mobility challenges and promote sustainable urban development. The integration of intelligent technologies and data-driven initiatives with renewable energy sources will be essential to promoting eco-friendly public transport systems.

4 Conclusions

This research into Sustainable Development on Public Transport Systems, 2020-2024: Commitment to Eco-friendly Technologies and Policies. The present study highlights the urgent need for a significant shift toward eco-friendly technologies and policies across all modes of transport. The drive behind the change under study is the urgent need to reduce GHG emissions and improve mobility within urban systems. The selected articles underscore the use of Intelligent Transport Systems and data-driven approaches to improve operational efficiency and increase user satisfaction.

Almost all the papers reviewed share the overarching theme: the ecological advantages of electric and hybrid buses. Substituting diesel buses significantly reduces emissions and yields substantial gains in energy efficiency. In this regard, there is a need to develop and implement models to fully exploit renewable energy in public transport. The results of our research clearly indicate that the effective working of all these technologies depends on user satisfaction and public acceptance. This underscores the need to fully implement strategies to engage the public. The SLR on sustainable public transport has several limitations.

The review primarily focuses on English-published articles, which may overlook studies in other languages or grey literature. The review's focus on Scopus databases may not capture emerging trends and technologies beyond 2024, resulting in shallow coverage. To improve coverage, recommendations include conducting broader, systemic reviews;

integrating research from grey literature; updating results to include advances and technologies beyond 2024; and addressing issues such as improving self-managed public transport, integrating renewable energy sources, and the environmental implications of green transport systems. Policymakers and researchers must keep pace with advances to stay ahead.

Future studies should investigate the impact of sustainable urban planning and transport policies on long-term development and the socio-economic benefits of sustainable transport, including job creation and improved health outcomes. Additionally, further studies should focus on developing novel measures that leverage innovations, such as renewable energy sources, to address challenges and increase public acceptance of new technologies. This will help policymakers and researchers stay ahead of the curve in sustainable public transport.

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Authors' contributions
Mohamed Ali Farah: conception and design, methodology, intellectual content, analysis and interpretation of data, and original draft preparation. Hassan Ahmed Mohamed Jakuula: conception, supervision, and reviewing.

Disclosure statement
The authors reported no potential conflict of interest.

Data availability statement
The data that support the findings of this study are available from the corresponding author, [Mohamud Ali Farah], upon reasonable request

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Smart infrastructure modeling

Bonniga Ravinder
NICMAR University of Construction Studies, Jaggamguda, Shamirpet, Medchal-Malkajgiri, Hyderabad, Telangana 500 101, India, bravinder@nicmar.ac.in

Keywords: digital twin, logistics management, asset management, predictive maintenance, digital transformation.
Abstract: Digital twin technology has emerged as a significant enabler of digital transformation in logistics and asset-intensive systems by integrating physical assets with real-time virtual models through continuous data exchange. This study investigates the role of digital twins in enhancing organizational and logistics performance, with particular focus on asset monitoring, predictive maintenance, and operational control. A conceptual and analytical approach is adopted to evaluate the impact of digital twin integration on system efficiency and decision-making processes under conditions of operational uncertainty. The results indicate that digital twin implementation substantially improves real-time diagnostics, automated fault detection, and predictive maintenance performance, leading to reduced downtime, enhanced operational efficiency, and improved responsiveness of logistics systems. Compared to conventional asset and logistics management practices, digital twins provide a scalable and cost-effective framework by strengthening data-driven decision-making and minimizing manual intervention. From a strategic perspective, adoption of digital twin technology supports the development of dynamic capabilities, enhances supply chain resilience, and extends asset life cycles. The study concludes that digital twin technology constitutes a critical technological foundation for achieving sustainable performance improvement and long-term competitive advantage in modern logistics environments.

1 Introduction

Manufacturing systems have progressively evolved from traditional production environments toward digitally enabled and data-driven operations in response to intensifying global competition, customization demands, and performance pressures. Within this transformation, digital twin (DT) technology has emerged as a central enabler by integrating physical assets with continuously updated virtual representations that facilitate real-time monitoring, analysis, and optimization. By synchronizing physical and digital systems through continuous data exchange, digital twins enhance system visibility and enable informed managerial decision-making across the product and operational lifecycle [1-16].

Initially conceptualized within product lifecycle management, digital twins have expanded their application to design, production, maintenance, and operational control. Recent advancements in enabling technologies, including the Internet of Things, artificial intelligence, cloud and edge computing, and advanced analytics, have accelerated organizational adoption of digital twin solutions. From a managerial and logistics perspective, digital twins contribute to improved organizational performance through predictive maintenance, process optimization, and adaptive control mechanisms under uncertain operating conditions. Unlike conventional static simulation tools, digital twins support continuous system learning, dynamic feedback, and enhanced organizational responsiveness [17-23].

Despite these advantages, the realization of performance benefits remains constrained by challenges related to data integration, interoperability across heterogeneous systems, cybersecurity considerations, and organizational readiness for digital transformation. Addressing these constraints is essential to fully leverage the strategic potential of digital twin technology [24-31].

Overall, digital twins represent a strategic digital capability that underpins digital transformation and sustained performance improvement in manufacturing organizations. To provide a structured understanding of digital twin typologies, the classification of digital twins based on structural functions is presented in Table 1, classification based on level of application is presented in Table 2, structural classification is detailed in Table 3, and application-oriented classification in smart manufacturing is presented in Table 4.

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Table 1 Classification of digital twins based on structural functions

Category	Physical System Exists	Data Update Mechanism	Data Flow Direction	Control of Physical System	Primary Purpose / Characteristics	Typical Applications
Pre-Digital Twin (PDT)	No	Manual / design-stage data	No real-time data flow	No	Virtual, generic executable model created before the physical system exists; supports early-stage decision-making and risk reduction	Conceptual design, feasibility analysis, virtual prototyping, design validation
Digital Model (DM)	May or may not exist	Manual updates	No automated data exchange	No	Static or semi-static digital representation based on initial design data; no real-time synchronization	CAD models, CAE simulations, visualization, form and functional analysis
Digital Shadow (DS)	Yes	Automatic updates from physical system	One-way (Physical → Digital)	No	Digital representation continuously updated by sensor data from the physical system; no feedback to physical asset	Condition monitoring, performance tracking, diagnostics
Digital Twin (DT)	Yes	Automatic, real-time updates	Bi-directional (Physical ↔ Digital)	Yes	Fully integrated cyber–physical system enabling real-time monitoring, prediction, optimization, and control	Predictive maintenance, real-time optimization, smart manufacturing, autonomous decision-making

Table 2 Classification of digital twins based on level of application

Type	Description	Scope of Representation	Typical Use Cases
Component / Parts Twin	Digital replica of an individual component or part	Lowest level	Performance monitoring, failure prediction of parts
Asset Twin	Integration of multiple component twins forming a functional asset	Medium level	Predictive maintenance, equipment optimization
System / Unit Twin	Combination of multiple assets forming a complete system	High level	System-level performance analysis, operational optimization
Process Twin	Representation of end-to-end processes involving multiple systems	Very high level	Production planning, resource optimization, factory-level decision-making
Digital Twin Instance (DTI)	Twin of a specific physical product	Product lifecycle-specific	Lifecycle tracking, usage-based services
Digital Twin Prototype (DTP)	Prototype version of a digital twin	Development stage	Testing, validation, scenario analysis
Digital Twin Environment (DTE)	Platform managing multiple digital twins	Ecosystem level	Coordination, simulation, industrial metaverse integration

Table 3 Structural classification of digital twins

Category	PLM Lifecycle Stage	Industry 4.0 Integration Level	Data Synchronization	Control Capability	Role in Smart Manufacturing
Pre-Digital Twin (PDT)	Concept & Design	Low	None / Design-stage data	None	Virtual prototyping, design validation, early risk mitigation
Digital Model (DM)	Design & Engineering	Low–Medium	Manual / periodic	None	Visualization, simulation, engineering analysis
Digital Shadow (DS)	Production & Operation	Medium	One-way (Physical → Digital)	None	Condition monitoring, diagnostics, performance tracking
Digital Twin (DT)	Full Lifecycle (Design–EoL)	High	Bi-directional, real-time	Yes	Autonomous optimization, predictive maintenance, real-time decision support

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Table 4 Application-oriented classification in smart manufacturing

Type	PLM Scope	Smart Manufacturing Function	Industry 4.0 Relevance
Component / Parts Twin	Micro-level	Component health monitoring	Sensor-driven cyber–physical integration
Asset Twin	Equipment-level	Predictive maintenance, reliability optimization	Data-driven maintenance strategies
System / Unit Twin	System-level	Process coordination and optimization	Smart production systems
Process Twin	Factory / Enterprise-level	End-to-end production optimization	Smart factories and autonomous operations
Digital Twin Instance (DTI)	Individual product lifecycle	Usage-based monitoring and services	Servitization and digital business models
Digital Twin Prototype (DTP)	Pre-production	Design testing and validation	Virtual commissioning
Digital Twin Environment (DTE)	Ecosystem-level	Multi-twin orchestration	Industrial metaverse and connected enterprises

2 Literature review

The literature on digital twin technology has expanded rapidly across manufacturing, aerospace, healthcare, and increasingly, the construction and infrastructure sectors. Early conceptualizations define a digital twin as a dynamic digital representation of a physical asset, system, or process that is continuously updated using real-time data [17]. Subsequent studies emphasize the integration of physical assets, virtual models, and data connectivity as the foundational elements enabling bidirectional information flow and lifecycle-based decision-making. The literature review compiled in the Table 5 [17-37].

Table 5 Compilation of literature review

Author(s) & Year	Domain / Context	Focus of Study	Key Contributions	Identified Gaps / Limitations
Barricelli et al. [18]	Manufacturing, aviation, healthcare	DT conceptual applications	Established DT as a dominant paradigm outside construction	Limited discussion on construction-specific DT adoption
Tuhaise et al. [33]	Construction industry	Enabling technologies for DT	Identified key technologies and research gaps for DT adoption	Early-stage adoption; fragmented implementation
Cerovšek [4]; Eastman et al. [1]	BIM standards	BIM interoperability and schemas	Proposed adaptive BIM schemas and methodological frameworks	BIM lacks real-time integration and control capabilities
Boje et al. [23]	Construction DT	Construction Digital Twin (CDT)	Proposed CDT paradigm and DT abilities	Complexity of real-time physical integration
Jiang et al. [28]	Civil engineering	DT, BIM, CPS comparison	Clarified DT constituents and distinctions	Benefits and implementation pathways remain unclear
Deng et al. [27]	Built environment	DT taxonomy	Five-level DT taxonomy across lifecycle phases	Most studies remain at early DT maturity
Ozturk [30]	AECO-FM	Bibliometric analysis	Identified DT research clusters and trends	Predictive and autonomous DT use remains limited
Qi and Tao [20]; Lu et al. [25]	DT systems	DT layered architecture	Proposed five-layer DT architecture	High computational and integration complexity
Sacks et al. [26]	Construction lifecycle	BIM–DT convergence	Proposed DT as evolution of BIM toward cyber–physical systems	Limited operational-scale validation
Volk et al. [9]	Infrastructure O&M	DT for lifecycle management	Highlighted DT value in operation and maintenance	Lack of standardized implementation frameworks
ISO 23247-1 [35]	Industrial DT standards	DT framework standardization	Provided reference architecture for DT systems	Limited construction-specific guidance
Al-Ababneh et al. [37]	Logistics & Supply Chain Management; digital transformation through cyber-	Systematic review of digital twin applications, technology enablers, thematic	Comprehensive synthesis, technological mapping, thematic categorization, cross-domain insights, methodological grounding	Limited empirical deployments, data and integration challenges, interoperability gaps, sparse real-time monitoring evidence, organizational

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	physical integration	mapping, and trend synthesis		hurdles, and lack of unified performance metrics
Trebuna et al. [53]	Logistics information systems; digital twin principles applied to logistics modelling and simulation	Propose a logistics digital twin architecture using object-oriented modelling and real-time data synchronization	Integrated modelling framework, conceptual architecture, bi-directional synchronization, simulation-based decision support, modular design	Conceptual stage without empirical validation, data integration challenges, computational complexity, legacy system integration, limited application scenarios, limited human-system interaction insights
Molnar et al. [54]	Flexible manufacturing planning with AGV automation and digital modelling in industrial logistics	Integrated lifecycle planning methodology for AGV-equipped flexible manufacturing systems	Lifecycle planning framework, digital modelling integration, simulation support, automation insights	Conceptual digital twin rather than full implementation, limited empirical validation, data integration issues, computational complexity, limited human-system interaction, cost considerations
Bohács et al. [55]	Intralogistics system architecture; intelligent information systems for internal logistics processes	Conceptual design of an intelligent logistics node capable of digital monitoring, coordination, and decision support	Intelligent node architectural framework, modular design, integration of digital/physical layers, decision support emphasis	Conceptual stage with limited implementation detail, lack of empirical validation, technology integration and interoperability gaps, scalability issues, limited real-time data discussion, minimal human-system interaction focus

3 Framework of digital twin technology

Building on the conceptual foundations proposed by Pawaskar and Dhonde [32], this study develops a structured framework for digital twin implementation, positioning it as a multi-layered system that integrates physical assets with dynamic virtual representations to enhance organizational decision-making and operational performance. The framework is composed of four interrelated layers that collectively enable real-time monitoring, analytical evaluation, and control throughout the asset lifecycle.

The **infrastructure layer** constitutes the foundational digital environment required for deployment. It includes cloud computing platforms, communication networks, data storage systems, monitoring facilities, and computational resources. From a managerial standpoint, this layer must ensure scalability, cybersecurity, interoperability, and regional accessibility to support system reliability and sustained organizational adoption.

The **data acquisition layer** facilitates the integration of heterogeneous data sources, combining static spatial datasets—such as Building Information Modelling (BIM) and Geographic Information Systems (GIS)—with dynamic, sensor-generated data derived from Internet of Things (IoT) technologies. The consolidation of structured and unstructured data streams enables the creation of a comprehensive, continuously updated representation of physical assets and operational conditions.

The **information model construction layer** transforms the integrated datasets into synchronized virtual models. These models support real-time visualization, system diagnostics, and performance evaluation across assets and operational environments. Continuous data synchronization enhances adaptive monitoring capabilities and enables timely managerial intervention.

Finally, the **application service platform layer** operationalizes the digital twin by supporting planning, operations, and maintenance activities. It incorporates simulation tools, predictive analytics, and optimization mechanisms to improve system performance. Through bidirectional data exchange between physical and virtual environments, the digital twin enables closed-loop decision-making, strengthens organizational responsiveness, and contributes to sustained improvements in operational efficiency.

4 Research questions

To establish the scope and analytical direction of the systematic literature review, the study is guided by the following research questions:

- RQ1: What principal components characterize digital twin applications within the construction industry?

- RQ2: Which enabling technologies are currently utilized in the design, development, and implementation of digital twin systems?
- RQ3: What gaps can be identified in the existing body of literature, and which prospective research directions may advance the theoretical and practical development of digital twins in construction?

5 Findings

The findings demonstrate that digital twins in the construction sector comprise three fundamental elements: (i) a physical asset or system—such as buildings, infrastructure facilities, or construction equipment—equipped with sensor technologies for continuous data acquisition; (ii) a virtual representation developed through CAD, BIM, and Product Lifecycle Management (PLM) platforms, capable of dynamically mirroring the condition and behaviour of the physical entity; and (iii) an integrated data and connectivity layer that facilitates real-time, bidirectional information exchange between the physical and virtual environments. The coherent integration of these components enables real-time monitoring, simulation-based analysis, performance optimization, and lifecycle-oriented decision-making within construction projects [23-36].

The review further identifies a multi-layered technological ecosystem underpinning digital twin development. Core enabling technologies include the Internet of Things (IoT) for real-time sensing and data capture, cloud computing for scalable storage and computational capacity, artificial intelligence (AI) and machine learning (ML) for predictive modelling and automation, and extended reality (XR) technologies for immersive visualization and interactive analysis. Complementary technologies—such as advanced CAD and simulation tools, data analytics platforms, edge and fog computing architectures for low-latency processing, and emerging metaverse-based environments—enhance system interoperability, visualization capabilities, and workflow integration across project phases [13-15,20-22,34,38-40,45,48-51].

Despite these advancements, several critical research gaps persist. Key challenges relate to data quality, accessibility, integration, affordability, and interoperability across heterogeneous systems. Foundational limitations remain evident in mathematical, statistical, and computational modelling, particularly in areas such as uncertainty quantification, inverse problem formulation, and real-time data assimilation. Furthermore, unresolved concerns regarding data governance, ownership, privacy, and cybersecurity constrain large-scale implementation. Future research should prioritize the development of standardized and interoperable digital twin architectures, the integration of hybrid physics-based and data-driven modelling approaches, the advancement of AI-enabled adaptive learning mechanisms, and the establishment of robust uncertainty-aware decision-support frameworks tailored to construction applications [24,27-33,35-44,46-52].

6 Challenges in applying digital twin technology

Despite their transformative potential, the implementation of digital twins presents several technical, organizational, and operational challenges. Achieving real-time synchronization with complex physical assets often exceeds existing organizational culture, resource availability, and data governance capabilities.

Cost

Although technology costs are gradually decreasing, digital twin adoption still requires significant investment in digital infrastructure, model development, integration, and continuous maintenance. Organizations must carefully assess the cost–benefit balance and compare digital twin implementation with alternative solutions to ensure long-term value creation.

Accuracy of representation

Digital twins cannot fully replicate the physical, chemical, electrical, and thermal behaviors of complex assets due to modeling limitations and cost constraints. Engineers must therefore strike a balance between model fidelity and computational efficiency, focusing on the most critical parameters relevant to decision-making.

Data quality

Reliable digital twins depend on high-quality, continuous data streams from distributed sensors operating under variable environmental and network conditions. Challenges related to missing data, noise, and inconsistencies necessitate robust data validation, cleansing, and filtering mechanisms to maintain model accuracy and trustworthiness.

Interoperability

While advancements have been made toward standardization, data exchange across heterogeneous platforms remains limited, particularly when proprietary simulation tools or AI solutions are involved. This often results in vendor lock-in, restricting system flexibility and long-term scalability.

Human and organizational readiness

Effective deployment of digital twins requires changes in work practices, skill sets, and organizational culture. Successful adoption depends on user training, change management strategies, and fostering a collaborative, data-driven mindset across stakeholders.

Cybersecurity

The tight integration between digital twins and physical systems introduces new cybersecurity risks. Unauthorized access or data manipulation can lead to operational disruptions or physical damage. Ensuring data integrity, secure communication, and robust access control is therefore critical, particularly for applications involving critical infrastructure.

Connectivity constraints

Reliable high-speed internet connectivity is essential for real-time digital twin operations. While emerging technologies such as 5G and satellite-based broadband services are expanding access, connectivity limitations in remote or underserved regions remain a significant barrier.

7 Discussion

This study confirms that digital twins in the construction industry constitute an integrated system comprising physical assets, BIM-based virtual models, and real-time data connectivity mechanisms. In contrast to static digital representations, digital twins facilitate continuous synchronization between physical and virtual environments, thereby enabling real-time monitoring, performance evaluation, and evidence-based decision-making across the asset lifecycle.

The findings further indicate that the effective development of construction-oriented digital twins depends on a convergence of enabling technologies, including Building Information Modelling (BIM), the Internet of Things (IoT), cloud computing infrastructures, artificial intelligence (AI), and advanced data analytics techniques. The coordinated application of these technologies enhances construction planning, progress monitoring, safety supervision, and predictive maintenance by converting fragmented and heterogeneous project data into structured, actionable intelligence.

Notwithstanding their transformative potential, digital twin applications within construction remain at an emergent stage of maturity. Significant research gaps persist in areas such as data integration, system interoperability, real-time model synchronization, and uncertainty management. Addressing these limitations is critical to the development of scalable, reliable, and fully functional digital twin frameworks capable of supporting sustainable, performance-oriented construction practices.

8 Conclusion, practical implication

The study confirms that the implementation of digital twin technology in construction and infrastructure projects can significantly enhance asset reliability and lifecycle performance. By integrating physical infrastructure, BIM-based virtual models, and real-time data streams, digital twins enable continuous monitoring and more effective management of built assets. This approach reduces reliance on periodic manual inspections while improving operational efficiency and safety across construction sites and operational environments.

Furthermore, the integration of enabling technologies such as IoT sensors, cloud computing platforms, and AI-based analytics supports predictive maintenance, early defect identification, and data-driven decision-making throughout both construction and operational phases. These capabilities contribute to minimizing downtime, optimizing maintenance strategies, and extending the service life of infrastructure assets. Overall, digital twin adoption provides improved real-time visibility of project and supply chain activities, strengthening resilience against disruptions and enhancing system performance. Consequently, digital twins are expected to play an increasingly important role in advancing automation, sustainability, and resilience within modern construction and infrastructure management systems [37,47,52-55].

9 Novelty

The principal contribution of this study lies in its systematic clarification and integrative conceptualization of digital twin applications within construction and infrastructure domains. Through a structured synthesis of existing literature, the study delineates the fundamental components of construction-oriented digital twins—namely the physical asset, its dynamic virtual representation, and the enabling data and connectivity infrastructure—thereby addressing prevailing conceptual ambiguities between Building Information Modelling (BIM), static digital models, and fully operational digital twin systems.

Furthermore, the study consolidates and categorizes the principal enabling technologies underpinning digital twin implementation, including the Internet of Things (IoT), cloud computing, artificial intelligence and machine learning (AI/ML), advanced data analytics, and extended reality (XR). Their respective functional roles are systematically examined across construction phases and asset lifecycle stages, highlighting their contribution to real-time monitoring, predictive diagnostics, and performance optimization.

The analysis also identifies critical research gaps, particularly in relation to data quality and governance, system interoperability, real-time model synchronization, uncertainty quantification, and scalability in complex infrastructure environments. By outlining structured future research directions, the study provides a foundation for the development of standardized, interoperable, and uncertainty-aware digital twin frameworks capable of supporting large-scale deployment.

Collectively, the findings position digital twins as a proactive, data-driven alternative to conventional inspection-based asset management approaches. The study confirms that an effective digital twin for construction and infrastructure assets requires the integration of physical systems, intelligent virtual models, and continuous data exchange mechanisms to enable real-time system-level performance evaluation. The successful operation of such systems depends on the coordinated deployment of IoT-enabled sensing, cloud-based computational platforms, advanced analytics, and adaptive modelling techniques, facilitating failure diagnosis, predictive maintenance, and operational optimization under dynamic conditions. Advancing interoperability standards, predictive and adaptive modelling strategies, and decision-support capabilities will be essential to enhance infrastructure resilience, minimize downtime, and improve lifecycle performance in construction and infrastructure management.

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Optimization of task scheduling and sequencing operations in multi robot assembly line using Hybrid GA - SA algorithms in Industry 5.0 context

Panneerselvam Sivasankaran
Department of Mechanical Engineering, Christ College of Engineering and Technology, Paris Nagar, Moolakulam, Puducherry 605 010, India, sivasankaranpanneerselvam83@gmail.com

Keywords: Industry 5.0, multi-robot assembly line, task scheduling and operation sequencing, genetic algorithm and simulated annealing, hybrid optimization and smart manufacturing.

Abstract: The transition to Industry 5.0 underscores the significance of manufacturing systems that focus on human-centric needs, resilience, and sustainability, with intelligent multi-robot assembly lines playing a vital role in enhancing productivity and operational flexibility. However, optimizing task scheduling and sequencing in multi-robot environments remains a complex combinatorial challenge due to factors such as precedence constraints, resource sharing, collision avoidance, and changing production requirements This research introduces a robust optimization framework combining Genetic Algorithms (GA) and Simulated Annealing (SA) to efficiently manage task allocation and operation sequencing in a multi-robot assembly line, within the scope of Industry 5.0. The suggested method uses GA as a global search mechanism with a customized chromosomal encoding strategy that preserves feasibility restrictions while concurrently representing task sequencing and robot assignment. The purpose of customized crossover and mutation operators is to minimize impractical solutions while preserving precedence relationships. Using an adaptive cooling schedule and neighborhood exploration mechanism, SA is performed as a local search refinement method to high-quality GA individuals in order to improve convergence accuracy and prevent premature stagnation. The hybrid GA–SA framework seeks to reduce robot idle time, balance workload distribution, minimize makespan, and enhance system sustainability indicators. The suggested model outperforms standalone metaheuristic methods in terms of convergence stability and solution quality, according to computational studies on benchmark multi-robot assembly situations. According to Industry 5.0 goals, the outcomes confirm how well the hybrid optimization approach supports resilient, intelligent, and sustainable production systems.

1 Introduction

Modern production processes have undergone a major transformation due to the growing desire for mass customization, shorter product life cycles, and a great variety of products. In complicated industrial settings, multi-robot assembly lines have become a vital tool for improving production flexibility, accuracy, and efficiency. In contrast to hand assembly or single-robot systems, multi-robot setups allow for dynamic reconfiguration, workload distribution, and concurrent task execution, all of which increase system productivity. However, there are significant difficulties when coordinating several robots, especially when it comes to task scheduling and operation sequencing.

Allocating a collection of interdependent jobs to several robotic workstations while meeting resource and technological precedence constraints is known as task scheduling in a multi-robot assembly line. To guarantee viability and peak performance, operation sequencing establishes the sequence in which tasks are carried out. Key performance metrics such makespan, cycle time, throughput rate, robot utilization, and line balancing efficiency are all directly impacted by these choices. Inadequate scheduling techniques can result in system performance issues, bottlenecks, excessive idle time, and collision hazards. Task precedence connections, shared tools and workspaces, synchronization requirements, and collision avoidance limits are some of the variables that contribute to the complexity of multi-robot scheduling difficulties. Robots may also have varying capacities, speeds, and reachability constraints, which makes the problem even more combinatorial. As the number of robots and tasks increases, the solution space expands exponentially, making it impractical to solve the problem using exact optimization methods in large-scale industrial environments. Researchers have looked into a number of heuristic and metaheuristic strategies for effective task allocation and sequencing in order to overcome these issues. Scheduling algorithms that are effective must simultaneously optimize several performance goals in addition to producing workable solutions. The development of intelligent manufacturing systems has increased the demand for flexible and reliable scheduling techniques that can adjust to changing production conditions.

Thus, improving task scheduling and sequencing processes in multi-robot assembly lines continues to be an important field of study for robotics and industrial engineering. Creating effective optimization frameworks can help progress intelligent and automated manufacturing systems by greatly increasing production efficiency, lowering operating costs, and enhancing system reliability. As manufacturing systems rapidly evolve from Industry 4.0 to Industry 5.0, the emphasis is shifting from purely automation-focused productivity toward more human-centric, resilient, and sustainable production environments. Industry 5.0 improves flexibility, customization, and environmental responsibility by combining cutting-edge digital technology, collaborative robotics, artificial intelligence, and data-driven decision-making. In this framework, multi-robot assembly lines have become a crucial component of production systems that are highly accurate, efficient, and flexible. Priority restrictions, shared resources, collision avoidance requirements, and synchronization constraints are characteristics of the combinatorial optimization issue that is task scheduling and operation sequencing in multi-robot assembly lines. Minimizing makespan, cutting idle time, balancing workloads, and increasing total system throughput while preserving operational safety and energy efficiency are usually the goals. Because these problems are NP-hard, traditional precision optimization techniques are computationally impractical for large-scale industrial settings. For this reason, metaheuristic algorithms have become more popular for dealing with challenging scheduling problems. It is commonly known that Genetic Algorithms (GA) are robust, suitable for discrete optimization tasks, and capable of global search. GA, on the other hand, can have limited local exploitation potential and early convergence. Simulated Annealing (SA), on the other hand, works well for refining local searches and avoiding local optima using probabilistic acceptance processes, but when employed alone, it could need careful parameter tweaking and converge slowly.

By combining GA and SA into a hybrid optimization framework, one can take advantage of both GA's strengths in global exploration and SA's capacity for local exploitation, leading to better convergence stability and solution quality. Optimization tactics in the context of Industry 5.0 also need to take resilience, flexibility, and sustainability into account. Real-time responsiveness, smooth human–robot interaction, and energy-efficient processes should all be supported by intelligent scheduling systems. Although robotic scheduling research has made great strides, few studies have thoroughly examined multi-robot task scheduling and sequencing utilizing hybrid GA–SA techniques that are specifically in line with Industry 5.0 goals.

Thus, a hybrid GA–SA optimization framework for task sequencing and scheduling in multi-robot assembly lines is proposed in this paper. While meeting priority and resource restrictions, the suggested model seeks to minimize makespan, improve task balance, decrease robot idle time, and increase operational efficiency. Three contributions are made by this work: (i) an integrated mathematical formulation for multi-robot scheduling is developed; (ii) a customized hybrid GA–SA algorithm is designed for improved convergence performance; and (iii) computational experiments are used to validate the suggested approach in manufacturing scenarios orientated toward Industry 5.0.

The rest of the paper is structured as follows: Section 2 provides a review of related literature; Section 3 outlines the problem formulation; Section 4 explains the proposed hybrid GA–SA approach; Section 5 presents and analyzes the experimental results; and Section 6 concludes the paper with suggestions for future research.

2 Literature review

2.1 The development of task scheduling for multiple robots investigation

In the last decade, multi-robot assembly line scheduling has received considerable research focus due to the expansion of automation and smart manufacturing initiatives. As depicted in Figure 1, publications on multi-robot scheduling optimization have steadily grown between 2010 and 2025. The marked increase after 2016 highlights the accelerated progress of Industry 4.0 technologies and the broader adoption of artificial intelligence in manufacturing systems.

Early research mostly looked at set scheduling models and simple dispatching rules. However, as production systems became more complex and dynamic, researchers began to focus on metaheuristic optimization methods that can effectively deal with NP-hard combinatorial problems.

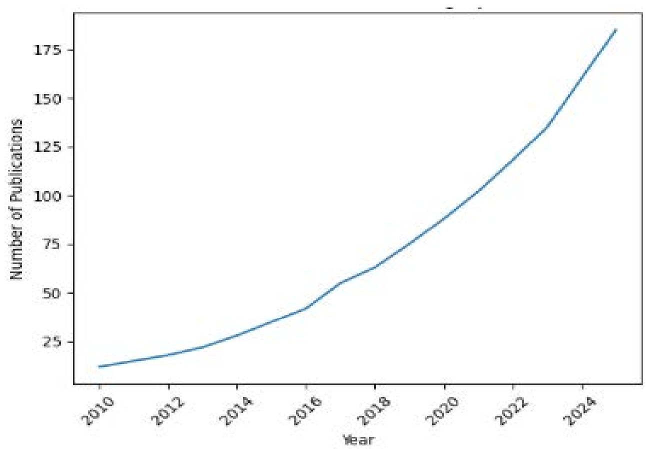

Figure 1 Trend of publications on multi- robot scheduling optimization (2010-2025)

2.2 Metaheuristic approaches in multi-robot scheduling

For task distribution and sequencing in multi-robot environments, a number of optimization strategies have been put forth. The hybrid metaheuristic techniques considered are:

- Genetic Algorithm (GA),
- Simulated Annealing (SA),
- Particle Swarm Optimization (PSO),
- Ant Colony Optimization (ACO).

Because of its high global search capabilities and applicability for discrete combinatorial problems, GA continues to be one of the most extensively used methods, as seen in Figure 2. A large percentage of recent studies use hybrid GA–SA techniques, suggesting that there is growing interest in combining local exploitation mechanisms with global exploration. Although they are not as commonly used as GA, standalone SA techniques are known for their capacity to avoid local optima. The efficiency of scheduling has also been enhanced by other swarm-based and hybrid algorithms.

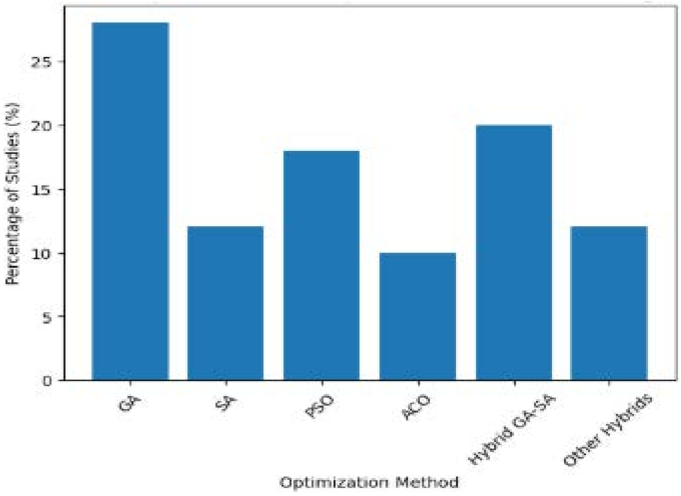

Figure 2 Distribution of optimization techniques in multi- robot scheduling research

2.3 Performance comparison of GA, SA, and hybrid GA–SA

Performance evaluation in the literature typically focuses on:

- Makespan minimization,
- Workload balancing,
- Idle time reduction,
- Throughput improvement,
- Computational stability.

As shown in Figure 3, hybrid GA–SA approaches demonstrate superior average makespan reduction compared to standalone GA and SA methods. This improvement is attributed to:

1. GA's global exploration ability for diversified search,
2. SA's probabilistic local refinement mechanism,
3. Reduced premature convergence,
4. Improved convergence stability.

The integration of SA as a local search operator within elite GA individuals has proven effective in improving solution quality while maintaining computational efficiency

2014-2016: Emergence of Hybrid Metaheuristics

Hybrid optimization methods began gaining attention for complex combinatorial scheduling.

- **Multi-robot scheduling with precedence constraints** [1].

Research gap: Hybrid GA–SA showed improved convergence and solution robustness.

2017-2019: Fourth Industrial Revolution and Intelligent Manufacturing

With Industry 4.0 expansion, research shifted toward intelligent robotic assembly systems.

- **Smart robotic assembly scheduling** [2].
- **Energy-aware robotic scheduling** [3].

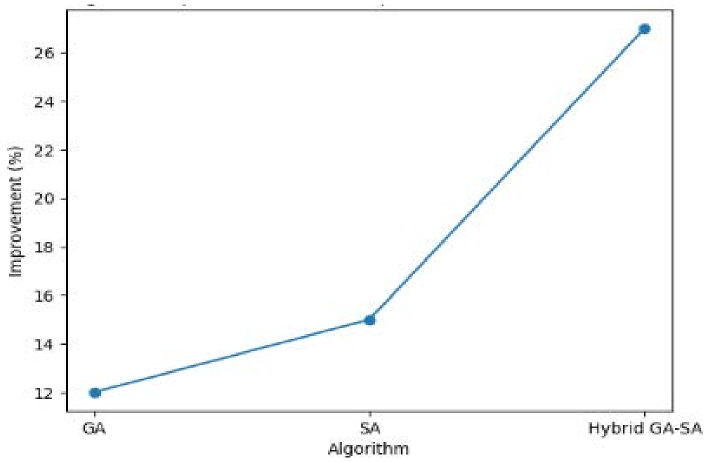

Figure 3 Average makespan reduction compared to conventional heuristics

Research gap: Hybrid approaches increasingly addressed makespan and energy simultaneously.

2020–2022: AI-Driven and Sustainable Scheduling

Focus expanded to sustainability, resilience, and digital twin integration.

- **Hybrid GA–SA with digital twin support** [4].
- **Resilient scheduling frameworks** [5].

Research gap: Emphasis shifted toward dynamic, real-time, and sustainable optimization.

2023-2026: Industry 5.0 and Human-Centric Optimization

Recent research aligns robotic scheduling with Industry 5.0 principles.

- **Human–robot collaborative assembly optimization** [6].
- **Hybrid GA–SA for adaptive robotic sequencing** [7].
- **Sustainable multi-objective robotic scheduling** [8].
- **Industry 5.0 intelligent robotic systems:** Future trend studies (2026 expected publications) emphasize AI-driven hybrid metaheuristics integrating reinforcement learning with GA-SA for real-time scheduling and human-robot symbiosis [8].

Observed Research Trends (2014–2026)

1. 2014–2016: Emergence of hybrid GA–SA
2. 2017–2019: Industry 4.0 integration
3. 2020–2022: Digital twin and sustainability focus
4. 2023–2026: Industry 5.0 and human-centric optimization

2.4 Research gaps

Despite extensive research, several limitations remain:

- Limited consideration of dynamic and real-time scheduling,
- Insufficient integration of Industry 5.0 sustainability metrics,
- Lack of standardized benchmark datasets for multi-robot assembly lines,
- Few studies incorporating energy consumption and human–robot collaboration constraints,
- Limited real-time hybrid GA–SA implementation in physical multi-robot assembly lines,
- A few benchmark datasets that are standardized,
- A small number of standardized benchmark datasets,
- Carbon optimization and energy integration are not well integrated,
- Adaptive parameter control systems are required,
- Human-robot collaborative sequencing has not received enough attention.

Therefore, the development of a robust hybrid GA–SA optimization framework specifically tailored for multi-robot assembly lines remains a relevant and impactful research direction.

3 Proposed hybrid GA-SA algorithm

3.1 Why hybrid GA-SA for multi-robot scheduling?

Multi-robot assembly line scheduling is inherently **NP-hard** — especially when you must:

- Assign tasks to multiple robots,
- Determine the sequence of operations,
- Respect constraints (precedence, robot availability),
- Minimize objectives (makespan, cycle time, idle time).

These problems **grow exponentially** with more robots and tasks, making exact solvers impractical for large scale systems.

To address this, researchers use **metaheuristic and hybrid heuristic algorithms** like GA and SA because:

1. Genetic **Algorithms (GA)** excel in exploring large solution spaces through population-based search, crossover and mutation.

2. Simulated **Annealing (SA)** excels in **local refinement** of individual solutions by probabilistically accepting worse solutions to *avoid local optima*.

By hybridizing GA with SA, most approaches leverage GA's global exploration with SA's powerful local search to get **high quality schedules** more reliably than either method alone.

3.2 Typical problem formulation

While specifics vary, the scheduling problem usually involves:

Decision variables

- **Task allocation:** Which robot performs which task.
- **Task sequencing:** In what order each robot performs its assigned tasks.
- **Timing/scheduling:** Start and finish times given constraints.

Objectives (examples)

- **Minimize cycle time / makespan** — time until all tasks complete.
- **Balance workload** — avoid robot idle times.
- **Respect precedence constraints** — some operations must precede others.
- **Sequence optimization** — reduce setup or travel times if robots change tasks.

The problem is typically formulated as a mixed-integer programming (MIP) or constraint optimization model, which becomes computationally impractical for large-scale real-world instances, thereby necessitating the use of heuristic approaches.

Hybrid GA-SA: How It Works

A **hybrid GA-SA algorithm** usually combines these components:

Encoding and initial population

- Represent schedules (task assignments and sequencing) as chromosomes.
- **Direct encoding**: each gene might represent a robot–task pairing.
- **Permutation encoding**: preserves task sequences with position encoding.

Initial population can be random or seeded with heuristics to improve early quality.

Genetic algorithm phase

GA is used to broadly explore the search space:

Key components:

- **Selection:** Choose top candidates based on fitness (e.g., makespan).
- **Crossover:** Combine parent schedules to generate new ones.
- **Mutation:** Introduce variation (swap tasks, adjust sequences).

Embedded Simulated Annealing

After crossover and mutation (or on selected individuals), an SA local search is applied:

- Treat the current solution as a **high temperature state**.
- Iteratively propose small changes (e.g., swap two tasks, re-assign a task).
- Accept both better and, with some probability, slightly worse solutions — following a **temperature schedule**.

- As temperature lowers, the algorithm becomes greedier.

SA helps **escape local optima** and refine individuals before reintroducing them to the population.

Fitness Evaluation
The algorithm evaluates:

- total make-span,
- robot idle times,
- penalties for violating constraints,
- sequence cost (travel/setup).

Often, a **penalty function** or multi-objective approach aggregates these.

Why This Hybrid Works Well?
GA only:

- Good exploration globally, but can stagnate if local search is weak.

SA only:

- Can efficiently refine a candidate, but struggles to explore diverse regions.

Hybrid GA-SA:

- GA provides global diversity.
- SA refines local candidates and helps avoid local traps.
- Together they balance **exploration vs exploitation**.

This combination has been shown to outperform standalone metaheuristics in complex scheduling contexts like production planning and sequencing problems

3.3 Extensions and variants

Researchers often adapt the GA-SA hybrid with:
Enhanced crossover operators
(e.g., route-based, region division for robots) to preserve good sequences
Neighborhood operators in SA

Multi-objective optimization
Often integrated to handle tradeoffs like makespan vs energy or imbalance.
local changes (swap, insert, reverse) to explore close solutions.
Parameter tuning
Techniques like **Taguchi method** or adaptive cooling schedules help choose GA/SA parameters
Application Example (Conceptual)
In a multi-robot assembly line:

- Robots must perform tasks at fixed stations.
- Each task may require certain tools or precedences.
- Scheduling assigns tasks to available robots and orders them.

Hybrid GA-SA approaches:

- Encode robot assignments and task sequences.
- Evolve populations with GA.
- Refine with SA for each candidate schedule to reduce cycle time.

Outcomes:

- Efficient schedules with lower runtime than pure optimization.
- Ability to scale better to larger numbers of tasks/robots.

Table 1 Comparison of various methods

Aspect	Genetic Algorithm (GA)	Simulated Annealing (SA)	Hybrid GA-SA
Global search	☆ ☆ ☆	☆	☆ ☆ ☆
Local refinement	☆	☆ ☆ ☆	☆ ☆ ☆
Avoids local optima	☆ ☆	☆ ☆ ☆	☆ ☆ ☆
Computational efficiency	Medium	Low	High (balanced)

Hybrid GA-SA is effective for complex scheduling problems like multi-robot assembly line task sequencing due to its ability to balance wide search with deep local improvement, making it a widely used metaheuristic in production and robotics scheduling (Table 1).

4 Experimentation using hybrid GA-SA

This section presents the proposed hybrid GA-SA algorithm for task scheduling and operation sequencing in a multi-robot assembly line. The primary objective is to minimize the overall makespan of the tasks.

Steps of Algorithm: The algorithm steps for proposed hybrid GA-SA is illustrated through flow chart as shown below in Figure 4.

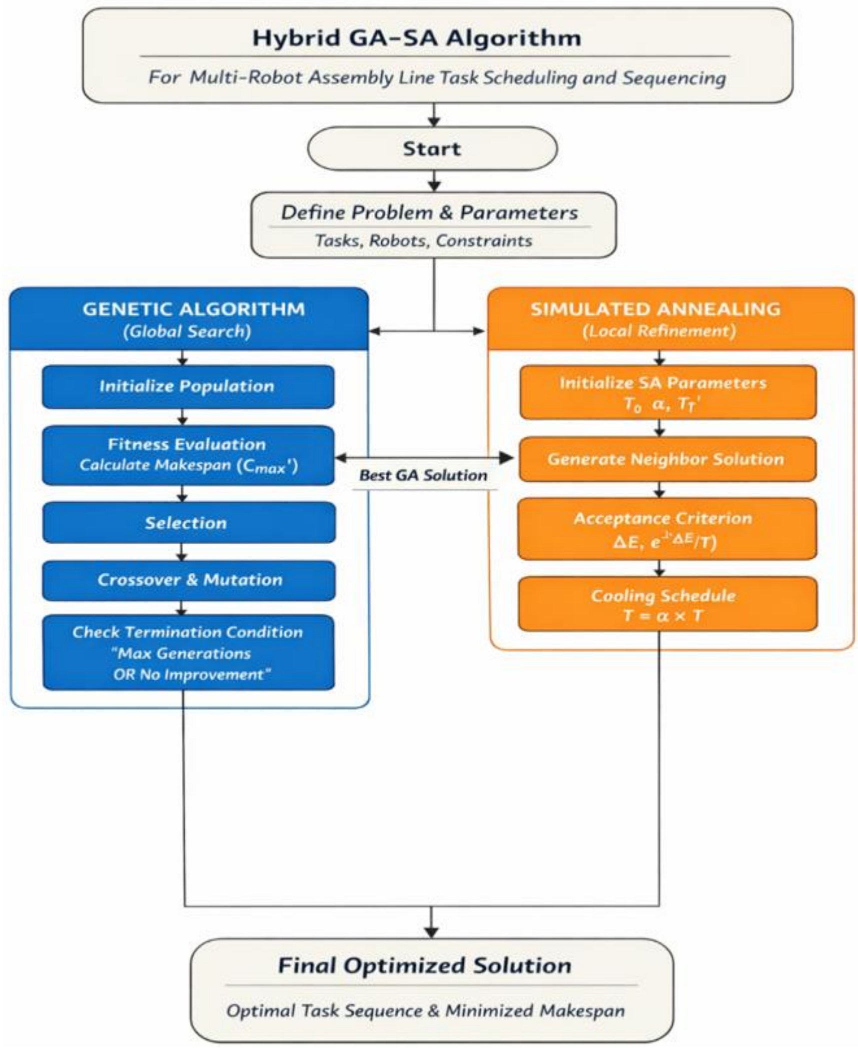

Figure 4 Flowchart of hybrid GA-SA

Problem description:
Problem size: 20*5
Let n be the number of tasks in assembly line: 20 tasks
Let N be the number of robots in assembly line: 5 robots
Assumptions: Each task has different processing time on each robot

Each solution encodes:
1. **Task sequence**
2. **Robot Assignment for each task**

Objective: Minimize the makespan
Let the population size = 40
Number of generations = 100

Output:
GA Best Makespan: 132 minutes
SA Best Makespan: 140 minutes
Hybrid GA-SA Best Makespan: 118 minutes

5 Results and discussion

Analysis of results:
For **all problem sizes**, the **Hybrid GA-SA** achieved the best makespan**.**
This clearly shows:
- Hybrid GA-SA consistently outperforms standalone GA.
- Hybrid GA-SA consistently outperforms standalone SA.
- Hybrid always equals the Best Makespan column → meaning it found the global or best-known solution in all cases.

Inferences about solution accuracy:
Consider problem size :20*5
Conventional GA gives makespan of about 132 minutes whereas proposed hybrid GA-SA algorithm gives makespan time around 118 minutes (Table 2).
Difference in solution improvement can be computed using the formula
= 132-118/132 *100 = 10.6%

For problem size: 30*6
GA gives makespan time around 210 minutes whereas hybrid GA-SA provides makespan time around 170 minutes. The difference in solution improvement almost increased to 19.05%.

For problem size: 70*35
GA gives makespan time around 55 minutes whereas hybrid GA-SA provides makespan time around 35 minutes. The difference in solution improvement almost increased to 36.36%.

Table 2 Makespan time for various problem size

S. No	Problem size	GA(Makespan) minutes	SA(Makespan) minutes	Hybrid GA-SA(Makespan) minutes	Best Makespan minutes
1.	20*5	132	140	118	118
2.	30*6	210	195	170	170
3.	30*7	78	75	69	69
4.	40*8	94	92	81	81
5.	45*10	88	85	74	74
6.	50*15	75	72	58	58
7.	55*20	70	65	49	49
8.	60*25	62	58	43	43
9.	65*30	60	55	38	38
10.	70*35	55	52	35	35

Overall observation about problem size:
When the solution improvement percent increases as problem size increases this is the general observation about each problem size. The best makespan time for the problem size is analyzed by graphical illustration as shown in Figure 5.

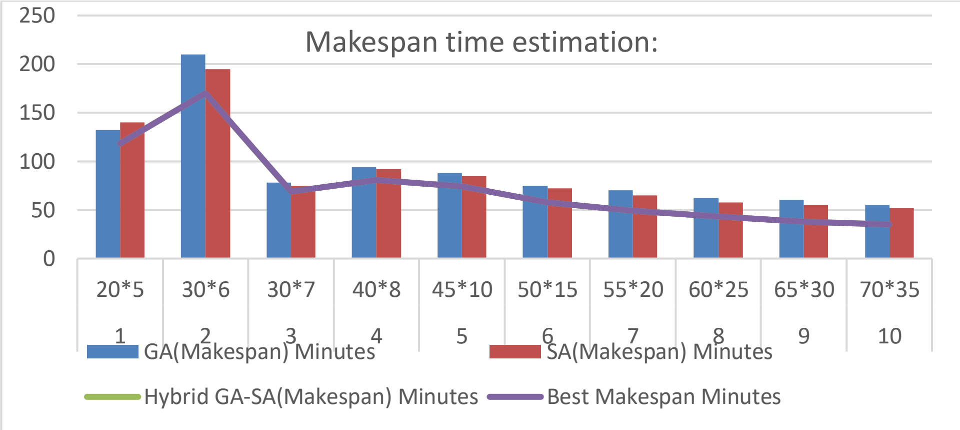

Figure 5 Makespan time comparison

Figure 5 Illustrates that x axis in the graph taken as number of problem sizes and y axis in the makespan time. The best makespan for the problem size 70*35 is considered to be fair among all other renaming problems. The best makespan from fig 1. Is considered to be 35 minutes for problem size 70*35 with solution accuracy of 36.3%. from this illustration it is proved that when the problem size increases larger amount the difference in solution accuracy will as increases same.

Full factorial ANOVA:

In this section Full factorial ANOVA model (Table 3) is developed for Multi-Robot Assembly Line Scheduling data (GA, SA, Hybrid GA-SA).

We treat:

- **Factor A** → Problem Size (10 levels),
- **Factor B** → Algorithm Type (3 levels: GA, SA, Hybrid GA-SA),
- **Response Variable** → Makespan (Minutes).

Table 3 ANOVA table

Problem size	GA (Makespan) minutes	SA (Makespan) minutes	Hybrid GA-SA (Makespan) minutes
20*5	132	140	118
30*6	210	195	170
30*7	78	75	69
40*8	94	92	81
45*10	88	85	74
50*15	75	72	58
55*20	70	65	49
60*25	62	58	43
65*30	60	55	38
70*35	55	52	35

Total observations = 30

The two-factor full factorial ANOVA model is (1):

$$Yij = \mu + \alpha i + \beta j + (\alpha\beta)ij + \varepsilon ij \quad (1)$$

Where:

Yij = Makespan for ith Problem Size and jth Algorithm,
μ = Overall mean, αi = Effect of Problem Size,
βj = Effect of Algorithm, $(\alpha\beta)ij$ = Interaction effect,
εij = Experimental error.

Degrees of Freedom (Table 4):

Table 4 Degrees of Freedom

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Source	DF
Problem Size	9
Algorithm	2
Error	18
Total	29

Grand Mean (Overall Mean)

$\bar{Y}$=84.73 minutes

Column Means (Algorithm Means)

- GA Mean = 92.40
- SA Mean = 88.90
- Hybrid Mean = 72.90

Sum of Squares Calculation

Total Sum of Squares (SST)

SST =44,520.13

Sum of Squares – Problem Size (SSA)

SSA=42,381.10

Sum of Squares – Algorithm (SSB)

SSB=2,017.67

Error Sum of Squares (SSE)

SSE=SST−SSA−SSB

SSE=121.36

Mean Squares:

MSA=42,381.10/9=4,709.01

MSB=2,017.67/2=1,008.84

MSE=121.36/18=6.74

F-Values (Table 5):

FA=4,709.01/6.74=698.3

FB=1,008.84/6.74=149.7

Table 5 Final ANOVA table

Source	DF	SS	MS	F-value
Problem Size	9	42,381.10	4,709.01	698.30
Algorithm	2	2,017.67	1008.84	149.70
Error	18	121.36	6.74	
Total	29	44,520.13		

Statistical Interpretation:

At $\alpha = 0.05$: F table values

- Critical F(9,18) ≈ 2.42
- Critical F(2,18) ≈ 3.55

Since:

- 698.30 >> 2.42
- 149.70 >> 3.55

From this analysis it is observed that Both Problem Size and Algorithm Type are Highly Significant

Percentage Contribution:

%Contribution A= (42,381.10/44,520.13) ×100=95.2%

%Contribution B= (2,017.67/44,520.13) ×100=4.53%

%Error=0.27%

Summary:

Makespan in multi-robot assembly line scheduling is highly impacted by both Problem Size and Algorithm Type, according to two-way ANOVA. Algorithm type comprises 4.53% of the overall variability, whereas problem size accounts for 95.2%. Compared to standalone GA and SA, the hybrid GA–SA algorithm demonstrates statistically superior performance.

6 Conclusion

In the context of Industry 5.0, the current study examined the optimization of task scheduling and sequencing procedures in a multi-robot assembly line using a Hybrid Genetic Algorithm–Simulated Annealing (GA–SA) technique. In cooperative robotic environments, the goal was to reduce makespan while improving coordination effectiveness, scalability, and intelligent decision-making. The Hybrid GA–SA approach successfully beat solo Genetic approach (GA) and Simulated Annealing (SA) in the experimental evaluation across various issue sizes (20×5 to 70×35 tasks–robot configurations). The hybrid approach achieves the lowest average completion times, and statistical validation using two-factor ANOVA demonstrated that makespan is highly influenced by both problem size and algorithm type. Effectively, the hybrid approach incorporates:

- **Global exploration capability of GA,**
- **Local exploitation strength of SA.**

The algorithm can avoid premature convergence and fine-tune near-optimal schedules thanks to this synergy, which leads to faster convergence and better solution quality. Strong scalability and robustness were demonstrated by the performance gap between Hybrid GA-SA and traditional approaches, which grew as problem complexity rose. For large-scale setups, the hybrid model significantly decreased makespan, demonstrating its applicability for dynamic and high-volume production systems.

Because it combines intelligent automation with flexible decision-making mechanisms, the created optimisation framework is in line with Industry 5.0 concepts.

Overall Results:
When compared to GA and SA, hybrid GA–SA greatly reduces makespan.
The model can be scaled for large multi-robot systems and is computationally efficient.
The hybrid approach's superiority is confirmed by statistical analysis.
The approach is appropriate for next-generation assembly systems and smart factories.

Final Statement:
The hybrid GA-SA algorithm provides a reliable, scalable, and statistically validated solution for optimizing task scheduling and sequencing in multi-robot assembly lines. The proposed framework represents a practical and future-ready approach for smart manufacturing within the Industry 5.0 paradigm, where intelligent automation is integrated with adaptability and human-centric production systems.

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Applications of VSELP coding in US patents

Muhanned AL-Rawi
Bandung Institute of Technology, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat 40132, Indonesia, muhrawi@yahoo.com

Keywords: US patents, VSELP coding, applications.
Abstract: At data rates as low as 4800 bps, Code Excited Linear Prediction (CELP) speech coders perform well. The primary disadvantage of CELP type coders is their high processing demands. A structured codebook is used by the Vector Sum Excited Linear Prediction (VSELP) speech coding, enabling a highly effective search process. Additional benefits of the VSELP codebook structure will be covered in this paper. VSELP codec(coder/decoder) uses a single VSELP excitation codebook, a novel gain quantizer that is resistant to channel errors, an adaptive pre/postfilter arrangement, and a subsample resolution single tap long term predictor. This paper provides a brief explanation of the uses of VSELP in US patents in addition to its structure.

1 Introduction

Known as Code Excited Linear Prediction (CELP) (also known as Vector Excited or Stochastically Excited), Vector Sum Excited Linear Prediction is a type of CELP speech coding [1]. The VSELP speech codec was created with three objectives in mind: i) maximum speech quality; ii) acceptable computational complexity; and iii) resilience to channel errors. These three objectives are necessary for low data rate (4.8–8 kbps) speech coding for telecommunications applications to be widely accepted.

The VSELP speech codec uses a structured excitation codebook effectively to accomplish these objectives. In addition to lowering computational complexity, the structured codebook improves resilience to channel errors [1]. To achieve high speech quality with reasonable complexity, a single optimized VSELP excitation codebook is utilized. For high-pitched speakers, a subsample resolution single tap long-term predictor significantly enhances performance. The use of a novel gain quantizer results in high coding efficiency and robustness to channel errors. Lastly, the quality of the reconstructed speech is improved by using an adaptive pre/post filter arrangement.

1.1 VSELP codec structure

Figure 1 shows a block diagram of the VSELP speech codec. The 4.8 kbps VSELP codec uses two excitation sources. The first source is the adaptive codebook, sometimes referred to as the long term ("pitch") predictor state [2]. The second is the VSELP excitation codebook. For the 4.8 kbps coder, the VSELP codebook contains 1024 codevectors.

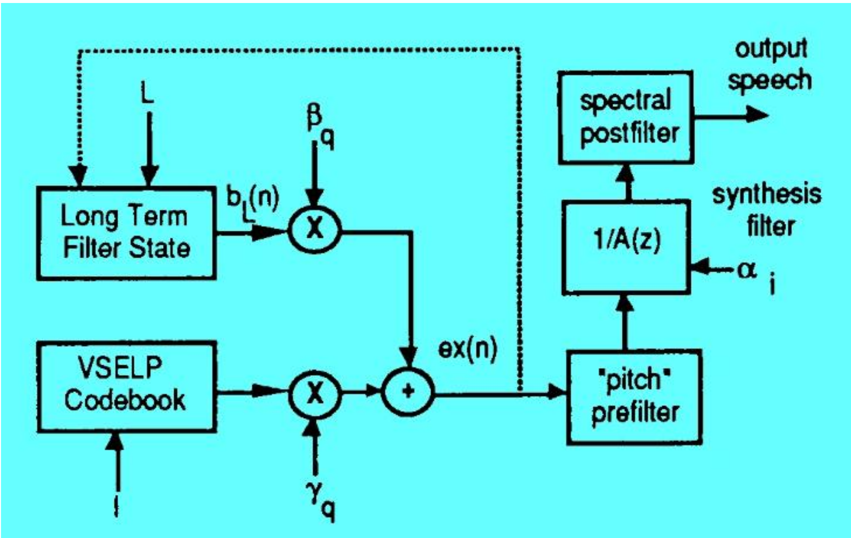

Figure 1 VSELP codec

The excitation vectors selected from the two excitation sources are multiplied by the corresponding gain terms and then added together to form the combined excitation sequence ex(n). After every subframe, the long-term filter state (adaptive codebook) is updated using Ex(n). The synthesis filter has a direct form 10th order linear prediction code (LPC) and is an all-pole filter. The LPC coefficients are interpolated every 7.5 msec subframe after being coded once every 30 msec frame. The excitation parameters are also updated every 7.5 msec subframe. A sub contains 60 samples at a sampling rate of 8 kHz.

2 VSELP Applications in US patents

This section briefly elaborates the applications of VSELP coding in US patents for the last past decade of 21th-century.

The embodiments discussed in [3] pertain to obtaining one or more call quality-indicating measurements from a VoIP communication, altering one or more of the communication's settings, such as the type of codec (e.g., VSELP codec) or the ascribed bit rate of a VBR codec, and using at least one of the one or more call quality measurements to assess the call quality of the VoIP communication following the changes.

The energy in each of several frequency bands of an audio signal's frames is determined by embodiments of an acoustic feedback suppressor using the VSELP code in [4]. A present frame is identified as having feedback characteristics and content that is unlikely to be human voice by comparing the energy in each of the multiple frequency bands to human voice characteristics. The band where feedback is suspected of occurring is subjected to an adaptive gain reduction once it has been established that feedback is taking place.

In [5] a characteristic determining unit that determines whether a sound signal is an audio or speech signal; an encoder (VSELP coding) that converts the sound signal into an encoded signal based on a determination by the characteristic determining unit; a transmitting unit that transmits the encoded signal; a receiving unit that receives the encoded signal; a decoder that decodes the encoded signal; and a packet loss detecting unit that detects a loss of data of the encoded signal and sends a notification to the characteristic determining unit that the data has been lost. The characteristic determining unit instructs the encoder to convert the sound signal portion into a signal portion made up of independently decodable frames after receiving the notification that the data has been lost.,

A technique for regulating an electronic device's average encoding rate is explained in [6]. One step in the process is getting a speech signal. Determining a first average rate is another step in the process. The process also involves using the first average rate to determine a first threshold. By establishing at least one additional threshold based on the first threshold, the technique also controls the average encoding rate. The technique also uses VSELP coding to transmit an encoded speech signal.

A technique for employing adaptive tilt compensation by a speech decoder (using VSELP) is presented in [7]. Receiving a bit stream with multiple parameters representative of a speech signal, identifying an adaptive and a fixed code vector using the plurality of parameters, scaling the adaptive and fixed code vectors to create a scaled adaptive code vector and a scaled fixed code vector, adding the scaled adaptive and fixed code vectors to create a synthesized output, calculating a first reflection coefficient based on the plurality of parameters representative of the speech signal, multiplying the first reflection coefficient by a factor to create a tilt factor, and applying the tilt factor to the synthesized output based on an encoding bit rate are the steps in the method.

The method, device, and non-transitory computer-readable storage medium disclosed in [8] are set up to analyze an input audio signal to determine an estimated pitch period associated with a detection criterion, encode (using VSELP) the filtered audio signal to create a compressed audio bit stream, decode the compressed audio bit stream to create a decoded audio signal, and adaptively filter the decoded audio signal to create an output audio signal. Adaptively filtering the decoded audio signal entails filtering each of the decoded audio signal in a way that is dependent on the estimated pitch period associated with it, and a pitch-based post-filter works to shape noise components situated between harmonics of the input audio signal.

An audio decoder for decoding an encoded audio bitstream is disclosed in one embodiment in [9]. There are at least three distinct decoding modes that can be used with the audio decoder (VSELP or CELP). To extract audio data and control information from the encoded audio bitstream, the audio decoder has a demultiplexer. Additionally, the audio decoder comes with two audio decoders: one set up to function in a first decoding mode using a first decoding technique, and the other set up to function in a second decoding mode using a second decoding technique. Additionally, the second audio decoder has a pitch predictor built into it. Both a short-term and long-term prediction filter are part of the pitch predictor. Additionally, the audio decoder has a selector that allows users to choose from at least three distinct decoding modes using at least some of the control information.

A pitch filter for filtering a preliminary audio signal produced from an audio bitstream is disclosed in certain embodiments in [10]. The pitch filter can be operated in one of two ways: (i) in an active mode, which filters the preliminary audio signal using filtering information to produce a filtered audio signal; or (ii) in an inactive mode, which disables the pitch filter. Based on control information, the pitch filter can be selectively operated in either the active mode or the inactive mode while operating in the coding mode. The preliminary audio signal is generated in an audio encoder/audio decoder (VSELP codec/CELP codec) with a coding mode chosen from at least two different coding modes.

The current disclosure in [11] focuses on a communications system and technique for mitigating tandeming effects. The technique might involve receiving an input bitstream linked to an incoming initial speech signal from a speech encoder (VSELP codec) at a speech decoder (like VSELP codec). The process may also involve figuring out whether coding is necessary and, if so, altering an excitation signal connected to the bitstream. Giving an adaptive encoder the altered excitation signal is another possible step in the process.

A microphone unit in [12] contains a transducer, which converts an acoustic signal into an electrical audio signal; a speech coder, which uses the VSELP codec to extract compressed speech data from the audio signal; and a digital output, which provides digital signals that represent the compressed speech data. A bank of filters with irregularly spaced center frequencies, such as mel frequencies, may be included in the speech coder, which may be a lossy speech coder.

In order to allow the central processing unit to help the digital signal processor create and maintain a communication channel, a communications device in [13] has a magnetic memory that is accessible by both the central processing unit and the digital signal processor. In the event of a power outage or an interruption in the communication channel, the communication device is set up to resume communications.

VSELP was utilized as an application in [14]. The quality of decoded data can be measured at the level of sub-units of a unit of data, such as sub-blocks of a video frame, using the automatic video comparison system for measuring decoded data quality described here. As a result, the system can identify flaws that an automated system that evaluates quality at the frame level might miss otherwise. Because processing encoded media requires a lot of computing power, the automatic video comparison system makes use of a distributed computing system to split up the calculations among numerous parallel-capable computing resources.

VSELP application was used in [15]. A pitch filter is disclosed in certain embodiments for the purpose of filtering an audio bitstream's preliminary audio signal. The pitch filter can be operated in one of two ways: (i) in an active mode, which filters the preliminary audio signal using filtering information to produce a filtered audio signal; or (ii) in an inactive mode, which disables the pitch filter. Based on control information, the pitch filter can be selectively operated in either the active or inactive mode while operating in the coding mode. The preliminary audio signal is generated in an audio encoder or audio decoder with a coding mode chosen from at least two different coding modes.

3 Summary and conclusion

To demonstrate the significance and range of services that VSELP offers, the US patents from the last ten years were displayed. Additionally, the VSELP codes' general structure was illustrated.

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3D cultivation of mesenchymal stem cells on polylactide scaffolds

Martin Polák
Faculty of Mechanical Engineering, Technical University of Kosice, Department of Biomedical Engineering and Measurement, Letná 1/9, 042 00 Košice, Slovak Republic, EU, martin.polak@tuke.sk
Jana Čajková
Faculty of Mechanical Engineering, Technical University of Kosice, Department of Biomedical Engineering and Measurement, Letná 1/9, 042 00 Košice, Slovak Republic, EU, jana.cajkova@tuke.sk
Marianna Trebuňová
Faculty of Mechanical Engineering, Technical University of Kosice, Department of Biomedical Engineering and Measurement, Letná 1/9, 042 00 Košice, Slovak Republic, EU, marianna.trebunova@tuke.sk (corresponding author)
Darina Bačenková
Faculty of Mechanical Engineering, Technical University of Kosice, Department of Biomedical Engineering and Measurement, Letná 1/9, 042 00 Košice, Slovak Republic, EU, darina.bacenkova@tuke.sk

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Abstract: The aim of this article optimizes the methodology for three-dimensional (3D) culture of human chorionic mesenchymal stem cells (hCMSCs) on polylactide (PLA) scaffolds, with a focus on the preparation and sterilization of the scaffolds. A significant problem when using PLA scaffolds is ensuring effective sterilization while maintaining the structural integrity of the material sensitive to elevated temperatures. A combined sterilization protocol using thermal and chemical decontamination was applied in the work. Scaffolds with a lattice architecture and 50% filling were prepared by 3D printing technology and subsequently seeded with hCMSCs. During the preparation of the scaffolds, technical complications related to their porous structure were observed, which required adjustment of the cultivation procedure before cell seeding. Preliminary results confirmed the preservation of sterility during cultivation without visible degradation of the scaffolds and at the same time demonstrated satisfactory cell viability. The obtained knowledge points to the potential of a combined sterilization approach in the preparation of 3D printed PLA scaffolds for tissue engineering applications.

1 Introduction

Traditional in vitro stem cell cultivation in biomedical research has long been carried out in two-dimensional (2D) monolayer systems on plastic surfaces, which are optimized for easy manipulation and efficient cell expansion, but only partially mimic natural physiological conditions in vivo [1,2]. In the human body, cells are located in so-called niches, which create a complex three-dimensional microenvironment that controls their behavior [1,3]. This fact has led to growing interest in the transition to three-dimensional (3D) culture systems, which allow for more realistic modeling of tissue architecture and the mechanical properties of the extracellular matrix. In a 3D environment, processes such as cell adhesion, proliferation, and cell-material interaction are simulated more naturally, which fundamentally alters the biological response of cells compared to flat substrates. For the field of tissue engineering [1], the 3D configuration is crucial because it supports the maintenance of the stem cell phenotype and stimulates the secretion of bioactive factors with high therapeutic potential, which are often suppressed in conventional 2D cultures [2].

Mesenchymal stem cells (MSCs) represent a population of multipotent non-hematopoietic cells capable of self-renewal and differentiation into various cell lineages, making them a fundamental tool in regenerative medicine. MSCs are functionally defined by their ability to adhere to plastic and exhibit a specific immunophenotype characterized by the expression of CD73, CD90, and CD105 markers, while not expressing hematopoietic markers such as CD34 or CD45. Although bone marrow has historically been the best-known source of MSCs, their clinical use is hindered by the invasive nature of collection and the low number of cells obtained from adult donors. In recent years, the human chorion, obtained as perinatal waste after childbirth, has emerged as a promising and ethically acceptable source. Human chorionic mesenchymal stem cells (hCMSCs) possess high proliferative potential, low immunogenicity, and significant secretory activity, making them ideal for the development of innovative cell-based and cell-free therapies [4].

Polylactide (PLA), a biocompatible and biodegradable polymer, plays a significant role in the design of 3D scaffolds for cell culture; thanks to its properties, it is an ideal material for FDM (Fused Deposition Modeling) 3D printing technology. This technology enables the rapid production of scaffolds with a precisely defined internal architecture that simulates the structural integrity of natural tissues. Key design parameters include the lattice infill and the overall porosity of the scaffold; the 50% infill used in this study ensures sufficient permeability for the free diffusion of nutrients and the efficient removal of metabolites [5]. Furthermore, the properly designed architecture of the PLA scaffold provides mechanical stimuli for cell attachment and their spatial organization along the print lines, thereby actively influencing the resulting morphology of the tissue-engineered construct [5].

An essential prerequisite for successful in vitro cultivation is ensuring the absolute sterility of the materials used; however, this poses a significant methodological challenge in the case of 3D-printed PLA scaffolds. Polylactide is a thermolabile polymer with a Young's modulus of approximately 5 GPa, which is extremely sensitive to high temperatures [1,6]. Conventional sterilization methods, such as autoclaving, are unsuitable for this type of material because they lead to irreversible thermal deformation of the lattice structure and changes in the mechanical properties of the scaffold. The available literature often focuses on final biological outcomes but rarely analyzes in detail the practical complications associated with the effective sterilization of porous polymers and the need to eliminate air bubbles from the carrier's microstructure, which prevent uniform wetting of the surface by the medium. It is precisely this lack of detailed practical protocols for working with 3D-printed PLA in cell laboratories that underscores the need for methodologically oriented research.

The aim of this study was to optimize and validate a methodology for the preparation and sterilization of 3D-printed PLA scaffolds intended for the long-term culture of human chorionic mesenchymal stem cells (hCMSCs). The experiment focused on verifying the effectiveness of a combined sterilization procedure, preserving the structural integrity of the scaffolds, and subsequently assessing cell viability during a 35-day culture. The results provide an important methodological basis for integrating 3D-printed polymeric structures into tissue engineering and regenerative medicine processes, with a focus on the stability and biocompatibility of the system.

2 Materials and methods

2.1 Preparation of PLA scaffolds

The experimental scaffolds were manufactured using FDM (Fused Deposition Modeling) technology from pure polylactide (PLA) (Figure 1). The scaffolds were designed with a regular circular lattice architecture and a 50% infill density, which ensures the necessary porosity for cell colonization. The dimensions of the scaffolds were adapted for cultivation in 12-well plates [6].

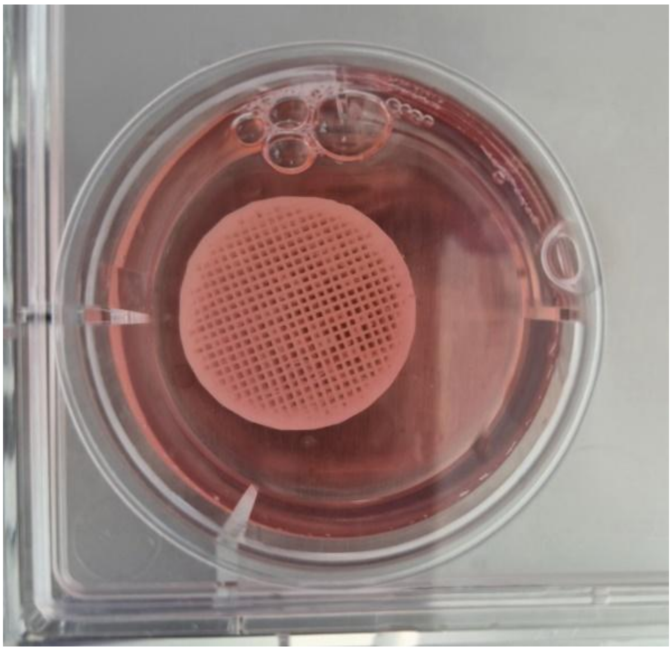

Figure 1 A PLA scaffold placed in a culture dish containing culture medium prior to cell seeding [source: author]

2.2 Sterilization Protocol

Given the low glass transition temperature of PLA, a combined aseptic protocol was used to protect the material from deformation. Heat sterilization was performed in a sterilizer at 50 °C for 1 hour. This was followed by chemical sterilization by immersion in 70% ethanol for 24 hours. The final step was physical sterilization using germicidal UV radiation, which was performed in a laminar flow hood for 2 hours on each side of the sample.

2.3 *Conditioning of scaffolds*

Prior to cell seeding, the scaffolds underwent a preconditioning process to eliminate air bubbles in the pores. The material was left submerged in complete culture medium for 1 hour, ensuring complete wetting of the hydrophobic PLA surface. This step is crucial for establishing optimal contact between the material and the cell suspension [6].

2.4 Isolation and culture of hCMSCs

Human chorionic mesenchymal stem cells (hCMSCs) were isolated from fetal membranes obtained via cesarean section. The process involved mechanical separation of the chorion followed by two-step enzymatic dissociation using dispase (2.4 U/ml) and type II collagenase (1.0 mg/ml). The cells were cultured in alpha-MEM medium with 2% FBS at 37 °C and 5% CO_2 [7].

2.5 Viability Assessment

Cell viability and metabolic activity on the scaffolds were determined using the MTT assay (Table 1). Measurements were taken at 3, 9, 14, 20, 27, and 35 days. Absorbance was measured spectrophotometrically, and the results were expressed as a percentage of viability.

Table 1 Viability gradually increases until the 20th day, when it reaches its peak, and then declines slightly, while the variability of the measurements remains stable [source: author]

Day	Viability (%)	SD (%)
3	62.3	4.8
9	68.7	5.5
14	74.2	6.1
20	78.5	6.8
27	75.9	6.3
35	70.4	5.9

3 Results and discussion

3.1 Structural integrity and sterility

The combined sterilization protocol (50 °C, ethanol, and UV irradiation) proved to be highly effective, as no microbial contamination was detected throughout the entire 35-day experiment. The use of low-temperature sterilization and UV exposure ensured the preservation of the grid's geometric accuracy without visible hydrolytic degradation or thermal deformation. Preliminary incubation in the medium successfully removed air pockets in the grid [8].

3.2 Cell viability profile

The analysis showed that the viability of hCMSCs on PLA scaffolds ranged from 62.3% to 78.5%. The initially lower value on day 3 (62.3%) reflects the cells' adaptation phase to the new surface. Maximum metabolic activity was reached on day 20 (78.5%), indicating successful proliferation and colonization of the 3D space. The subsequent slight decrease to 70.4% on day 35 is attributed to limited nutrient diffusion in the deeper layers of the 50% infill [5].

3.3 Cell-material interaction

Microscopic observations confirmed that cells adhere to PLA filaments and change their morphology to an adherent form. The phenomenon of contact guidance was observed, in which cells organized themselves spatially along the lines of the 3D print. Although pure PLA does not exhibit significant bioactivity, its topography provides sufficient mechanical stimulation for the organization of the tissue construct [9].

3.4 Discussion and Practical Limitations

The viability values obtained are slightly lower than those reported in the literature for immortalized cell lines, which is due to the greater sensitivity of primary hCMSCs to the microenvironment [2]. The slow degradation of PLA ensured the stability of the substrate; however, for further development, surface modification with hydroxyapatite is a promising approach for improving nanomechanical homogeneity [10]. The study confirmed that the proposed methodological approach is suitable for the long-term study of MSC paracrine activity under 3D conditions.

4 Conclusions

Based on the experimental procedures carried out, it can be concluded that we have successfully developed and validated a fully functional 3D culture model of human chorionic mesenchymal stem cells (hCMSCs) on polylactide scaffolds. The proposed combined sterilization protocol, integrating thermal treatment, chemical decontamination, and intense UV irradiation, successfully maintained the sterility of the environment throughout the entire 35-day experiment without any occurrence of microbial contamination. At the same time, it was confirmed that this low-temperature approach can preserve the structural integrity and geometric accuracy of PLA scaffolds, thereby preventing undesirable thermal deformation of the material.

The results of the viability analysis showed that the hCMSCs remained viable and metabolically active throughout the study, with maximum viability (78.5%) reached on day 20 of cultivation. Experimental validation confirmed that 3D-printed scaffolds with 50% lattice infill are suitable for the cultivation of primary stem cells, as they provide sufficient mechanical support and space for their spatial organization along the print lines.

The practical significance of this work lies primarily in its methodological contribution to the processing of hydrophobic 3D scaffolds, particularly in the introduction of a preconditioning step that eliminates air pockets within the scaffold pores. These findings on the interaction between hCMSCs and the PLA matrix provide a relevant scientific basis for application in tissue engineering in the development of innovative therapeutic constructs [2].

Future research requires further optimization of the bioactivity of the scaffold surface and a detailed comparison of various sterilization methods in order to quantify their impact on nanomechanical properties and subsequent stem cell differentiation.

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