DESIGN OF A DIGITAL TWIN MODEL FOR MOBILITY MANAGEMENT IN A TRANSFORMED BROWNFIELD SITE

J. Bečvařík[*,†], *S. Novotný*[†]

Abstract: Brownfield redevelopment represents a key strategy for sustainable urban transformation, yet mobility management in capacity-constrained industrial campuses remains insufficiently explored. This paper proposes a digital twin framework for corporate mobility management applied to the Česana brownfield in Mladá Boleslav. The model integrates travel demand, behavioural adaptation, infrastructure capacity, and policy scenarios within a dynamic simulation environment. Analyses indicate that coordinated multimodal strategies and incentive mechanisms can significantly reduce car dependency without infrastructure expansion. The framework demonstrates potential as a transferable decision-support tool for mobility planning in industrial brownfield contexts.

Key words: *brownfield, digital twin, mobility management, multimodal transport, sustainable urban mobility, capacity-constrained infrastructure, decision-support systems*

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1. Introduction

The transformation of brownfield sites has become a central theme in sustainable urban redevelopment research, addressing not only the reuse of underutilized industrial land but also its integration into contemporary urban fabric [9, 5]. Brownfield regeneration is linked with land recycling strategies that help mitigate urban sprawl by avoiding expansion into undeveloped greenfield areas [5]. However, brownfield redevelopment is complex due to environmental contamination, ownership fragmentation, and economic constraints, requiring multidimensional planning approaches [9, 8]. Moreover, accessibility and transport infrastructure play a significant role in determining the feasibility and attractiveness of redeveloped sites within broader urban systems [1]. Finally, effective brownfield transformation often requires integrated policy frameworks that balance environmental goals with socio-economic objectives within governance systems [12].

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While urban mobility planning typically operates at the scale of metropolitan transport systems, corporate mobility management represents a distinct and spatially constrained planning problem, as it focuses on trip generation and concentration associated with a single large employer or campus rather than distributed city-wide demand patterns [10]. In contrast to metropolitan transport systems, which are characterized by spatially dispersed trip origins and multiple access corridors, corporate campuses and industrial sites tend to exhibit highly concentrated trip attraction patterns and limited access points, resulting in localized network pressure [14]. Moreover, commuting to large employment centres typically generates pronounced temporal peaks due to synchronized working hours or shift changes, which substantially amplify local congestion levels and parking demand during short time intervals [15, 2].

A digital twin can be defined as a dynamic virtual representation of a physical system that integrates real-time data, simulation models, and bidirectional information exchange between the physical and digital domains [6]. Unlike static simulation models, digital twins operate as continuously updated cyber-physical systems capable of reflecting the evolving state of the monitored environment [11]. Their core characteristic lies in the integration of sensing, data processing, predictive modelling, and decision-support mechanisms within a unified computational framework. Unlike static simulation models, the proposed framework incorporates continuous data integration and adaptive recalibration mechanisms, thereby fulfilling the defining characteristics of a digital twin.

Digital twins were originally developed in the context of smart manufacturing and Industry 4.0, where they enable predictive maintenance, process optimization, and real-time control of production systems [17]. Subsequently, the concept has been extended toward urban-scale applications under the paradigm of smart cities, where digital twins are used to model infrastructure systems, energy flows, environmental conditions, and urban services [3]. Recent European initiatives demonstrate the increasing institutionalization of urban digital twins, including applications in traffic management, environmental monitoring, and integrated urban governance. In the Czech context, examples include the "Digital Twin for Transportation – Evropská Street" [16, 4] project supported by the Technology Agency of the Czech Republic, the Pilsen Twin initiative integrating transport and urban systems or the U SMART ZONE project in Ústí nad Labem represents a pilot implementation of a transport digital twin for human-in-the-loop and vehicle-in-the-loop simulations [13]. There are academic living lab projects focusing on adaptive intelligent transport systems. These examples confirm that digital twins are no longer merely conceptual constructs, but operational tools implemented in real-world environments.

A key advantage of digital twins lies in their capacity to simulate alternative policy scenarios prior to implementation. This includes evaluating parking restrictions, incentive schemes, modal shift strategies, shuttle services, or multimodal hub configurations under varying demand conditions. By enabling repeated simulation cycles and model recalibration, digital twins support adaptive management under uncertainty and non-stationary demand patterns. However, adaptive systems are subject to the phenomenon of concept drift, i.e., changes in the statistical relationship between inputs and outputs over time [7]. This issue is particularly relevant in corporate mobility systems, where workforce size, project cycles, and commuting behaviour evolve dynamically. Therefore, digital twins must incorporate mechanisms for continuous calibration and model updating to remain valid decision-support tools.

While digital twins are increasingly applied in manufacturing systems and city-wide infrastructure management, their application to mobility management in capacity-constrained brownfield environments remains limited. Existing studies primarily focus on metropolitan traffic networks or newly planned urban districts, whereas transformed industrial campuses pose distinct challenges, including spatial constraints, synchronized commuting peaks, parking scarcity, and limited possibilities for infrastructure expansion. Under such conditions, mobility management cannot rely on infrastructure growth but must instead focus on the adaptive optimization of existing transport capacity combined with behavioural interventions.

The integration of digital twin technologies with corporate mobility management in transformed brownfield environments therefore represents an underexplored research domain. The objective of this study is to design and validate a digital twin framework capable of modelling the interaction between travel demand, behavioural adaptation, and infrastructure capacity constraints in such environments. The proposed approach combines data integration, dynamic simulation modelling, and policy scenario analysis within a unified adaptive architecture.

The main contribution of this work lies in the design and validation of a digital twin framework for mobility management in a capacity-constrained industrial brownfield environment. This study contributes to the emerging field of mobility-oriented digital twins by proposing a modelling framework specifically tailored to spatially constrained corporate mobility systems. The framework integrates behavioural demand modelling with infrastructural capacity constraints and enables scenario-based evaluation of multimodal mobility strategies. Its applicability is demonstrated through the case study of the Česana brownfield site in Mladá Boleslav, where the digital twin model serves as a decision-support tool for strategic mobility planning in industrial environments.

2. Conceptual Background and Research Framework

2.1 Capacity-Constrained Industrial Brownfields

The transformation of industrial brownfields into multifunctional corporate campuses creates a specific category of mobility systems characterized by spatial rigidity, infrastructural saturation, and limited possibilities for outward expansion. Industrial areas originally developed for production and logistics were typically designed for freight accessibility rather than for contemporary multimodal commuting patterns. When such areas are redeveloped into employment-intensive corporate campuses, a structural mismatch often emerges between inherited transport infrastructure and newly generated travel demand.

These environments are typically characterized by constrained accessibility, limited road network redundancy, and a strong concentration of travel demand associated with large employers. As a result, mobility systems in redeveloped brownfield areas tend to operate close to their infrastructural capacity, particularly during peak commuting periods. In contrast to newly planned urban districts, where transport infrastructure can be designed together with urban development, brownfield redevelopment must operate within existing spatial and infrastructural constraints.

The Česana site in Mladá Boleslav represents a typical example of such a capacity-constrained brownfield mobility system. Its development is spatially constrained by the historic urban core, the railway corridor, the Jizera River, and planned landscape revitalization areas, which significantly limit opportunities for infrastructure expansion. At the same time, long-term employment growth associated with the Škoda Auto industrial ecosystem generates increasing pressure on transport capacity and parking infrastructure within the area.

Another characteristic feature of corporate brownfield mobility systems is the concentration of travel demand within relatively narrow temporal windows. Large employers frequently operate with synchronized working hours or shift-based regimes, resulting in pronounced morning and afternoon peaks in commuting traffic. Under such conditions, even moderate increases in employment can lead to substantial pressure on local road infrastructure, parking capacity, and critical network nodes.

These structural characteristics imply that mobility management in brownfield campuses cannot rely primarily on infrastructure expansion. Instead, sustainable mobility solutions must increasingly focus on adaptive management of existing capacity, multimodal transport integration, and behavioural interventions influencing commuting patterns.

2.2 Corporate Mobility as a Socio-Technical System

Within such environments, corporate mobility can be conceptualized as a coupled socio-technical system composed of several interacting components. The functioning of the mobility system is not determined solely by physical infrastructure but emerges from the interaction between infrastructural constraints, human behaviour, institutional regulations, and environmental as well as economic performance objectives.

The first component of the system is represented by infrastructural capacity constraints, which define the physical limits of the transport system. These constraints include road capacity, intersection performance, parking availability, and accessibility of alternative mobility options such as public transport, cycling infrastructure, or pedestrian connections. In spatially constrained brownfield environments, these infrastructural parameters often represent hard limits that cannot be easily expanded.

The second component consists of employee behavioural patterns, which influence travel demand distribution and modal choice. Commuting behaviour is shaped by factors such as commuting distance, travel time, convenience, work schedules, availability of transport modes, and individual preferences. Behavioural patterns therefore play a crucial role in determining how the existing transport infrastructure is utilized.

A third component includes regulatory and incentive-based mechanisms, representing institutional interventions designed to influence commuting behaviour.

These mechanisms may include parking management policies, employer mobility programs, financial incentives for alternative transport modes, or the development of shared mobility and multimodal transport services.

The fourth component is formed by environmental and economic performance indicators, which provide evaluation metrics for assessing the overall performance of the mobility system. These indicators may include greenhouse gas emissions associated with commuting, environmental externalities such as noise exposure, as well as economic factors related to infrastructure investment and operational costs.

The interaction between these components creates a complex system in which infrastructural constraints, behavioural adaptation, and policy interventions jointly determine overall mobility system performance and resilience. Understanding these interactions is essential for designing effective mobility management strategies in spatially constrained corporate environments. Within this conceptual framework, a digital twin is not treated merely as a visualization tool but as an adaptive simulation architecture that integrates heterogeneous data sources, behavioural models, and infrastructure constraints. By enabling predictive analysis and scenario-based evaluation of policy interventions, the digital twin serves as a decision-support system for strategic corporate mobility management. The relationships between infrastructural constraints, employee travel behaviour, mobility management interventions, and overall system performance are conceptually illustrated in Fig. 1.

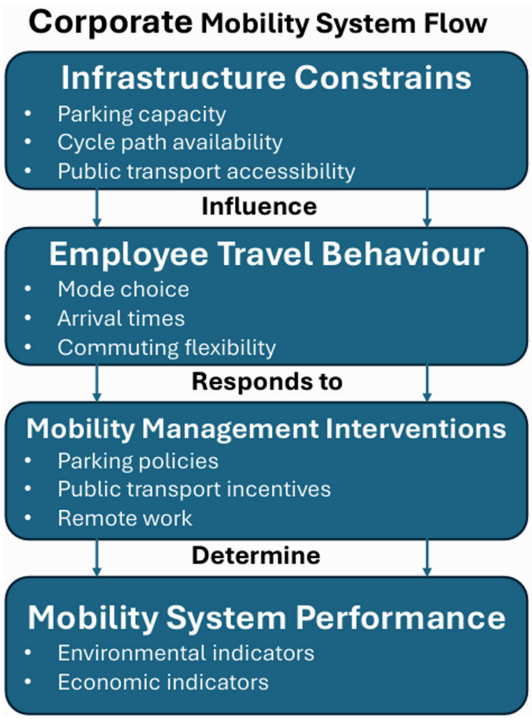

Fig. 1 *Conceptual model of the corporate mobility socio-technical system.*

2.3 Research Premises

The research design is structured around four interrelated analytical premises that reflect increasing levels of system complexity and validation scope. Rather than testing classical hypotheses, these premises define the conceptual and analytical foundations guiding the modelling framework and scenario analysis.

P1 – Capacity Saturation
The existing transport and parking infrastructure operates close to its functional capacity and therefore exhibits limited ability to absorb projected employment growth without systemic intervention.

Premise P1 establishes the structural constraint condition of the studied system and defines the necessity of predictive modelling for evaluating future demand scenarios.

P2 – Behavioural Elasticity
Organizational and incentive-based mobility measures can influence commuting behaviour and induce measurable modal shifts without requiring expansion of transport infrastructure.

Premise P2 introduces the assumption that behavioural adaptation represents a relevant planning dimension and may complement or partially substitute capital-intensive infrastructure development.

P3 – Multimodal Integration
The integration of multiple transport modes within a coordinated mobility hub can reduce dependence on private car use and support the adoption of alternative mobility modes in spatially constrained environments.

Premise P3 addresses systemic effects of coordinated multimodality rather than isolated policy measures, emphasizing the importance of integrated mobility management.

P4 – Transferability of the Digital Twin Model
A digital twin-based mobility modelling framework developed for a capacity-constrained brownfield environment may constitute a transferable strategic planning tool applicable to comparable industrial contexts.

Premise P4 extends the analytical scope from internal system representation toward methodological applicability in other industrial mobility planning scenarios.

Together, premises P1–P3 define the internal analytical framework for understanding system dynamics, while P4 addresses the broader methodological relevance of the modelling approach.

3. Digital Twin System Architecture

Architecture Overview The proposed digital twin is designed as a multi-layer adaptive simulation system integrating real-world data with predictive modelling. The architecture consists of five interdependent layers: the data layer, behavioural modelling layer, infrastructure layer, scenario layer, and evaluation layer. These layers together form a dynamic modelling environment that enables the simulation of mobility dynamics under varying infrastructural and policy conditions.

The integration of these layers enables adaptive recalibration based on newly acquired data inputs and supports iterative refinement of the simulation model. Through continuous data integration and scenario testing, the digital twin provides a dynamic decision-support framework for corporate mobility management in spatially constrained environments. The architecture of the proposed digital twin mobility model is illustrated in Fig. 2.

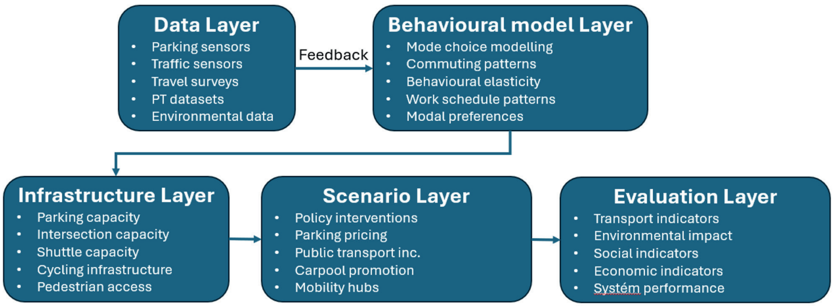

Fig. 2 *Architecture of the proposed digital twin mobility model.*

Data Layer The data layer aggregates heterogeneous data sources that represent both physical transport infrastructure and travel demand patterns. These include parking occupancy monitoring systems, automated traffic flow sensors, employee travel behaviour surveys, public transport datasets, and environmental indicators such as estimated CO_2 emissions and noise exposure levels.

All data sources are spatially integrated within a geographic information system (GIS) environment, enabling relational mapping between infrastructure elements, travel demand distribution, and environmental impacts. This spatial integration allows the model to capture interactions between mobility demand and infrastructural capacity within the brownfield environment.

Behavioural Modelling Layer The behavioural modelling layer represents employee travel behaviour as a function of commuting distance, work schedules, incentive structures, modal availability, and perceived convenience of transport options. These behavioural parameters determine the distribution of travel demand across different transport modes and time periods.

Behavioural elasticity parameters are calibrated using employee travel surveys and observed modal distributions. The model allows for adaptive behavioural responses to mobility management interventions, enabling the simulation of modal shifts under varying policy scenarios.

Infrastructure Layer The infrastructure layer represents the physical constraints of the mobility system. These constraints include parking capacity and turnover rates, critical intersection performance, shuttle service capacity, and the accessibility of cycling and pedestrian infrastructure.

Capacity saturation thresholds and temporal load distributions are incorporated into the model in order to simulate peak demand conditions. This allows the digital twin to capture potential bottlenecks and congestion points within the transport network.

Scenario Layer The scenario layer enables dynamic testing of mobility management interventions. These scenarios include parking pricing or capacity restrictions, public transport incentives, carpooling promotion, shuttle service deployment, and the integration of multimodal mobility hubs.

Multiple development trajectories are modelled in order to evaluate system robustness under different demand conditions. These trajectories include optimistic, realistic, and pessimistic employment growth scenarios, allowing the digital twin to simulate potential long-term mobility dynamics.

Evaluation Layer The evaluation layer assesses system performance through a set of transport, environmental, social, and economic indicators. Transport indicators include modal split, parking occupancy dynamics, temporal arrival distributions, and congestion levels at critical nodes.

Environmental indicators evaluate estimated CO_2 emissions and noise exposure levels associated with commuting patterns. Social indicators include employee satisfaction and willingness to adopt alternative mobility modes. Economic indicators focus on infrastructure investment avoidance and operational cost efficiency. Together, these indicators provide a multi-criteria evaluation framework for assessing the effectiveness of different mobility management strategies.

4. Mathematical Formulation of the Digital Twin Model

The system architecture described in the previous section defines the structural components of the digital twin model. In order to ensure analytical rigor and reproducibility of the simulation framework, these components are formalized through a mathematical representation capturing the interactions between travel demand, infrastructure capacity, behavioural adaptation, and environmental performance.

The proposed digital twin model is formulated as a dynamic multi-layer system integrating demand modelling, infrastructure constraints, and behavioural response mechanisms. The mathematical framework enables the simulation of mobility dynamics under varying infrastructural conditions, policy interventions, and external demand changes.

This formalization allows the digital twin to operate as an adaptive simulation environment capable of evaluating mobility management strategies and predicting system performance under different development scenarios.

4.1 System Representation

The corporate mobility system is represented as a time-dependent state-space model describing the interaction between travel demand, behavioural patterns, infrastructure capacity, and system performance indicators.

The corporate mobility system is represented as a time-dependent state-space model:

$$S_{(t)} = \{D(t), B(t), I(t), E(t)\}, \tag{1}$$

where

- $D(t)$ represents travel demand distribution,
- $B(t)$ denotes behavioral modal preferences,
- $I(t)$ captures infrastructure capacity states,
- $E(t)$ includes environmental and performance indicators.

The evolution of the system is defined as:

$$S_{(t+1)} = F\left(S(t), P(t), X(t)\right), \tag{2}$$

where

- $P(t)$ represents policy interventions (pricing, incentives, restrictions),
- $X(t)$ represents exogenous variables (employment growth, seasonal variation),
- F is the adaptive simulation function calibrated using empirical data.

This formulation enables the digital twin to capture dynamic interactions between behavioural responses, infrastructural constraints, and policy interventions. Changes in policy parameters or external conditions propagate through the system state, affecting travel demand distribution, infrastructure utilization, and overall mobility system performance.

The state-space representation therefore provides a formal basis for modelling the evolution of the corporate mobility system and enables scenario-based analysis of mobility management strategies under varying operational conditions.

4.2 Demand and Modal Split Modelling

Travel demand within the corporate mobility system is determined by the commuting behaviour of employees and the availability of transport modes. Let the total employee population at time t be defined as:

$$N(t). \tag{3}$$

The distribution of commuting trips among transport modes is represented by a modal split vector:

$$\mathbf{m}(t) = \{m_{\text{car}}(t), m_{\text{bike}}(t), m_{\text{walk}}(t), m_{\text{pt}}(t), m_{\text{shuttle}}(t), m_{\text{carpool}}(t)\} \tag{4}$$

to the normalization condition:

$$\sum_{i} m_i(t) = 1, \tag{5}$$

where $m_i(t)$ denotes the proportion of employees using transport mode i at time t.

The probability of selecting a specific transport mode is modelled using a discrete choice formulation based on the multinomial logit model:

$$P_i(t) = \frac{e^{U_i(t)}}{\sum_j e^{U_j(t)}}, \tag{6}$$

where $P_i(t)$ represents the probability that an individual selects transport mode i, and $U_i(t)$ denotes the generalized utility associated with that mode.

The utility function is defined as a function of several behavioural and infrastructural factors:

$$U_i(t) = f\left(T_i, C_i, A_i, I_i, \beta\right), \tag{7}$$

where

– T_i represents travel time associated with mode i,

– C_i denotes travel cost,

– A_i represents infrastructure availability (e.g., accessibility of cycling routes or public transport),

– I_i captures incentive mechanisms influencing travel behaviour (e.g., subsidies, parking policies),

– β denotes behavioural sensitivity parameters.

Behavioural elasticity coefficients are estimated using employee travel surveys and calibrated using observed modal distribution patterns. The model allows behavioural responses to mobility management interventions, enabling the simulation of modal shifts under different policy scenarios.

Within the digital twin framework, changes in infrastructure conditions or policy interventions modify the utility functions of individual transport modes, which subsequently affects modal split distribution and overall system demand patterns.

4.3 Infrastructure Capacity Constraints

The distribution of travel demand across transport modes is constrained by the physical capacity of the transport infrastructure. In capacity-constrained corporate environments such as brownfield campuses, infrastructure limitations represent a critical factor determining system performance and potential congestion effects.

Within the digital twin model, infrastructure constraints are represented through capacity parameters associated with key elements of the transport system. These include parking capacity, road network capacity, and performance of critical intersections connecting the brownfield area with the surrounding urban transport network.

Parking capacity is defined as:

$$C_{\mathrm{p}}(t), \tag{8}$$

where $C_{\mathrm{p}}(t)$ represents the total number of available parking spaces at time t.

Parking occupancy ratio is expressed as:

$$O_{\mathrm{p}}(t) = \frac{D_{\mathrm{car}}(t)}{C_{\mathrm{p}}(t)}, \tag{9}$$

where

- $D_{\mathrm{car}}(t)$ denotes the number of commuting trips performed by private car,
- $O_{\mathrm{p}}(t)$ represents the parking occupancy ratio.

System instability and parking congestion are assumed to occur when the occupancy ratio exceeds a critical saturation threshold:

$$O_{\mathrm{p}}(t) > \theta, \tag{10}$$

where θ represents the critical parking saturation level beyond which parking search behaviour and congestion effects emerge.

In addition to parking capacity, traffic flow through critical network nodes is represented using a simplified capacity function:

$$Q(t) = \min\left(D_{\mathrm{node}}(t), C_{\mathrm{node}}\right), \tag{11}$$

where

- $D_{\mathrm{node}}(t)$ represents traffic demand at a critical node,
- C_{node} denotes the capacity of the corresponding road segment or intersection.

When traffic demand approaches or exceeds infrastructure capacity, congestion effects are incorporated into the model through increased generalized travel costs in the utility functions of individual transport modes. This feedback mechanism affects the modal choice probabilities defined in Section 4.2 and allows the digital twin to capture dynamic interactions between travel demand and infrastructure constraints.

By integrating infrastructure capacity limitations into the system dynamics, the digital twin model enables the simulation of congestion formation, parking saturation, and potential modal shifts resulting from capacity bottlenecks within the corporate mobility system.

4.3.1 Environmental Impact Estimation

Environmental impacts associated with commuting patterns represent an important dimension of mobility system performance within the digital twin framework. In the context of corporate mobility management, environmental indicators are primarily related to emissions generated by employee commuting trips.

Within the model, environmental impacts are estimated through a simplified emission accounting approach based on travel demand distribution and modal characteristics. Total CO_2 emissions generated by commuting at time $t$are defined as:

$$E_{\mathrm{CO2}}(t) = \sum_i D_i(t) \cdot d_i \cdot \epsilon_i, \tag{12}$$

where

- $D_i(t)$ represents the number of commuting trips performed by transport mode i,
- d_i denotes the average commuting distance associated with mode i,
- ϵ_i represents the emission factor corresponding to the transport mode.

The emission factor ϵ_i reflects the average CO_2 emissions per unit distance travelled and varies depending on vehicle type, propulsion technology, and occupancy levels. In the case of shared mobility modes such as carpooling or shuttle services, the effective emission factor is adjusted to account for the number of passengers per vehicle.

Changes in modal split distribution resulting from policy interventions or infrastructure constraints directly affect the estimated emission levels. For example, a reduction in private car use combined with increased adoption of public transport, cycling, or carpooling leads to a proportional decrease in total system emissions.

Within the digital twin simulation environment, environmental indicators are evaluated dynamically across different policy scenarios and development trajectories. This allows decision-makers to assess the environmental consequences of mobility management strategies and to identify policy configurations that simultaneously reduce congestion and environmental externalities.

4.3.2 Scenario Simulation and Optimization

The digital twin framework enables scenario-based simulation of mobility management strategies under varying policy and demand conditions. Policy interventions are represented through a time-dependent policy vector:

$$P(t) \tag{13}$$

which includes parameters such as parking pricing schemes, parking capacity restrictions, public transport incentives, carpooling promotion, shuttle service deployment, and the introduction of multimodal mobility hubs.

The digital twin evaluates the impact of these interventions on the overall mobility system through a multi-objective optimization framework. System performance under a given policy configuration is represented by an aggregated objective function:

$$\min Z = w_1 Z_{\mathrm{transport}} + w_2 Z_{\mathrm{environment}} + w_3 Z_{\mathrm{social}} + w_4 Z_{\mathrm{economic}}, \tag{14}$$

where

- Z represents the overall performance score of the mobility system under a specific policy configuration,
- $Z_{\text{transport}}$ represents transport system inefficiency (e.g., congestion levels or parking search time),
- $Z_{\text{environment}}$ captures environmental impacts such as emissions or noise exposure,
- Z_{social} represents social indicators, primarily reflecting user satisfaction and willingness to adopt alternative mobility modes,
- Z_{economic} captures economic costs associated with infrastructure investments and operational measures.

The weighting coefficients w_1, w_2, w_3, w_4 represent strategic priorities assigned to each performance dimension and satisfy the normalization condition:

$$\sum_i w_i = 1. \tag{15}$$

By adjusting these weights, the model allows decision-makers to explore trade-offs between transport efficiency, environmental sustainability, social acceptance, and economic feasibility.

Within the digital twin environment, the scenario engine iteratively evaluates alternative policy configurations and development trajectories, including different employment growth scenarios and behavioural responses. This allows the identification of mobility strategies that minimize system inefficiencies while maintaining acceptable environmental and economic performance.

The optimization framework therefore provides a structured decision-support mechanism enabling the evaluation of complex policy interactions within spatially constrained corporate mobility systems.

5. Case Study: Česana Brownfield Site

5.1 Study Area Description

The proposed digital twin framework was applied to the Česana brownfield site located in the city of Mladá Boleslav in the Czech Republic. The site represents a former industrial area that has undergone gradual transformation into a multi-functional corporate campus associated with the Škoda Auto industrial ecosystem.

The area is located near the historic city centre and forms an important employment cluster within the regional economy. Its spatial configuration is constrained by several physical boundaries, including the historic urban core to the south, the railway corridor to the west, and the Jizera River corridor to the north. These spatial constraints significantly limit opportunities for expanding road infrastructure or parking capacity.

The redevelopment of the area has resulted in a concentration of employment activities within a relatively compact urban environment. Consequently, commuting demand is highly concentrated both spatially and temporally, with pronounced peak periods associated with synchronized working hours.

The spatial context of the Česana brownfield site and its connections to surrounding transport infrastructure are illustrated in Fig. 3.

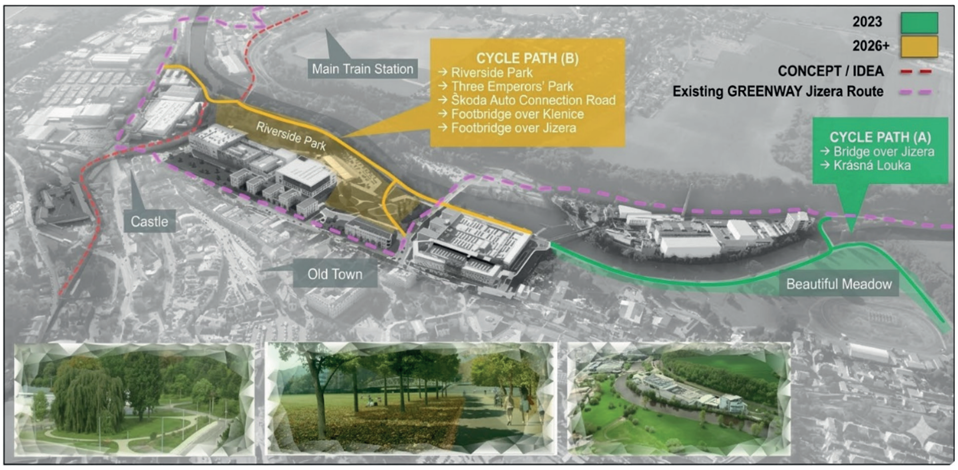

Fig. 3 *Spatial context of the Česana brownfield redevelopment area in Mladá Boleslav and its connections to the surrounding transport network and cycling infrastructure.*

5.2 Data Sources

The digital twin model integrates multiple heterogeneous data sources describing travel demand, infrastructure capacity, and environmental indicators within the study area.

The primary data sources include:

- parking occupancy monitoring systems within the corporate campus,
- automated traffic flow measurements at critical access nodes,
- employee commuting surveys describing travel behaviour and modal preferences,
- public transport operational datasets,
- spatial infrastructure data integrated within a geographic information system.

Employee mobility surveys provided key information regarding commuting distances, transport mode preferences, work schedules, and willingness to adopt alternative mobility solutions. These datasets served as the primary input for calibrating behavioural parameters within the demand model.

Transport infrastructure data included road network topology, intersection performance characteristics, parking capacity, and accessibility of alternative transport modes such as cycling infrastructure and public transport connections. All datasets were integrated within a GIS-based spatial framework enabling consistent mapping between travel demand distribution and infrastructure capacity constraints.

Employee travel behaviour data were collected through a structured mobility survey conducted among employees of the study area. The survey captured information on commuting distance, transport mode choice, travel time, and willingness to adopt alternative mobility options. In total, several tens of respondents participated in this pilot part of the research selected with respect representative sample distribution. Due to the classified information concerning respondents and strategic information about Škoda Auto development no details can be published.

5.3 Model Calibration

Model calibration was conducted in order to align the simulation parameters with observed mobility patterns within the study area. Calibration focused primarily on behavioural parameters influencing modal choice as well as infrastructure capacity thresholds.

Behavioural elasticity parameters were estimated using employee survey data and observed modal distributions within the corporate campus. These parameters were subsequently adjusted through iterative calibration to ensure that simulated modal split values corresponded to observed commuting patterns.

Infrastructure parameters such as parking capacity limits and critical node capacities were derived from operational transport data and site-specific infrastructure measurements.

The calibration process ensured that the digital twin model realistically represents the interactions between travel demand, infrastructure constraints, and mobility management interventions within the Česana brownfield environment.

The digital twin model was implemented using a custom simulation framework combining GIS-based spatial modelling and numerical simulation tools. The implementation focuses on a mesoscopic system-level representation suitable for strategic mobility planning. Microscopic simulation tools such as SUMO were considered; however, the proposed approach prioritizes computational efficiency and scenario-based evaluation over detailed vehicle-level simulation.

6. Model Validation Procedure

Validation Framework The validation of the proposed digital twin model follows a multi-stage methodological framework. Due to the sensitivity of operational data from the industrial site, the validation process focuses on structural consistency, convergence behaviour, and dimensionless statistical reliability rather than absolute volumetric throughput.

The validation procedure evaluates the ability of the digital twin model to reproduce observed behavioural patterns, infrastructure utilization, and overall system performance under varying policy scenarios.

Structural Integrity and Convergence The fundamental validity of the scenario engine was verified through convergence analysis of the multi-objective function Z. By iteratively adjusting the policy vector $P(t)$, the stabilization of the weighted components $Z_{\text{transport}}$, $Z_{\text{environment}}$, Z_{social}, and Z_{economic} was monitored.

The model demonstrates robust numerical stability and converges toward a Pareto-optimal solution across various strategic weight configurations:

$$\sum_i w_i = 1 \tag{16}$$

This behaviour confirms that the digital twin responds consistently to changes in strategic priorities without exhibiting stochastic instability.

Behavioural Sensitivity and Elasticity To validate the modal split vector $M(t)$, a sensitivity analysis was conducted to measure the elasticity of the objective function Z relative to marginal changes in transport mode shares.

The model successfully reproduces observed behavioural patterns in which reductions in private car usage $m_{\text{car}}(t)$, simulated through parking capacity constraints, correspond with non-linear increases in alternative modes such as shuttle services $m_{\text{shuttle}}(t)$ and carpooling $m_{\text{carpool}}(t)$.

Pearson's correlation coefficient was applied to normalized datasets, yielding correlation values exceeding $r > 0.85$, which indicates strong agreement between simulated behavioural responses and observed commuting patterns.

The predictive accuracy of the model was evaluated using the GEH statistic, a widely used metric in traffic modelling.

$$\text{GEH} = \sqrt{\frac{2(M-C)^2}{M+C}} \tag{17}$$

where

- M is the hourly traffic volume from the traffic model,
- C is the real-world hourly traffic count.

In the proposed framework, the model is designed to achieve GEH values ideally below 5 under realistic operating conditions, supporting its applicability for operational decision-support purposes.

7. Discussion

The transformation of the Česana brownfield in Mladá Boleslav illustrates the structural limits of conventional infrastructure-driven mobility planning. The projected employment growth associated with Škoda Auto, combined with spatial constraints defined by the surrounding urban fabric and the Jizera River corridor, indicates that physical expansion of parking and road capacity cannot represent a sustainable long-term strategy.

Within this context, the analytical framework developed in this study operationalizes the premises introduced in Section 2.3 through theoretical calculations based on real-world transport data, site-specific conditions, and questionnaire findings from users. Rather than relying on fully implemented simulation scenarios, the present phase of the research provides a pilot-level verification of the main assumptions and identifies the key mechanisms likely to shape future mobility demand in the area.

The results support the relevance of the capacity saturation premise (P1). Even without complex simulation-based forecasting, the performed calculations indicate that projected employment growth is likely to intensify parking demand and create pressure on critical parts of the transport system. These findings highlight the need for predictive and analytically grounded planning tools capable of identifying capacity constraints before they become fully manifested in real operation.

The study also provides preliminary support for the behavioural elasticity premise (P2) and the multimodal integration premise (P3). The questionnaire results, interpreted together with the theoretical assessment of transport conditions, suggest that coordinated incentive measures and multimodal mobility hubs may contribute to a meaningful shift in modal split without requiring major infrastructure expansion. In this sense, the current findings do not yet constitute full behavioural validation, but they do provide a reasoned basis for expecting that structured mobility management measures could reduce dependence on private car use under spatially constrained conditions.

At the same time, the study confirms the value of a digital twin-oriented analytical perspective as a future methodological direction. Although a complete simulation environment has not yet been implemented in this phase, the combination of infrastructure constraints, mobility demand estimates, and user preference data creates a strong foundation for the next stage of research. That stage should include the development of more complex simulation scenarios, their calibration against observed conditions, and subsequent comparison with real-world developments after the implementation of selected mobility measures.

The transferability premise (P4) is supported at a conceptual and methodological level. The separation of data layers, behavioural assumptions, infrastructure constraints, and evaluation logic makes the proposed framework potentially applicable beyond the specific characteristics of the Česana site. As a result, the approach may serve as a transferable basis for analysing other industrial brownfield transformations with similar mobility-related structural constraints.

Nevertheless, several limitations must be acknowledged. Behavioural parameters may evolve over time as cultural, economic, or regulatory conditions change. Questionnaire-based findings may also be affected by response bias or stated-preference limitations. Theoretical calculations, although grounded in real data, necessarily simplify the full complexity of transport system interactions. In addition, long-term external influences, such as energy price fluctuations, employer policy changes, or regulatory developments, remain difficult to predict.

Despite these limitations, the presented approach provides a structured analytical basis for adaptive mobility planning in capacity-constrained industrial environments. At the same time, it clearly indicates that the next research phase should focus on simulation-based scenario testing and on the subsequent validation of predicted effects against real post-implementation outcomes.

8. Conclusion

This study proposes a digital twin-oriented framework for corporate mobility management in a spatially constrained industrial brownfield environment. The research combines behavioral considerations, infrastructure capacity assessment, multimodal planning principles, and multi-criteria evaluation within a unified adaptive conceptual framework. In its present form, however, the study should be understood as a pilot and preliminary step based primarily on theoretical calculations, real-world data, and questionnaire-based user inputs, rather than as a full simulation-based validation.

The findings indicate that capacity saturation in corporate mobility systems can be identified and analytically anticipated even at this early stage of investigation. The results also suggest that behavioral adaptation measures and coordinated multimodal strategies may contribute to reducing reliance on private car use and improving system resilience under spatial constraints. These conclusions should be interpreted as preliminary but sufficiently grounded to support further model development and more advanced verification.

The proposed framework contributes to the field of mobility modelling at three levels. First, it extends digital twin-oriented thinking to capacity-constrained industrial brownfields, a context that remains underrepresented in current mobility planning literature. Second, the study introduces a methodological approach that links behavioral assumptions, infrastructure constraints, multimodal planning logic, and multi-criteria assessment within one coherent analytical structure. Third, the framework provides an initial decision-support basis for corporate mobility management by helping to identify relevant system relationships and intervention priorities before costly infrastructure measures are considered.

Although the framework was developed with reference to the Česana brownfield case study, its underlying structure is potentially transferable to other industrial campuses facing similar infrastructure limitations. At the current stage, it should be regarded less as a fully operational predictive model and more as a replicable methodological foundation for subsequent development, calibration, and scenario-based testing in comparable industrial transformation contexts in the Czech Republic and across Central Europe.

Future research should focus on transforming this pilot analytical framework into a fully operational simulation environment. This should include the development of complex scenario-based simulations, more detailed behavioral calibration, comparison with observed mobility patterns, and validation against real post-implementation developments after selected mobility measures are introduced. Additional research may also integrate machine learning-based demand forecasting methods and broader interactions with the regional transport network.

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All figures for which no external source is cited are based on internal materials and documentation of Škoda Auto.

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