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AN INTELLIGENT DIGITAL SHADOW FRAMEWORK FOR UNAUTHORIZED PARKING MANAGEMENT AND DECISION MAKING IN RESIDENTIAL COMMUNITIES

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Abstract
Administrators and security personnel are relied on to manage shared parking, but manual enforcement is slow, resource intensive, and contributes to resident conflict over parking. Digital Shadow (DS) technology, a one-way, continuously updated digital representation of a physical system, offers a lower-cost alternative to Digital Twins for operational decision support, but its use in residential parking management remains unexplored. This work was an attempt to design and evaluate the validity of an Unauthorized Parking Management Decision Support framework using DS approach. No system was implemented or tested, a Design Science Research approach was used, which involved requirements analysis, conceptual framework development and Delphi-based expert validation. It consists of nine architectural layers that connect IoT sensing, RFID, automatic number plate recognition (ANPR), CCTV, edge and cloud computing, rule-based detection, analytics and automated alerting. The experts on the Delphi panel rated the 58 statements for relevance, design, feasibility, operational effectiveness, decision support, governance and user acceptance. For all 58 statements, the consensus criteria (mean ≥ 4.0, SD ≤ 1.0, IQR ≤ 1.0, ≥ 75% agreement) were satisfied, the mean was 4.99 and the median 5.00 with only Q8 (4.59) and Q10 (4.78) failing to reach unanimity. Because 56 of the 58 statements showed no response variability (all 27 experts rated 5), the validation relied on descriptive statistics and expert consensus assessment. The framework was therefore seen to be relevant, feasible and acceptable by experts. Potential advantages such as reduced workload of staff on supervision, quicker response to incidents, more efficient use of space and clear governance will not be fully realised until data on implementation is available. The study provides a conceptual framework for business information systems research in the field of decision support for residential facility management with a managerial perspective, as well as an expert-validated base for further research in the field.

Keywords: *Digital Shadow, Decision Support Systems, Residential Parking Management, Business Intelligence, Operational Efficiency, Delphi Technique*

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1. Introduction

Digital transformation has changed how built assets are designed, constructed, and operated, supported by building information modeling (BIM), the Internet of Things (IoT), artificial intelligence, and cloud computing (Eastman et al., 2018; Lu et al., 2024). Many stakeholders are involved in operations, and there are constant information needs (Sacks et al., 2020). Digital Twins (DT) are the most advanced reaction but are very challenging to implement (Ammar et al., 2022; Lu et al., 2020). A lower-cost alternative is the Digital Shadow (DS), as it only links back to the physical system for monitoring and decision-making, and has no control system of its own (Kritzinger et al., 2018; Sepasgozar, 2021).

Residential community reserved parking is a shared resource that is administered by the administration, facility managers and security personnel. Administrative inefficiency, lack of visibility of parking use and complaints are common consequences of unauthorised parking, which is typically dealt with by periodic manual patrols, which hinder enforcement, are time consuming for supervisory staff and compromise evidence. Business intelligence converts operational data to information to make decisions on time. The DS concepts bring purpose-specific, query-based representations which provide decision makers efficiently (Bauernhansl et al., 2018; Liebenberg & Jarke, 2023). Occupancy views, violation histories and utilization reports for parking could be a sensor, RFID, camera and visitor record.

The gaps identified were three by using thematic synthesis:

Domain gap: Only recently have domain representatives started to get close to residential parking management in terms of DS application use in manufacturing and construction monitoring.

Automated detection and enforcement is weak: emphasis is on monitoring and guiding people to park and using smart parking systems.

Lack of integration: No system combines DS technology, IoT sensing, ANPR surveillance, RFID validation, edge computing and decision support in real-time to manage parking.

Research Aim and Objectives

This study will have two objectives: designing and expertly validating a decision-support framework for the management of unauthorized parking based on a DS.

The objectives are:

- to develop a conceptual DS framework giving a real-time virtual representation of parking activities in residential gated communities from IoT devices, surveillance systems and sensor data
- to develop an unauthorized parking detection mechanism using automated monitoring, vehicle identification and rule-based substantiation
- to support rapid decisions through real-time alerts, analytics and insights for facility managers and security officers
- to validate the framework through Delphi expert evaluation

2. Literature Review and Theoretical Foundations

2.1. Digital Transformation and Business Information Systems in Facility Management

Table 1 provides an overview of the development of construction: from manual to intelligence, the setting in which DS and DT arose. BIM is the foundation for this digitalization (Eastman et al., 2018) and transitioning from BIM to DT has the potential to enhance decision making, but there is a lack of standardized protocol for sensor-integration (Revolti et al., 2024).

Table 1. Technology Comparisons

Stage	Main feature	Key technology
Construction 0.0	Manual work	Hand tools
Construction 1.0	Mechanization	Heavy machinery
Construction 2.0	Automation	CAD, computers
Construction 3.0	Digitalization	BIM, cloud systems
Construction 4.0	Intelligence	AI, IoT, Digital Twin

2.2. Digital Shadow and Digital Twin Technologies for Operational Management

The definition of a DS, by Kritzinger et al. 2018, is that it is a one-way data flow from a physical object to a digital object and it is passive, meaning that it does not push data back to the physical object; a DT is the same, but with the return flow. The differences between the two are presented in Figure 1 and Table 2.

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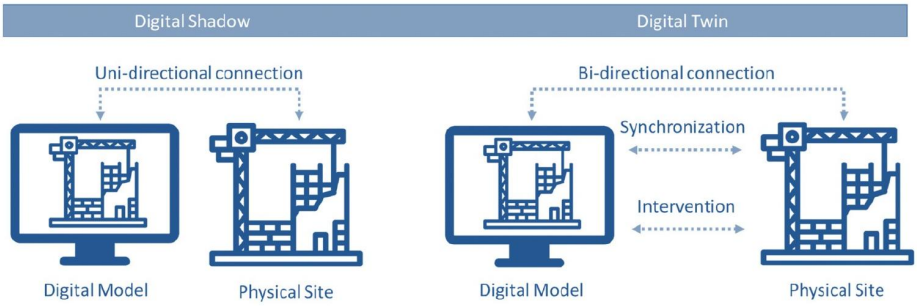


Figure 1. Digital Shadow and Digital Twin in the Construction Sector

Table 2. Comparison between Digital Shadow and Digital Twin

Criterion	Digital shadow	Digital twin
Data flow	One-way	Two-way
Control capability	Monitoring only	Monitoring + autonomous control
System complexity	Moderate	High
Implementation cost	Lower	Higher
Practical adoption	Immediate	Long-term

According to Becker et al. (2021), a DS is "contextual data traces" that are "aggregated and abstracted for a certain purpose with respect to an original system. Michael et al. (2024) formalize purpose, data trace, data point, metadata, asset and model in a reference model (Figure 2) and Heithoff et al. (2022, 2025) extend it with the addition of workflows and engineering models.

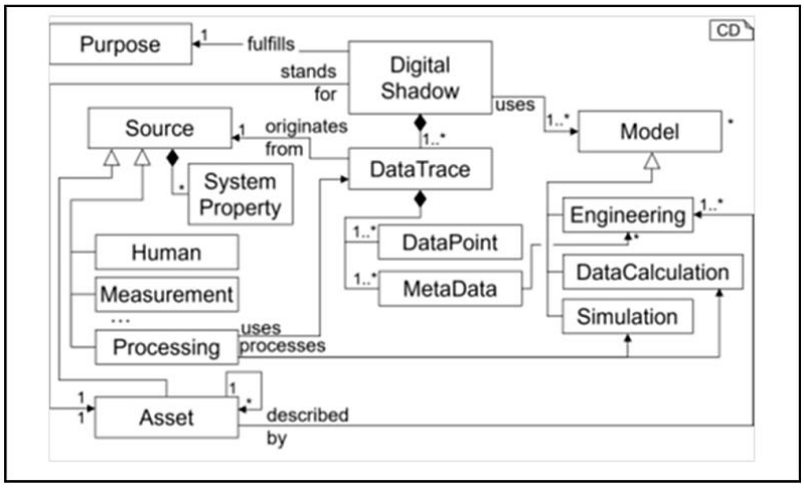


Figure 2. Digital Shadow Reference Model as a UML Class Diagram
Source: Bauernhansl et al., 2018

Liebenberg and Jarke (2023) describe DS as query-driven, flexible representations using real-time data but with simplified models, whilst Brauner et al. (2022) highlight that a DS is constructed for a specific purpose and asset. It can be used in the fields of earthwork monitoring (Rogage et al., 2022) and foundation-pit risk assessment (Yuan et al., 2022). Others are camera-based monitoring of a 345.8-m supertall building (Gu et al., 2024) and quality-risk analysis (Kropatschek et al., 2022).

2.3. Intelligent Parking Management and Unauthorized Parking Detection

Smart parking systems are made up of various sensors and technologies such as RFID, ANPR and cloud platforms that allow them to monitor parking spaces in real time, but most focus mainly on real-time occupancy and guidance, with only a few systems supporting parking violation management. The low cost sensing recently demonstrated by camera-based DS, as well as the real-time DS risk identification that

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provides a template for rule-based violation detection (Kropatschek et al., 2022), are examples of sensing infrastructure that can be developed with DS.

2.4. Business Intelligence and Analytics for Operational Decision Support

A data quality, feedback and scalable data ecosystems are essential for DS information supply (Bauernhansl et al., 2018). The delay of analysis (Liebenberg & Jarke, 2023) and efficiency of data-processing (Becker et al., 2021) are improved with query-driven DS and DS conceptual models, respectively. For parking, analytics can transform the data into occupancy, violation, utilization indicators for parking managers.

2.5. Theoretical Foundations of Digital Decision-Support Systems

The study is presented from three points of view. The decision-support view is one that believes that systems should provide decision-makers timely and relevant information instead of replacing their decisions; a DS is suited for this because it provides information without autonomous control (Kritzinger et al., 2018). The information processing perspective suggests that an organisation should have information capacity commensurate with the uncertainty that it needs, which purpose-based information paths provide (Michael et al., 2024). Design Science Research is an approach to designing a useful artifact that is created to solve a problem that has been identified (Heithoff et al., 2022). Governance is based on guiding principles for digital information management, such as purpose, trust and function (Bolton et al., 2018). The literature provides support for DS in the manufacturing industry, the construction and infrastructure sector but not for the residential parking governance sector. The study consequently situates DS in the context of business information system for operational decision support and thus tries to bridge the three gaps.

3. Research Methodology

3.1. Research Design and Methodological Approach

A Design Science Research (DSR) approach was used: Requirements Analysis, conceptual framework development and expert validation (Delphi) (Flow Chart 1). The operations that are intended for the framework are described in the latter stages of figure 3 (Flow Chart 1). No implementation was done and no performance tested.

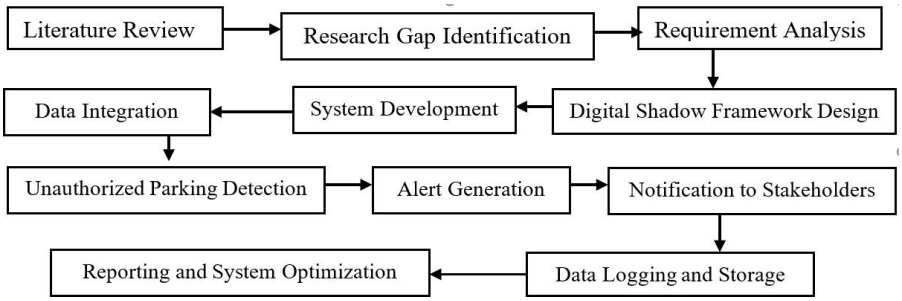


Figure 3. Flow Chart 1: Research Design

3.2. Research Problem Identification and Requirements Analysis

Through literature search, the following issues of DS, DT, IoT, intelligent transportation and intelligent parking management were identified: Unauthorized parking, poor monitoring, delayed enforcement and manual supervision. The needs were to monitor in real time, automatically validate parking authorizations, detect violations, alert and provide information to help facility managers make decisions.

3.3. Conceptual Framework Development Process

Data-driven DS design or purpose-driven DS design, both require problem identification, asset and model analysis, and the identification of data traces, data points and metadata (Heithoff et al., 2022; Michael et al., 2024). The following path was used: purpose: purpose unauthorised parking detection & decision support assets: parking slots, vehicles & gates output: architecture in section 4.

3.4. Expert Selection and Delphi Panel Composition

Delphi is suitable for problems where there is a need to gain consensus from participants' subjectivities, where participants are diverse and need to be heterogeneous (Linstone & Turoff, 1975). Expert panelists were chosen, based on expertise (Giannarou & Zervas, 2014; Stewart & Shamdasani, 2014). Twenty-seven experts were chosen from seven stakeholder groups (Table 4) which is a range within the most frequently recommended 15–30.

3.5. Delphi Questionnaire Design and Validation Dimensions

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The questionnaire was answered on each of the following validation dimensions: completeness of components, relevance of the architecture, effectiveness of the AI-based detection, real-time processing, scalability, security and privacy, ease of implementation, effectiveness of the decision making, user-friendliness and overall applicability. The 58 statements were grouped by stakeholder group, grouped by three thematic areas - Appendix A - and scored on a five-point scale with 5 being the highest level of agreement.

3.6. Delphi Validation Procedure

The proposed Intelligent Digital Shadow Framework was evaluated using the Delphi technique to obtain expert consensus regarding its conceptual design, technological feasibility, operational effectiveness, decision-support capabilities, and practical applicability in residential communities. A multidisciplinary panel comprising 27 experts from seven stakeholder groups participated in the validation process. All experts evaluated the 58 questionnaire statements using a five-point Likert scale, with 5 representing the highest level of agreement.

The Delphi validation's were completed in three rounds. In round 1 the key issues, components of the framework and evaluation criteria were identified and explored. In the second round, the experts evaluated the proposed framework by giving ratings to the 58 statements and then the level of agreement was analyzed using descriptive statistical measures. Expert re-thinking of their evaluations in the third round was to ensure consensus around the suitability and applicability of the framework in the context of the group's consolidated feedback. Responses from the experts were then compared to the literature to add support for methodological triangulation and enhance the ability to validate this process (Lincoln & Guba, 1985). The 27 ratings for the 58 statements (27 × 58 rating matrix) returned by the experts during the Delphi validation process and required for the consensus process were analysed in this study. Authors to confirm and complete information: Dates of each Delphi round, percentage of experts that responded to each round, the format in which the controlled feedback was sent to the experts between each round (group mean, median, and distribution of ratings, or experts' comments), and rating changes and/or comments received from experts.

The results of the expert consensus were determined by calculating the mean, median, standard deviation, interquartile range and percentage agreement as explained in Section 3.7. This led to the development of the conceptual validity and acceptance of the proposed framework based on evaluations.

3.7. Data Analysis and Expert Consensus Assessment

The response of Delphi was analyzed by descriptive statistical indicators such as mean, median, standard deviation (SD), interquartile range (IQR) and percentage agreement according to the standard Delphi consensus assessment methodology (Diamond et al., 2014; Esmaeilpoorarabi et al., 2018). Mean rating scores that are higher and fewer in the number of standard deviations will suggest greater agreement of the experts (Holey et al., 2007; Jordan & Javernick-Will, 2013).

The four criteria used for consensus were: a mean ≥ 4.0, a SD ≤ 1.0, an IQR ≤ 1.0, and a $\geq 75\%$ agreement. Mean and median were used for the measure of central tendency of expert ratings and SD and IQR were used for the measure of dispersion of the responses. A percentage agreement was provided to calculate the percentage of experts that agreed with each item. The relevance, feasibility, operational effectiveness, decision support capabilities, governance and the applicability of the proposed framework were evaluated based on these indicators. Previous studies that applied the Delphi method for the development of frameworks (Adu-McVie et al., 2021; Ruppert & Duncan, 2017; Mustakim et al., 2023) have used similar techniques. The final consensus results are shown in Section 5.

The analysis is limited to descriptive statistics, (frequency, mean, median, SD and IQR), percentage agreement and consensus assessment because the aim of the study is to develop and validate a conceptual Digital Shadow framework by expert evaluation. The answers of the experts (27 experts with 58 statements) were very similar: 56 of the 58 statements were answered by all experts with 5 points. Only for Q8 and Q10 there are differences. The findings are thus not explanatory or causal but are taken as an indication of the degree of experts' consensus and agreement about the framework.

3.8. Ethical Considerations and Research Limitations

Participants: professionals who are evaluating a conceptual framework; Consent/Anonymity: addressed in Declarations. Identity and video data of vehicles are treated in the framework and privacy protection is detailed in Section 4.8. Delphi has identified some drawbacks such as lack of depth, consensus building and manipulation by anonymity (Green, 2014). In addition, the panel is small (n = 27) and unequal in size across the seven stakeholder groups (two to five experts per group).

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4. Development of the Intelligent Digital Shadow-Based Decision-Support Framework

4.1. Framework Objectives and Managerial Requirements

Managerial requirements provide a relationship between parking-related information and administrative decision making that is systematic. The concept is to overcome the disjointed monitoring of vehicles by combining vehicle ID, parking authorization, parking occupancy and vehicle violation within a single decision support environment. The availability of information on a constant basis would help facility managers determine if there are any irregularities in operations and would allow them to prioritize reported incidents and coordinate a response to security issues. The proposed approach also has a focus of accountability as it will share the records of violations that are detected and the administrative measures taken as a result. As a result, the framework not only fulfils technological monitoring needs but also organisational ones for having to rely on reliable information, to enforce consistently and to allocate efficiently supervisory resources.

4.2. Overall Architecture of the Proposed Digital Shadow Framework

The 9 layer architecture separates out the responsibilities for managing information into a series of interrelated functional components whereby parking observations are progressively turned into actionable administrative information. The information source and information transmission environment is the physical layer and communication layer, and the preliminary processing is provided by the edge computing. The Digital Shadow and intelligence layers handle operational records, and assist in identifying irregularities related to parking. The decision-support and application layers then provide access to appropriate stakeholders with the information. Security and data storage serve as layers of protection and maintenance of information and operational records. This structure allows for a conceptual separation of data acquisition, information processing, interpretation of the data and managerial response. Importantly, the architecture is not designed to provide autonomous physical intervention but it does enable information to flow from physical operations to digital representation to human decision-making, which is the hallmark of a Digital Shadow.

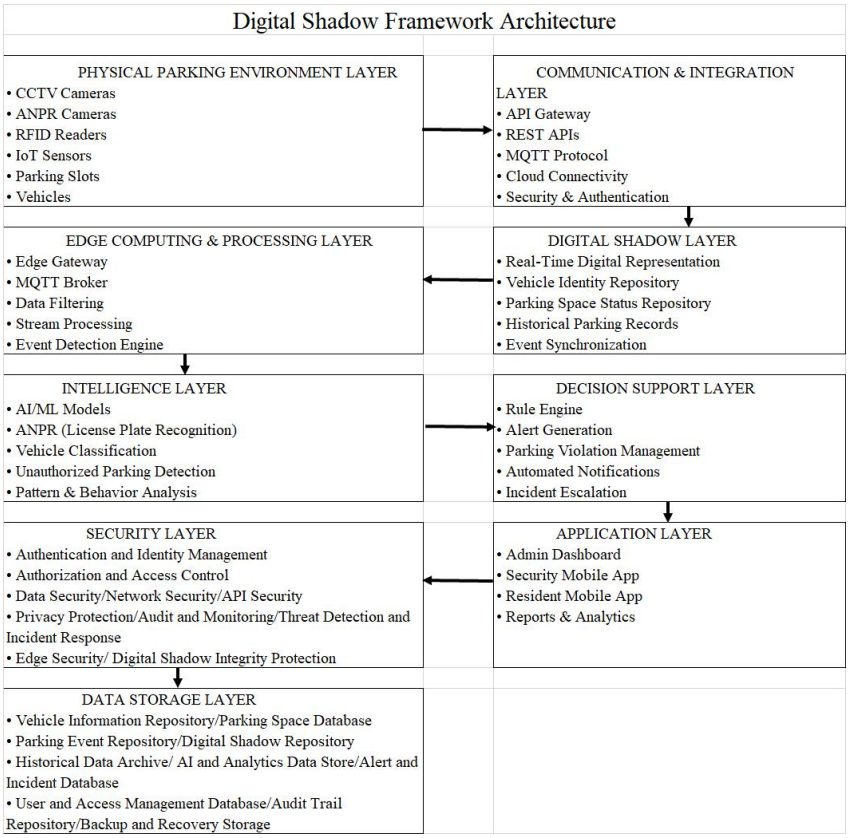


Figure 4. (Flow Chart 2): Digital Shadow Framework Architecture

4.3. Physical Monitoring and Data Acquisition Components

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The aim is to develop a comprehensive information base to observe parking activity, based on these components. The occupancy sensors provide information about the use of parking areas and the RFID/ANPR is used to identify vehicles and compare with the authorised parking information. CCTV will provide yet another visual resource that may be beneficial to security officers in any review of any potential occurrences. Even vehicle movements and parking duration can be recognized with the help of entry/exit observations thanks to the lightweight design with high precision. The proposed approach is to reduce the reliance of using isolated observations and manual recording, by bringing together the various information sources. Increased sharing of the vehicle identity, occupancy, location and timing of a vehicle in a common information environment may be leveraged to more thoroughly monitor and simplify administrative verification of the availability of a vehicle. However, in the actual use, they would have to be assessed for reliability and accuracy for the integrated sources of information.

4.4. Data Integration, Edge Computing, and Cloud Infrastructure

The proposed integration structure is intended for continuity and consistency of monitoring equipment in various locations and information management functions in a central location. Communication interfaces allow for observations related to parking to be shared among connected components and edge computing offers a means to process relevant information closer to where the observations are made. This could be used to help pre-identify and prioritize parking events prior to transferring information for centralized storage and further analysis. Historic information can be stored in the cloud for backup and administration reports and analysis of local processing, while providing cloud-based infrastructure. The use of local processing with central information management from a Business Information Systems point of view can enhance the ability to access information and coordinate organizations. Of course the actual impact on the processing time, communications speed and reliability of the system will be dependent on the type and performance of the infrastructure implemented.

4.5. Digital Shadow Representation and Real-Time Parking Analytics

The Occupied Slot Monitor gives the occupancy and free space data in real time and the Vehicle Location Tracker associates the identified vehicles with the location they are in and the zone they are assigned to. Available timestamps are used in the Parking Duration Calculator to calculate the parking duration of the parking activities and the Slot Availability Engine maintains the status of parking spaces up to date. The components should turn the information of the observations into an organised operational information. This information can all be used to study how parking spaces are used, parking patterns and/or any irregularities in the allocation of parking. The historical records could also be used to compare with parking conditions at different time periods. The proposed analytics will therefore offer the operational visibility and analytics-based resource planning – which has not been tested in real system testing.

4.6. Unauthorized Parking Detection and Rule-Based Decision Mechanisms

The rule-based detection mechanism is the main link between parking information and identification of instances of potential parking violations. It suggests a verification action to check what kind of action the vehicles have taken (park or unpark) and to compare this with the conditions that were used to determine the parking authorization, which it is stored in the system database. This could result in parking in an inappropriate space (e.g. visitor's vehicle in residential parking restricted space) or the duration of a parking space being too long (e.g. a car parked in a space for more than the allowed time) being possible violations. Vehicle identification, parking occupancy and documentation of parking should facilitate this if desired to make parking conditions easier to understand. The proposed architecture also makes use of the potentials of the analytical functions and artificial intelligence, to improve the other classification and pattern recognition capabilities. These, however, are conceptual system functions, and not detection mechanisms, that are experimentally validated. Admin verification is still a vital part since if discrepancies are noted prior to enforcement, then it may be an interpretation error.

4.7. Intelligent Decision Support, Automated Alerts, and Stakeholder Communication

The decision support layer includes the rule engine, the generation of alerts, generation of responses to violations, the automatic generation of alerts and escalation of incidents. The mobile alerts, Short Message Service (SMS) and alerts via email or security dashboard also are utilized to alert stakeholders to vehicle information, location, slot, date, time and photographic evidence. The applications are an admin dashboard, security applications, a resident mobile app and reports and analytics.

Security layer offers authentication, access control, data, network and API security, privacy protection, audit, threat detection, incident response and edge security with DS integrity protection. It helps to ensure

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confidentiality, integrity, availability, authenticity and accountability; audit trails enable governance and trust (Bolton et al., 2018). The data storage layer (vehicle and space databases, event repository, historical archive, analytics store, incident and access databases, audit trail, backup) enables historical analysis, tracking of recurring violations, assessment and reporting on usage. The enforcement is decisions are left to managers.

5. Results: Delphi-Based Framework Validation

5.1. Expert Panel Characteristics

Table 4 shows the composition of the Delphi panel and how the 58 questionnaire statements were allocated across the expert groups. The panel comprised 27 experts from seven stakeholder groups. All experts rated all 58 statements (Q1–Q58), so every item was evaluated by 27 raters.

Table 4. Delphi Panel Composition and Questionnaire Allocation

Expert group	Experts	Statements	Items
Academicians and researchers	5	8	Q1–Q8
Residential community management professionals	4	8	Q9–Q16
Transportation and parking experts	4	8	Q17–Q24
Technology and industry experts	5	9	Q25–Q33
Security and enforcement personnel	3	8	Q34–Q41
Government and policy representatives	2	8	Q42–Q49
End-user representatives (residents)	3	9	Q50–Q58
Total	27	58	Q1–Q58

5.2. Relevance, Design, Feasibility and Data Management

Table 5 summarises the Delphi results by validation block, giving the items, number of statements, mean range, block mean and number of consensus criteria met. The results are described in this order.

Table 5. Summary of Delphi Results by Validation Block

Validation block	Items	n	Mean range	Block mean*	Criteria met
Relevance and design	Q1–Q8	8	4.59–5.00	4.95	8/8
Feasibility and data	Q25–Q33	9	5.00	5.00	9/9
Operations and parking	Q9–Q11, Q17–Q24	11	4.78–5.00	4.98	11/11
Decision support	Q12–Q14	3	5.00	5.00	3/3
Security and policy	Q34–Q49	16	5.00	5.00	16/16
Acceptance and practicality	Q15–Q16, Q50–Q58	11	5.00	5.00	11/11
Overall	Q1–Q58	58	4.59–5.00	4.99	58/58

Note. Computed from the reported item means (27 raters per item). Unanimous items have SD = IQR = 0.00.

Q1–Q7 each received a rating of 5.00. Q8 (potential for future research and practical applications) had the lowest mean of all items (4.59), yet it still met every consensus criterion. The relevance and design block therefore had a mean range of 4.59–5.00, a block mean of 4.95 and 8/8 criteria met. All nine feasibility and data items (Q25–Q33) were rated 5.00 (block mean 5.00; 9/9). Every expert therefore agreed that the architecture is technically feasible, integrates IoT devices, supports real-time processing, employs an appropriate data flow, ensures reliable transmission and storage, enhances AI-based detection, integrates existing systems and is scalable.

5.3. Operational Effectiveness and Decision Support

The operations and parking block (Q9–Q11 and Q17–Q24; 11 items) yielded a block mean of 4.98 (range 4.78–5.00; 11/11). Q10 (Residential Parking - Reducing Conflicts) scored a mean of 4.78 with all other scored 5.00. These included efficiency, monitoring, space usage, enforcement, circulation, sustainability, indicators and implementation of policy. The decision support items (Q12–Q14) were all rated 5.00 (3/3). The framework was seen to facilitate timely decision making, automated alerts for faster responses to be made and reporting for community management, by experts.

5.4. Security, Governance, Acceptance and Practicality

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All sixteen security and policy items (Q34–Q49) were rated 5.00 (16/16). They discussed how to verify the identity of vehicles, how to enforce the regulations, how to respond to an incident, how to identify the security risks in the vehicles, how to verify vehicles, how to collect evidence, how to make them easier to use, how to avoid manual monitoring, how to align with policy, how to comply with regulation, how to make them more sustainable, how to better use of resources, and how they would benefit society. The acceptance and practicality items (Q15, Q16 and Q50–Q58; 11 items) were also all rated 5.00 (11/11). Experts agreed that implementation would be practical, that the benefits would justify the effort, that space availability and resident experience would improve, that conflicts would fall, that notifications would be useful, that transparency would improve, and that they would support implementation.

5.5. Overall Expert Consensus and Framework Validation Outcomes

Table 6 presents the consensus criteria and outcomes. Consensus was assessed using the mean, median, SD, IQR and percentage agreement, as described in Section 3.7.

Table 6. Delphi Consensus Criteria and Outcomes

Criterion	Threshold	Outcome
Mean	≥ 4.0	Met for all 58 (lowest: Q8, 4.59)
Standard deviation	≤ 1.0	Met for all 58 (0.00 for 56 items)
Interquartile range	≤ 1.0	Met for all 58 (0.00 for 56 items)
Percentage agreement	≥ 75%	Met for all 58 (100% for 56 items)
Overall mean / median	—	4.99 / 5.00

All 58 statements (58/58) met every criterion. The overall mean was 4.99 and the median was 5.00 for every statement. The overall mean is consistent with 56 items at 5.00 plus Q8 and Q10. The SD and IQR were 0.00 and agreement was 100% for 56 statements. Only Q8 and Q10 showed any dispersion, and both remained within the consensus thresholds. These evaluations provide the basis for the conceptual validity and expert acceptance of the proposed framework.

6. Discussion

The results of Delphi validation show that the proposed framework of Intelligent Digital Shadow (DS) for Unauthorized Parking Management in a residential community has been well accepted by the experts. There was consensus on all 58 statements of the questionnaire with a mean of 4.99 and a median of 5.00. These results show the high level of perceived relevance, technical viability, applicative potential and acceptance by stakeholders. But, as it is conceptual validation, not evidence of the effectiveness of implementation by experts. The unanimous responses could also suggest a ceiling effect, such that there was not enough variation in their responses to differentiate between the different components of the framework. Indeed, 56 of the 58 statements had zero variance, so the data support descriptive and consensus interpretation only. Interestingly, the lower ratings for Q8 (4.59), about the feasibility of future research and practical applications, and Q10 (4.78), regarding reduction of a parking dispute, indicate that having a technology that is feasible does not guarantee that it can be widely applied or lead to behavioral changes. This is significant because Delphi consensus is based on informed opinions, and not on the actual performance (Diamond et al., 2014; Giannarou & Zervas, 2014).

The framework from the business information systems point of view, treats DS technology as a whole information-management and decision-support system. The framework brings together information that is distributed across a variety of IoT sensors, RFID systems, automatic number plate recognition, CCTV surveillance and operational databases and maintains an up-to-date, consistent model of residential parking activity. One-way flow of information is relevant to its purpose as it provides management supervision without the need for physical control, in line with existing Digital Shadow principles (Kritzinger et al., 2018; Becker et al., 2021). The proposed approach differs from traditional Digital Twins, which focus on two-way information exchange, in that it involves observing, analyzing, and interpreting information and intervening in it through human actions. For residential organizations that want digital transformation but don't always have the time or resources to invest in the technology, this distinction is a potentially less complicated option. Currently, there is an expert consensus that the framework can lead to better administrative efficiency by continuous monitoring, automatic checking of authorizations, identification of violations, collection of evidence and timely notifying of violations. These functions can help to minimize reliance on manual

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inspections as needed periodically, and enhance incident priority and organizational reaction. The ability to view real-time parking data, historic parking violation information, and usage reports would also help to inform evidence-based patrol scheduling, parking, and resource planning. These are in line with the Digital Shadow applications' focus on operational risk identification and efficient information processing (Liebenberg & Jarke, 2023; Kropatschek et al., 2022). Although there is no operational implementation or assessment of the performance against this, there are still expected benefits due to the reduction in the response time, operational cost, monitoring workload and parking incidents.

The framework also offers suggestions on how managerially co-ordinating and communicating the co-ordinating and governing residential parking process. Centralized dashboards would track incidents, analyze parking facility usage and security guards would be alerted to parking identity, parking location, time and date of the incident and a photo of the incident. A history of the facility might assist administrator in decisions regarding the operation and administration of the facility. There could be a need for better authorization processes, enforcement and communication for residents. But it seems that residents' actions, organizational strategies and involvement of stakeholders play a role because the level of agreement on reducing dispute is significantly lower. Thus, using technology to monitor should be considered complementary to the current administration and government process. The framework is also in line with overall information-management principles outlined by Bolton et al. (2018) which include ‘purpose', ‘trust' and ‘functionality'.

In theory this study takes Digital Shadow applications to a new level where it can be implemented in the residential facilities operations, not just manufacturing and construction monitoring and infrastructure management. The importance of digital representations in infrastructure surveillance and risk assessment (RSA) has been proven in previous research (Rogage et al., 2022; Yuan et al., 2022). The proposed framework extends this view by embedding the implementation of the unauthorized parking detection, the documentation of the parking violations, the notification of the stakeholders and the managerial decision support in one conceptual framework. As such, it is most significant in bridging the technology information processing and organizational governance and operational decision-making.

In theory this study takes Digital Shadow applications to a new level where it can be implemented in the residential facilities operations, not just manufacturing and construction monitoring and infrastructure management. The responses showed almost no variability and the sample is small, so the findings are interpreted as expert agreement only. No working system was established, so the accuracy of detection, responsiveness, use of resources, cost and satisfaction of the residents were not measured. In addition, there are privacy, data-security and organisational adoption issues raised with vehicle identification and surveillance technologies. There are other factors that may require evaluation for implementation such as infrastructure cost and employee capacity, system interoperability and community acceptance.

Further studies are needed focusing on controlled pilot implementation in residential areas and a comparison with the traditional parking management. Confusion-matrix related detection accuracy, response time, administrative cost, parking utilization, level of complaints and level of resident satisfaction should be included in performance evaluation. There is a need to further investigate the various elements of privacy protection, stakeholder acceptance, scalability and economic feasibility. Future data may also be collected from a larger and more diverse sample of data with increased variance in the results to further quantitatively test the framework. Finally, the framework serves as an expert validated groundwork for management oriented digital transformation, but the effectiveness of it and its value for the organization needs to be empirically proven later on.

7. Conclusion

Delayed enforcement, supervisory workload and limited visibility are all management issues associated with unauthorised parking in residential communities. The present research work suggested an intelligent DS based decision support framework comprising nine layers, which is an information resource for monitoring, operational control and managerial decisions incorporating IoT, RFID, ANPR, Edge and cloud computing and analytics. The 58 statements were rated by a Delphi panel of 27 experts who reached a consensus on all of them, with a mean rating of 4.99 and a median rating of 5.00; the mean ratings of Q8 and Q10 were 4.59 and 4.78 respectively, which were below 5.00. The framework is thus considered to be relevant, feasible and acceptable. These are expected to be the benefits that can be achieved, such as reduction in supervision workload, speeding up of escalation, utilization of space, and more transparent governance. The main

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limitations are the conceptual design based on experts, which lacks implementation and performance data, and the limited response variability and small sample. The framework needs to be piloted, its accuracy needs to be verified, its response time needs to be timed, its cost needs to be calculated, its utilization and satisfaction needs to be assessed, privacy and adoption issues needs to be addressed for future research.

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