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SOCIO-TECHNOLOGICAL PATHWAYS TO SUSTAINABLE SMART CITIES: A DEMATEL ANALYSIS OF IoT CHALLENGES AND STRATEGIC RESPONSES

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Mohd Hisyam Jahimi[1]*, Lee Chia Kuang[2], Alvin Zhi Xun LUM[3], Thong Jun Zhou[2], Mohd Ruzaimi Bin Mohd Ariffin[2], Marian Bujna[4]

[1] *Department of Electrical and Electronics Engineering Technology, Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia*
Email: ir.mohdhisyam@gmail.com
[2] *Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia*
Emails: chia@umpsa.edu.my; junzhou@umpsa.edu.my; mohdruzaimi@umpsa.edu.my
[3] *Universiti Malaysia Pahang*
Email: alvinlum101@gmail.com
[4] *Institute of Automotive Engineering, Faculty of Engineering, Slovak University of Agriculture in Nitra, Slovakia*
Email: marian.bujna@uniag.sk

Corresponding author:* ***Mohd Hisyam Jahimi*
Corresponding author's email: ir.mohdhisyam@gmail.com

ABSTRACT

Smart cities are widely promoted as a response to urbanisation pressures, with the Internet of Things (IoT) providing the core enabling technology. IoT adoption at the city scale involves coupled technical, organisational, and financial challenges that are rarely studied as a connected system. This study applies the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, grounded in a socio-technical systems perspective, to model the perceived causal relationships among five recurring IoT challenges (interoperability, scalability, data analytics, data security and privacy, and financial constraints) and five widely proposed strategic responses (standardisation of IoT protocols, microservices-oriented architecture, edge computing, data-protection regulation, and public–private partnerships). Twenty-five purposively selected experts engaged in IoT-enabled smart city projects in Malaysia provided the influence judgments analysed here. The analysis identifies data security and privacy as the dominant perceived causal driver among the challenges, financial constraints as the most prominent receiving challenge, and the standardisation of IoT protocols as the strategy with the strongest net influence and the broadest perceived reach across the challenges. Rather than asserting universal causal claims, the study provides a context-specific, expert-based prioritisation framework for Malaysian smart city implementation, with implications for how policymakers, urban planners, and technology providers sequence interventions in resource-constrained settings.

Keywords: Decision Making and Trial Evaluation (DEMATEL), Internet of Things (IoT), IoT Challenges, Smart Cities, Urban Sustainability, Socio-Technical Systems

1.0 INTRODUCTION

Cities face mounting pressure from rapid urbanisation, including congestion, environmental degradation, and infrastructural strain. The United Nations (2022) projects that about 68 per cent of the world's population will live in urban areas by 2050, with the Asia-Pacific region taking a substantial share of this growth (Ismagilova et al., 2019). The search for technology-enabled approaches to urban management has intensified in response.

The smart city concept has emerged as one such approach. It combines digital infrastructure, data analytics, and connected devices to deliver public services more efficiently (Kim et al., 2021). The Internet of Things (IoT) is the data-generating layer that underpins this approach, connecting sensors, actuators, and platforms to support real-time monitoring and decision-making in traffic, utilities, public safety, and waste management (Alavi et al., 2018; Al-Obaidi et al., 2022; Hoang, 2024).
IoT deployment at the city scale is not a purely technical exercise. It involves coordination among public agencies, private operators, infrastructure providers, and end-users (Bibri et al., 2023; Hussain, 2024). Documented obstacles include weak system interoperability, scaling problems, gaps in data analytics capacity,

persistent data security and privacy risks, and recurring financial constraints (Rejeb et al., 2022; Singh et al., 2024). Prior studies have examined these obstacles individually (Bhardwaj et al., 2024; Hassan et al., 2021; Rafiq et al., 2023; Ratnakar et al., 2020), but few have analysed how they interact as a connected system. Weak data protection can amplify financial exposure, and interoperability gaps can raise integration costs and constrain scalability. Treating these obstacles in isolation risks misallocating limited resources and overlooking the points where intervention would yield the greatest effect.

A second weakness in the existing literature is methodological. Most prior work is descriptive or single-issue, with limited use of analytical techniques that can map mutual influence among multiple factors (Janssen et al., 2019). This study addresses both gaps by applying the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to model perceived causal relationships among IoT challenges and strategic responses. DEMATEL is particularly suited to problems characterised by interconnected qualitative factors and limited large-sample data, as it derives an influence structure from structured expert judgments and visualises it through cause–and–effect diagrams (Chen et al., 2023; Makki & Alqahtani, 2024).
The study is situated in Malaysia, where smart city initiatives have advanced under the Malaysia Smart City Framework but remain unevenly distributed across states and sectors. This context offers a useful test bed: ambitions are high, expertise is concentrated within an identifiable group of professionals, and implementation outcomes vary, making the setting suitable for expert-based causal mapping. Twenty-five purposively selected experts engaged in IoT-enabled smart city projects in Malaysia evaluated the perceived influence of five widely cited challenges and five corresponding strategies.

Two research questions guide the study:

> **RQ1**: How do the major challenges of IoT implementation in Malaysian smart cities perceptually influence one another?
> **RQ2**: Which strategic responses exert the strongest perceived influence on these challenges, and how should they be prioritised?

The study makes two contributions, both framed conservatively to reflect what DEMATEL can support. First, it offers a Malaysia-focused, expert-based causal mapping of IoT barriers and responses, situating findings within a specific socio-technical environment rather than claiming universal causal truth. Second, it provides a DEMATEL-based prioritisation framework that policymakers, planners, and technology providers can adapt when sequencing interventions under resource constraints. The study draws on a socio-technical systems perspective in which effective IoT adoption depends on the coordinated treatment of technical, organisational, and financial factors rather than the improvement of any one dimension in isolation.

2.0 LITERATURE REVIEW

2.1 *Smart City and the Role of IoT*

Smart cities have been widely studied as urban configurations that combine information and communication technologies (ICT), physical infrastructure, and citizen participation to deliver services more efficiently (Bellini et al., 2022; Syed et al., 2021). Early scholarship emphasised technology-centric definitions, but more recent work positions smart cities as socio-technical systems in which technical, organisational, and human dimensions are tightly coupled (Bibri et al., 2023; Hussain, 2024). The implication is that gains in one dimension, such as sensor coverage, cannot be sustained without parallel progress in others, such as governance, data ethics, and financing.

IoT is the principal data-generating layer of this system. It comprises sensing devices, communication networks, computing resources, and analytics platforms that together enable real-time decision-making (Ali et al., 2023; Whaiduzzaman et al., 2022). Documented application domains include energy management, mobility, e-governance, health, and environmental monitoring (Bauer et al., 2021; Houssein et al., 2024; Zaman et al., 2024). Several reviews argue that IoT delivers value only when paired with appropriate governance, standardisation, and investment frameworks (Alam, 2024; Gade & Aithal, 2022).

2.2 *Critical Review of IoT Implementation Challenges*

Prior studies identify a wide range of obstacles to IoT-enabled smart city implementation. Synthesising and comparing this work reveals that five challenges appear consistently across reviews and case studies, regardless of geography.
(i) Interoperability. Whaiduzzaman et al. (2022) and Ali et al. (2023) note that heterogeneous protocols and

proprietary platforms continue to fragment IoT ecosystems, while Saidala et al. (2024) argue that the absence of harmonised standards is the principal source of integration cost.
(ii) Scalability. Gade and Aithal (2022) and EI et al. (2023) document difficulties in extending pilot projects to city-wide deployments, particularly when architectures are not modular.
(iii) Data analytics capacity. James et al. (2022) and Zaman et al. (2024) point to bandwidth limits, processing constraints, and data-quality issues as recurring bottlenecks.
(iv) Data security and privacy. Al-Turjman et al. (2022) and Hussain (2024) document the expanded attack surface of dense IoT deployments and emphasise that public trust hinges on credible data governance.
(v) Financial constraints. Popova (2020) and Gyimah et al. (2021) show that capital intensity, uncertain returns, and procurement complexity persistently limit municipal investment.

These five challenges are retained as the analytical variables in this study because (a) they recur across the reviewed literature, (b) they span the technical–organisational–financial dimensions of the socio-technical framework adopted here, and (c) they were validated through an initial consultation with three senior smart-city experts in Malaysia, whose responses were not retained in the final dataset, who confirmed their salience for the local context. Other plausible factors, such as workforce skill gaps and political continuity, were considered but excluded to keep the DEMATEL matrix tractable. This is consistent with prior work that has applied DEMATEL with five to eight factors (Khan et al., 2022; Yadav et al., 2020).

2.3 *Critical Review of Strategic Responses*

A parallel literature has examined strategies to address these challenges, although most studies discuss strategies in isolation rather than as a coordinated portfolio. Five responses recur most frequently: (i) standardisation of IoT protocols, which reduces fragmentation and supports interoperability (Amjad et al., 2021; Saidala et al., 2024; Shahbazian, 2023); (ii) microservices-oriented architecture (MSA), which enables independent scaling of services and decouples failure domains (Ali et al., 2023); (iii) edge computing, which mitigates latency and bandwidth constraints by performing analytics close to data sources (Alam, 2024); (iv) regulatory frameworks for data protection, which strengthen public trust and provide a legal basis for data governance (Hussain, 2024); and (v) public–private partnerships (PPPs), which mobilise capital and operational expertise that municipalities frequently lack (Bauer et al., 2021; Chang et al., 2023).

The selection of these five strategies follows the same logic applied to the challenges: they appear consistently in the literature, span the same socio-technical dimensions, and represent levers that policymakers in Malaysia can plausibly influence in the medium term.

2.4 *Research Gap and the Case for DEMATEL*

Three observations together justify the present study. First, prior work generally treats challenges and strategies as separable lists rather than as a coupled system. Second, where causal modelling has been attempted, it has usually relied on interpretive structural modelling (ISM), the analytic network process (ANP), or structural equation modelling (SEM), each of which has limitations for the present problem. ISM produces hierarchies but cannot quantify the strength of influence (Janssen et al., 2019). ANP captures dependencies but requires consistent pairwise comparisons that involve many factors. SEM requires large samples and an a priori measurement model. DEMATEL, by contrast, is well-suited to small expert panels, quantifies both prominence and net influence, and visualises causal structure through influence diagrams (Chen et al., 2023; Makki & Alqahtani, 2024). It does not establish empirical causality in the experimental sense; it yields a structured map of perceived influence among factors, which is the appropriate inferential target for the questions posed here.

Third, country-specific evidence is limited. Despite Malaysia's active smart city agenda, no published study has applied DEMATEL to map the relationships among IoT challenges and strategies in this context. The present study addresses this gap by combining a socio-technical conceptual lens with a DEMATEL analysis of expert judgments from Malaysian practitioners.

3.0 CONCEPTUAL FRAMEWORK

The study adopts a socio-technical systems perspective on smart city IoT implementation. This perspective holds that technological subsystems and social subsystems are mutually constitutive: outcomes depend on the joint optimisation of technical, organisational, and human components rather than on any one component in isolation (Bibri et al., 2023; Hussain, 2024).

Under this lens, IoT-enabled smart cities can be conceptualised as a system with three interacting subsystems. The technical subsystem comprises devices, networks, protocols, and analytics platforms; the organisational subsystem comprises governance arrangements, regulations, partnerships, and operational practices; and the financial subsystem comprises investment models, cost structures, and value flows. The five challenges identified above map directly onto these subsystems: interoperability, scalability, and data analytics are primarily technical; data security and privacy span technical and organisational domains; and financial constraints are primarily financial but also reflect organisational decisions about procurement and risk-sharing. The five strategies span the same subsystems: standardisation and edge computing are technical interventions; regulation and PPPs are organisational and financial interventions; and MSA is technical, with organisational implications for service ownership.

This mapping yields two analytical expectations that the DEMATEL analysis can examine. First, because socio-technical subsystems are coupled, the perceived causal structure among the five challenges should not be flat; some challenges should serve as drivers, while others serve as receivers. Second, strategies that touch multiple subsystems simultaneously, such as standardisation, which has both technical and governance implications, should be perceived as having broader influence on challenges than strategies operating within a single subsystem.
The framework also informs interpretation. Because socio-technical influence operates partly through human and organisational judgment, expert-based causal mapping is an appropriate, theoretically motivated method for surfacing influence structures in this domain. At the same time, the framework cautions that DEMATEL outputs reflect modelled perceptions of how the system works rather than empirical measurements of how it actually does; this caution shapes the interpretation of results in Section 6.

4.0 RESEARCH METHODOLOGY

4.1 Method Selection and Justification

The study applies the DEMATEL method to model perceived causal relationships among IoT challenges and strategies. As outlined in Section 2.4, DEMATEL was selected over alternative multi-criteria methods because: (i) it accommodates small expert panels, which is the standard data condition for technology-adoption studies in emerging implementation contexts; (ii) it quantifies both prominence (R + C) and net causal direction (R − C), allowing the analysis to distinguish prominent factors from causally dominant ones, an important distinction in this study; and (iii) it produces visual influence diagrams that communicate findings to non-specialist policymakers (Khan et al., 2022; Pinto et al., 2022; Yadav et al., 2020).

4.2 Expert Selection

DEMATEL is an expert-judgment method; the quality of its outputs depends on the panel's relevance and consistency rather than on a large random sample. Published DEMATEL applications in technology and urban systems research typically involve between 5 and 30 experts (Khan et al., 2022; Makki & Alqahtani, 2024; Wang et al., 2021). The present study used a panel of 25 experts, which sits comfortably within this range.

Recruitment followed a purposive sampling strategy, supplemented by limited snowball sampling. The inclusion criteria required that each participant: (a) had at least five years of professional experience in IoT, ICT, or smart city projects; (b) had direct involvement in at least one operational or pilot IoT-enabled smart city initiative in Malaysia; and (c) held a technical, managerial, or strategic role with sufficient breadth to evaluate cross-cutting influences among the factors. Candidates were initially identified through professional registries, conference participant lists, and project documentation. Each candidate was then contacted individually, and those who consented were invited to nominate one additional qualified colleague. Participation was voluntary, and responses were anonymised.
To mitigate bias arising from a relatively homogeneous sample, three procedural measures were used: (i) participants were drawn from multiple project sites across Malaysia rather than from a single municipality; (ii) the questionnaire was piloted with three senior experts, whose responses were not retained in the final dataset, to allow item refinement; and (iii) participants were instructed to evaluate influence in general project conditions rather than relative to a single project.

The resulting panel nonetheless skews male, private-sector, and concentrated in Pulau Pinang, Kuala Lumpur, and Cyberjaya. These features are discussed as limitations in Section 7.

4.3 Data Collection

Each expert completed a structured questionnaire in which they evaluated the direct perceived influence of each factor on every other factor using a five-point scale: 0 = no influence, 1 = low, 2 = moderate, 3 = high, 4 = very high. Three matrices were elicited from each respondent: (a) challenges × challenges (5 × 5), (b) strategies × strategies (5 × 5), and (c) strategies × challenges (combined 10 × 10). Diagonal cells were fixed at zero.

4.4 DEMATEL Analytical Procedure

The DEMATEL procedure was applied identically to each of the three matrices.

Step 1: Collect Expert Opinions and Compute the Average Matrix (Z)

Experts assessed the pairwise relationships among the factors, producing a set of direct influence matrices. For each expert k, a non-negative $n \times n$ matrix $X_k = [x_{ij}^k]$was created, where x_{ij}^k denotes the influence of factor i on factor j. These matrices were then averaged across all m experts to obtain the overall average matrix $Z = [z_{ij}]$as follows:

$$Z_{ij} = \frac{1}{m}\sum_{i=1}^{m} X_{ij}^k \qquad \text{……Equation 1}$$

This aggregation captures the collective perception of the expert group.

Step 2: Calculate the Normalised Initial Direct-Relation Matrix (D)

To normalise the matrix Z, all elements were divided by the maximum row sum, ensuring that every , d_{ij} element lies between 0 and 1. The normalised direct-relation matrix $D$is expressed as:

$$D = A \times S, \quad S = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \qquad \text{……Equation 2}$$

This step adjusts the values to maintain consistency and comparability across factors.

Step 3: Derive the Total Relation Matrix T

Using the normalised matrix *D*, a total influence matrix *T* was calculated to account for the direct and indirect effects of all variables. The mathematical formula is provided as:

$$T = D(I - D)^{-1} \qquad \text{……Equation 3}$$

where I represents the identity matrix. The total influence t_{ij} represents the combined impact of one factor i on another j. This matrix summarises all interdependencies within the system.

Step 4: Calculate the Sum of Rows and Columns (R and C)

To determine the overall influence and dependence of each factor, the sum of rows (R_i) and the sum of columns (C_j) in the matrix T was computed as:

$$R_i = [r_i]_{n \times 1} = \left(\sum_{j=1}^{n} t_{ij}\right)_{n \times 1} \qquad \text{……Equation 4}$$

$$C_j = [c_j]'_{1 \times n} = \left(\sum_{j=1}^{n} t_{ij}\right)'_{1 \times n} \qquad \text{……Equation 5}$$

Here, R_i represents the total influence that factor i exerts on others, while C_j reflects the total influence received by factor j. The values of $(R_i + C_j)$ indicate the importance or prominence of a factor within the system, whereas $(R_i - C_j)$identifies whether the factor acts as a cause (positive value) or an effect (negative value).

Step 5: Determine the Threshold Value (α)

The threshold is computed as the mean of all elements in T:

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]}{N} \qquad \text{……Equation 6}$$

where $N = n^2$ is the total number of elements in the matrix T. Only entries $t_{ij} > \alpha$ are retained when drawing the influence digraph; smaller entries are treated as negligible (Ahmad et al., 2021; Boutkhoum et al., 2021; Lin, 2022).

Step 6: Construct the Cause-and-Effect Diagram
Each factor is plotted on a two-dimensional plane with prominence ($R_i + C_j$) on the horizontal axis and net relation ($R_i - C_j$) on the vertical axis. Factors with $R_i - C_j > 0$ are perceived causes; those with $R_i - C_j < 0$ are perceived effects (Khan et al., 2022; Pinto et al., 2022; Xu et al., 2023).

4.5 Reliability and Consensus Assessment
Two reliability considerations apply to DEMATEL data. The first is internal consistency of the expert ratings, which was assessed using Cronbach's alpha:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum i \sigma_i^2}{\sigma_t^2}\right)$$

……*Equation 7*

where K is the number of items, σ_i^2 is the variance of item i, and σ_T^2 is the variance of total scores (Tavakol & Dennick, 2011). Cronbach's alpha is not a DEMATEL-specific statistic, and its limitations for influence data are acknowledged: it indicates the consistency with which respondents rated related items, not the convergence of their causal judgments. It is reported here as a supplementary check rather than as a definitive consensus measure, and the values obtained, all exceeding 0.90 in this study, are interpreted accordingly. Specialist DEMATEL consensus indices, such as Kendall's coefficient of concordance and the average gap between successive elicitation rounds, were considered; the present design used a single round, and these alternative measures are noted as appropriate extensions for future work.

4.6 Application Context and Variable Coding
Three DEMATEL analyses were conducted:

(i) challenges × challenges
(ii) strategies × strategies
(iii) strategies × challenges.

The variables were coded as follows.
Challenges:

A – Interoperability issue
B – Scalability issue
C – Data analytics issue
D – Data security and privacy issues
E – Financial issue

Strategies:

F – Standardisation of IoT protocols
G – Microservices-oriented architecture (MSA)
H – Edge computing for IoT data analytics
I – Data protection regulations and standards
J – Public–private partnerships (PPP)

5.0 RESULTS

5.1 Respondent Profile

Table 1 summarises the demographic profile of the 25 respondents. The panel was 84 per cent male and predominantly aged 36–45 years. Educational attainment was high, with 96 per cent holding at least a bachelor's degree. Most respondents had 6–10 years of relevant experience (56 per cent), with a further 32 per cent reporting 11–15 years. Engineering (56 per cent) and information technology (20 per cent) were the dominant fields of expertise. Twenty-two respondents (88 per cent) worked in the private sector, and 60 per cent were employed in large organisations. Project sites were concentrated in Pulau Pinang (44 per cent), Kuala Lumpur (16 per cent), and Cyberjaya (16 per cent). Smart industry and production (32 per cent), smart living (20 per cent), and smart mobility (16 per cent) were the most common project categories.

Table 1: Demographic Profile of Respondents (n=25)

Background Information	Characteristic	Frequency	Percentage (%)
Gender	Male	21	84.00
	Female	4	16.00
Age	26 - 30 years old	1	4.00
	31 - 35 years old	3	12.00
	36 - 40 years old	8	32.00
	41 - 45 years old	6	24.00
	46 - 50 years old	1	4.00
	51-55 years old	5	24.00
	Above 55 years old	1	4.00
Education Level	Bachelor’s degree	16	64.00
	Master’s degree	8	32.00
	PhD’s degree	1	4.00
Years of Experience	1-5 years	3	12.00
	6-10 years	14	56.00
	11-15 years	8	32.00
Nature of organization	Developer	1	4.00
	Private Company	18	72.00
	Government Agency	3	12.00
	Government-Linked Company (GLC)	3	12.00
Field of expertise	Information Technology	5	20.00
	Engineering (e.g., Electrical etc..)	13	56.00
	Project Management	2	8.00
	Internet of Things	3	12.00
	Strategy and Business Development	1	4.00
	Mixed ofmechanical engineering and internet technology	1	4.00
Role in the company	Director	8	32.00
	Project Manager	5	20.00
	Executive	1	4.00
	Quantity Surveyor	1	4.00
	Electrical Engineer	2	8.00
	Network Engineer	2	8.00
	Embedded System Engineer	2	8.00
	Cloud Infrastructure Engineer	1	4.00
	IoT Architect	1	4.00
	Senior Manager	1	4.00
	Head Data Analytic	1	4.00
Organization type	Government	3	12.00
	Private Sector	22	88.00
Company Size	Small (1-50 employees)	7	28.00
	Medium (51-250 employees)	3	12.00
	Large (251+ employees)	15	60.00
Familiarity with IoT technologies	Moderately familiar	6	24.00
	Very familiar	19	76.00
Level of involvement in Smart City project	Occasional Involvement	1	4.00
	Moderate Involvement	8	32.00
	Significant Involvement	11	44.00
	Extensive Involvement	5	20.00
Project Location	Kuala Lumpur	4	16.00
	Putrajaya	2	8.00
	Cyberjaya	4	16.00

Background Information	Characteristic	Frequency	Percentage (%)
	Selangor	3	12.00
	Pulau Pinang	11	44.00
	Pahang	1	4.00
Type of Smart City project involved in	Smart governance	2	8.00
	Smart industry and production	8	32.00
	Smart economy	2	8.00
	Smart energy	2	8.00
	Smart health	1	4.00
	Smart environment	1	4.00
	Smart mobility and transportation	4	16.00
	Smart living	5	20.00
Smart City Project Sum	RM 1,000,001 – RM 5,000,000	11	44.00
	RM 5,000,001 – RM 10,000,000	4	16.00
	RM 10,000,001 – RM 15,000,000	1	4.00
	RM 15,000,001 – RM 20,000,000	2	8.00
	More than RM 20,000,000	3	12.00
Biggest Perceived Challenge in IoT for Smart Cities	Interoperability issue	7	28.00
	Scalability issue	2	8.00
	Data security and private issue	1	4.00
	Data analytic issue	2	8.00
	Financial issue	13	52.00

When asked to identify the single biggest perceived challenge in their projects, 52 per cent of respondents named financial issues, followed by interoperability (28 per cent). This descriptive ranking should not be confused with the DEMATEL analysis that follows, which models perceived influence relationships rather than self-reported importance.

5.2 DEMATEL Analysis I: Challenges versus Challenges

The 25 expert matrices were averaged using Equation 1 (Table 2), normalised using Equation 2 (Table 3), and used to compute the total-relation matrix T via Equation 3 (Table 4). Row and column sums (Equations 4–5) yielded the prominence and net-relation values shown in Table 5. The threshold α computed from Equation 6 was 1.424. Table 6 shows the entries of T exceeding this threshold.

Table 2. Average direct-relation matrix Z (Challenges vs Challenges)

Factors	A	B	C	D	E	Sum
A	0.000	2.480	2.480	2.600	3.080	10.640
B	2.280	0.000	1.680	2.160	3.080	9.200
C	2.480	2.040	0.000	2.400	2.760	9.680
D	2.760	2.360	2.480	0.000	3.000	10.600
E	3.000	3.200	2.800	2.920	0.000	11.920
SUM	10.520	10.080	9.440	10.080	11.920	-

Table 3. Normalised direct-relation matrix D (Challenges vs Challenges)

Factors	A	B	C	D	E
A	0.000	0.208	0.208	0.218	0.258
B	0.191	0.000	0.141	0.181	0.258
C	0.208	0.171	0.000	0.201	0.232
D	0.232	0.198	0.208	0.000	0.252
E	0.252	0.268	0.235	0.245	0.000

Table 4. Total relation matrix T (Challenges vs Challenges)

Factors	A	B	C	D	E
A	1.318	1.451	1.379	1.453	1.659
B	1.335	1.141	1.200	1.288	1.500
C	1.392	1.330	1.117	1.346	1.533
D	1.503	1.441	1.376	1.270	1.650
E	1.637	1.605	1.503	1.584	1.584

Table 5. Sum of Rows and Columns of Matrix T (Challenges vs Challenges)

Factors	Sum R_i	Sum C_j	$R_i + C_j$	$R_i - C_j$
A	7.259	7.185	14.445	0.074
B	6.464	6.968	13.432	-0.504
C	6.719	6.575	13.294	0.144
D	7.240	6.941	14.181	0.298
E	7.914	7.926	15.840	-0.012

Table 6. Inner-dependency matrix above threshold α = 1.424 (Challenges × Challenges)

Factors	A	B	C	D	E
A	-	1.451	-	1.453	1.659
B	-	-	-	-	1.500
C	-	-	-	-	1.533
D	1.503	1.441	-	-	1.650
E	1.637	1.605	1.503	1.584	1.584

Table 7. Cronbach's alpha (Challenges vs Challenges)

Items/Questions/Components, K	20
Sum of Item Variances, i	22.166
Variances of Total Scores, t	176.998
Cronbach's alpha	0.921

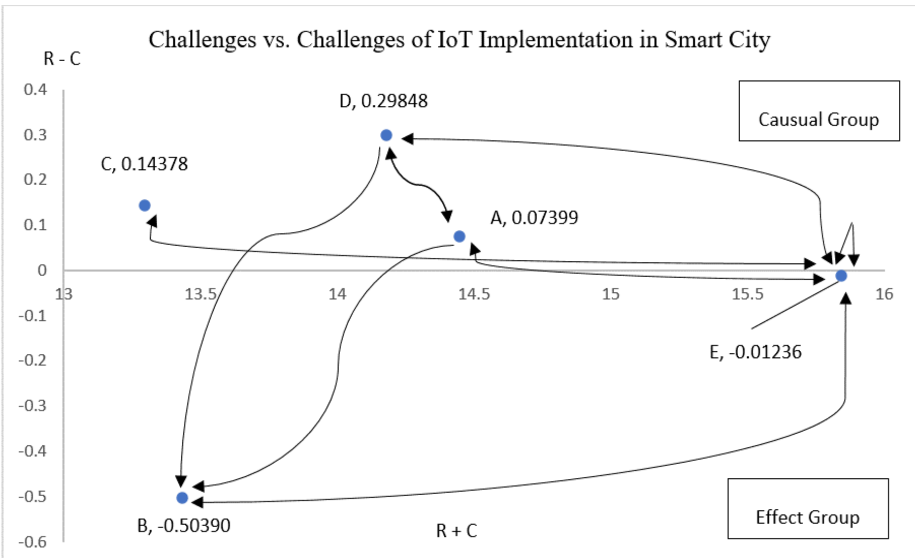

Fig. 1: Impact-direction diagram of Challenges vs Challenges of IoT Implementation in Smart City

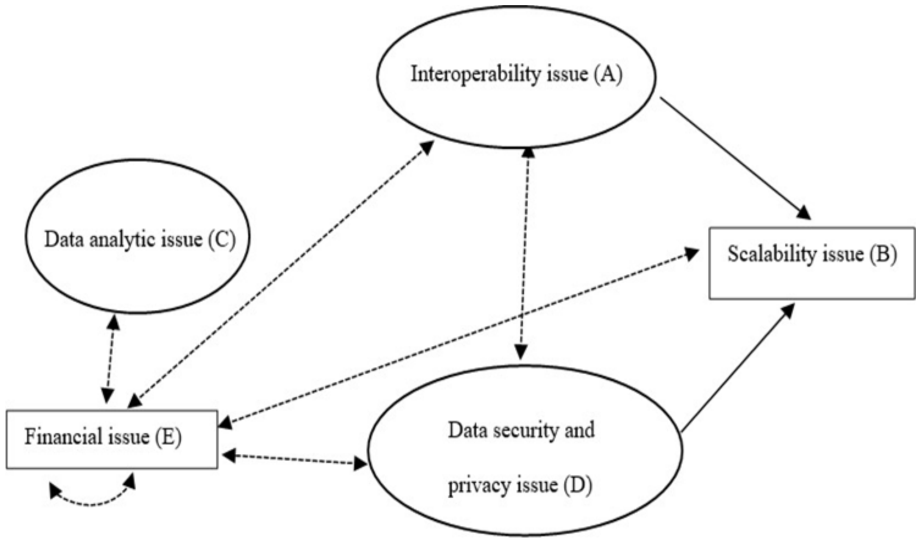

Fig. 2: Relationship Diagram of Challenges vs Challenges of IoT Implementation in Smart City

The Cronbach's alpha for this matrix was 0.921 (Table 7), indicating high internal consistency in expert ratings. As noted in Section 4.5, this is reported as a supplementary check rather than a substitute for DEMATEL-specific consensus measures. Reading Table 5, financial issues (E) recorded the highest prominence ($R_i + C_j = 15.840$), meaning that experts perceived this factor as the most active participant in the influence network. However, its net-relation value ($R_i - C_j = -0.012$) is close to zero and marginally negative, indicating that financial constraints are perceived as roughly as influential as they are influenced, with a slight tilt toward being an effect rather than a cause. A factor can therefore be highly prominent without being a strong perceived driver, a distinction frequently underused in DEMATEL applications. Financial constraints are pervasive across the system but are perceived as substantially shaped by other factors, an interpretation consistent with Popova (2020) and Gyimah et al. (2021), who argue that financial pressure in technology projects is partly downstream of technical and governance choices.

Data security and privacy (D) recorded the largest positive net-relation value ($R_i - C_j = 0.298$), making it the strongest perceived causal driver among the five challenges. Interoperability (A) and data analytics (C) also fall on the cause side, with small positive net values (0.074 and 0.144, respectively). Scalability (B) is the clearest perceived effect ($R_i - C_j = -0.504$). Table 6 shows above-threshold influence flowing from D and E to multiple other factors, and from A to D and E, suggesting reciprocal links between security, interoperability, and financial pressure.

These findings should be read as expert perceptions of causal structure rather than as objective causal facts. In the Malaysian panel's collective judgment, weaknesses in data security and privacy are seen as triggering downstream costs and integration difficulties, an interpretation consistent with prior arguments by Al-Turjman et al. (2022) and Liu et al. (2024).

5.3 DEMATEL Analysis II: Strategies versus Strategies

The same procedure was applied to the strategies. Tables 8 to 11 report the average, normalised, total-relation, and prominence and net-relation matrices, respectively. The threshold α was 2.336; Table 12 shows entries exceeding it; Cronbach's alpha was 0.901 (Table 13).

Table 8. Average direct-relation matrix Z (Strategies × Strategies)

Factors	F	G	H	I	J	SUM
F	0.000	2.520	2.480	3.320	3.080	11.400
G	2.160	0.000	2.240	2.240	2.640	9.280
H	2.520	2.360	0.000	2.720	2.440	10.040
I	2.960	2.160	2.840	0.000	2.680	10.640
J	3.080	2.360	2.680	2. 88	0.000	11.000
SUM	10.720	9.400	10.240	11.160	10.840	-

Table 9. Normalised direct-relation matrix D (Strategies × Strategies)

Factors	F	G	H	I	J
F	0.000	0.221	0.218	0.291	0.270
G	0.189	0.000	0.196	0.196	0.232
H	0.221	0.207	0.000	0.239	0.214
I	0.260	0.189	0.249	0.000	0.235
J	0.270	0.207	0.235	0.253	0.000

Table 10. Total relation matrix T (Strategies vs Strategies)

Factors	F	G	H	I	J
F	2.399	2.320	2.485	2.701	2.622
G	2.179	1.802	2.106	2.248	2.217
H	2.338	2.096	2.074	2.418	2.343
I	2.476	2.185	2.382	2.343	2.471
J	2.544	2.252	2.432	2.608	2.342

Table 11. Sum of Rows and Columns of Matrix T (Strategies vs Strategies)

Factors	Sum R_i	Sum C_j	$R_i + C_j$	$R_i - C_j$
F	12.527	11.936	24.463	0.591
G	10.552	10.656	21.208	-0.104
H	11.270	11.477	22.747	-0.208
I	11.856	12.318	24.174	-0.462
J	12.178	11.996	24.174	0.183

Table 12. Inner-dependency matrix above threshold α = 2.336 (Strategies × Strategies)

Factors	F	G	H	I	J
F	2.399	-	2.485	2.701	2.622
G	-	-	-	-	-
H	2.338	-	-	2.418	2.343
I	2.476	-	2.382	2.343	2.471
J	2.544	-	2.432	2.608	2.342

Table 13. Cronbach's alpha of Strategies vs Strategies

Items/Questions/Components, K	20
Sum of Item Variances, i	22.480
Variances of Total Scores, t	155.830
Cronbach's alpha	0.901

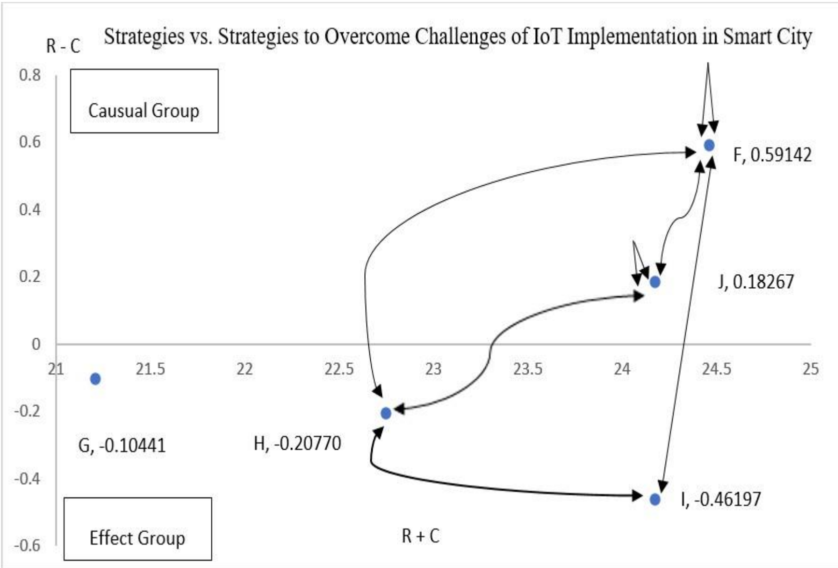

Fig. 3: Impact-direction Diagram of Strategies vs Strategies to Overcome the Challenge of IoT Implementation in Smart City

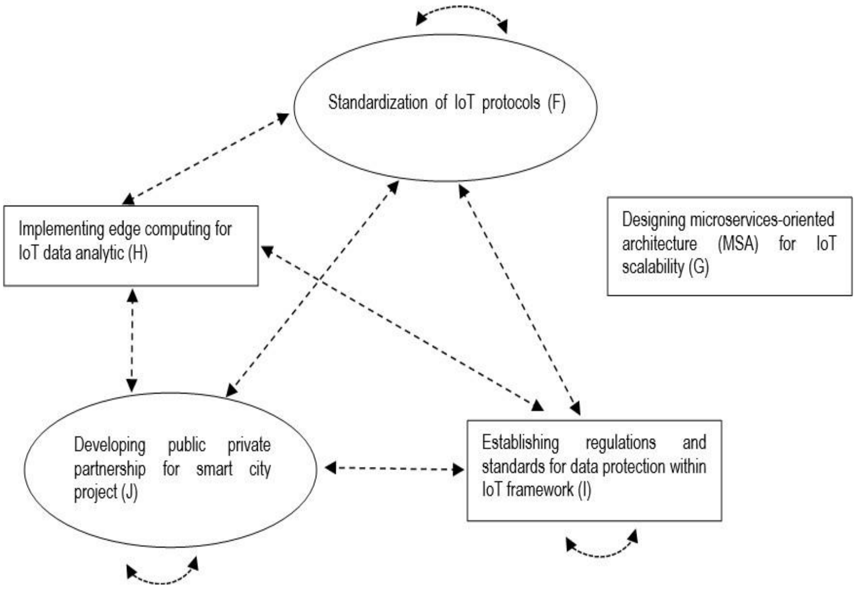

Fig. 4: Relationship Diagram of Strategies vs Strategies to Overcome the Challenge of IoT Implementation in Smart City

Standardisation of IoT protocols (F) recorded both the highest prominence ($R_i + C_j = 24.463$) and the largest positive net relation ($R_i - C_j = 0.591$), identifying it as the strongest perceived causal strategy among the five. Public–private partnerships (J) recorded a positive net relation (0.182) and high prominence (24.174), placing it as a secondary perceived driver. Microservices-oriented architecture (G), edge computing (H), and regulatory frameworks (I) fell on the effect side, indicating that they are perceived as shaped by other strategic choices, plausibly because their effectiveness depends on prior agreement on protocols and partnership arrangements.

Above-threshold linkages in Table 12 indicate that standardisation extends to edge computing, regulation, and PPPs, supporting the interpretation that standardisation serves as connective tissue across the strategy set. This pattern is consistent with arguments by Adepoju et al. (2025), Amjad et al. (2021), and Shahbazian (2023) that standardisation underpins both technical interoperability and policy convergence.

5.4 DEMATEL Analysis III: Strategies versus Challenges

The combined strategy–challenge analysis examined how each of the five strategies is perceived to influence each of the five challenges. Tables 14 to 18 report the corresponding matrices; the threshold α was 0.133; Cronbach's alpha was 0.964 (Table 19).

Table 14. Average direct-relation matrix Z (Strategies × Challenges)

Factors	F	G	H	I	J	A	B	C	D	E	SUM
F	0.000	2.520	2.480	3.320	3.080	3.320	2.880	2.800	2.720	2.760	25.880
G	2.160	0.000	2.240	2.240	2.640	2.320	2.480	2.000	2.240	2.800	21.120
H	2.520	2.360	0.000	2.720	2.440	2.640	2.240	2.560	2.880	3.160	23.520
I	2.960	2.160	2.840	0.000	2.680	3.000	2.440	2.520	3.080	2.800	24.480
J	3.080	2.360	2.680	2.880	0.000	2.800	2.840	2.680	2.800	3.320	25.440
A	0.000	0.000	0.000	0.000	0.000	0.000	2.480	2.480	2.600	3.080	10.640
B	0.000	0.000	0.000	0.000	0.000	2.280	0.000	1.680	2.160	3.080	9.200
C	0.000	0.000	0.000	0.000	0.000	2.480	2.040	0.000	2.400	2.760	9.680
D	0.000	0.000	0.000	0.000	0.000	2.760	2.360	2.480	0.000	3.000	10.600
E	0.000	0.000	0.000	0.000	0.000	3.000	3.200	2.800	2.920	0.000	11.920
SUM	10.720	9.400	10.240	11.160	10.840	24.600	22.960	22.000	23.800	26.760	-

Table 15. Normalised direct-relation matrix D (Strategies × Challenges)

Factors	F	G	H	I	J	A	B	C	D	E
F	0.000	0.094	0.093	0.124	0.115	0.124	0.108	0.105	0.102	0.103
G	0.081	0.000	0.084	0.084	0.099	0.087	0.093	0.075	0.084	0.105
H	0.094	0.088	0.000	0.102	0.091	0.099	0.084	0.096	0.108	0.118
I	0.111	0.081	0.106	0.000	0.100	0.112	0.091	0.094	0.115	0.105
J	0.115	0.088	0.100	0.108	0.000	0.105	0.106	0.100	0.105	0.124
A	0.000	0.000	0.000	0.000	0.000	0.000	0.093	0.093	0.097	0.115
B	0.000	0.000	0.000	0.000	0.000	0.085	0.000	0.063	0.081	0.115
C	0.000	0.000	0.000	0.000	0.000	0.093	0.076	0.000	0.090	0.103
D	0.000	0.000	0.000	0.000	0.000	0.103	0.088	0.093	0.000	0.112
E	0.000	0.000	0.000	0.000	0.000	0.112	0.120	0.105	0.109	0.000

Table 16. Total relation matrix T (Strategies vs Challenges)

Factors	F	G	H	I	J	A	B	C	D	E
F	0.064	0.142	0.146	0.177	0.168	0.310	0.286	0.275	0.285	0.310
G	0.128	0.046	0.128	0.132	0.143	0.245	0.242	0.219	0.237	0.274
H	0.143	0.131	0.054	0.151	0.141	0.271	0.249	0.252	0.273	0.303
I	0.160	0.128	0.153	0.062	0.151	0.290	0.263	0.258	0.287	0.300
J	0.165	0.136	0.150	0.161	0.062	0.291	0.281	0.268	0.284	0.323
A	0.000	0.000	0.000	0.000	0.000	0.059	0.142	0.138	0.145	0.169
B	0.000	0.000	0.000	0.000	0.000	0.130	0.050	0.106	0.125	0.161
C	0.000	0.000	0.000	0.000	0.000	0.139	0.123	0.049	0.134	0.153
D	0.000	0.000	0.000	0.000	0.000	0.152	0.138	0.138	0.056	0.166
E	0.000	0.000	0.000	0.000	0.000	0.165	0.169	0.153	0.160	0.072

Table 17. Sum of Rows and Columns of Matrix T (Strategies vs Challenges)

Factors	Sum R_i	Sum C_j	$R_i + C_j$	$R_i - C_j$
F	2.163	0.659	2.822	1.504
G	1.794	0.583	2.377	1.211
H	1.967	0.632	2.599	1.336
I	2.052	0.683	2.735	1.369
J	2.122	0.664	2.786	1.458
A	0.652	2.053	2.705	-1.400
B	0.572	1.942	2.515	-1.370
C	0.598	1.856	2.454	-1.257
D	0.650	1.988	2.638	-1.337
E	0.721	2.232	2.952	-1.511

Table 18. Inner-dependency matrix above threshold α = 0.133 (Strategies × Challenges)

Factors	F	G	H	I	J	A	B	C	D	E
F	-	0.142	0.146	0.177	0.168	0.310	0.286	0.275	0.285	0.310
G	-	-	-	-	0.143	0.245	0.242	0.219	0.237	0.274
H	0.143	-	-	0.151	0.141	0.271	0.249	0.252	0.273	0.303
I	0.160	-	0.153	-	0.151	0.290	0.263	0.258	0.287	0.300
J	0.165	0.136	0.150	0.161	-	0.291	0.281	0.268	0.284	0.323
A	-	-	-	-	-	-	0.142	0.138	0.145	0.169
B	-	-	-	-	-	-	-	-	-	0.161
C	-	-	-	-	-	0.139	-	-	0.134	0.153
D	-	-	-	-	-	0.152	0.138	0.138	-	0.166
E	-	-	-	-	-	0.165	0.169	0.153	0.160	-

Table 19. Cronbach's alpha of Strategies vs Challenges

Items/Questions/Components, K	65
Sum of Item Variances, i	69.962
Variances of Total Scores, t	1383.210
Cronbach's alpha	0.964

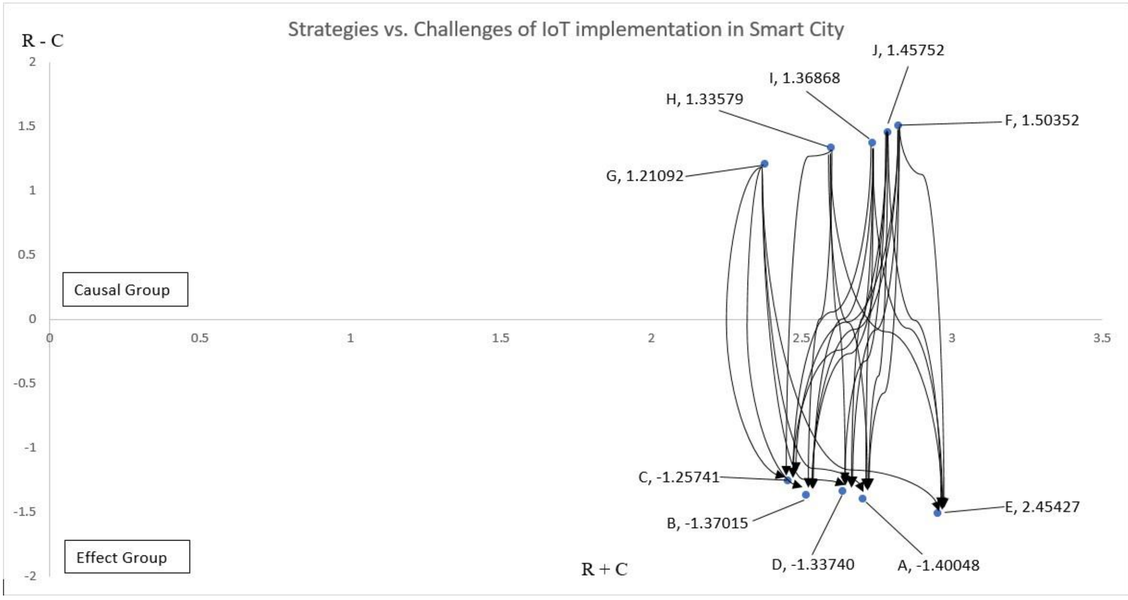

Fig. 5: Impact-direction diagram of Strategies versus Challenges of IoT implementation in a smart city

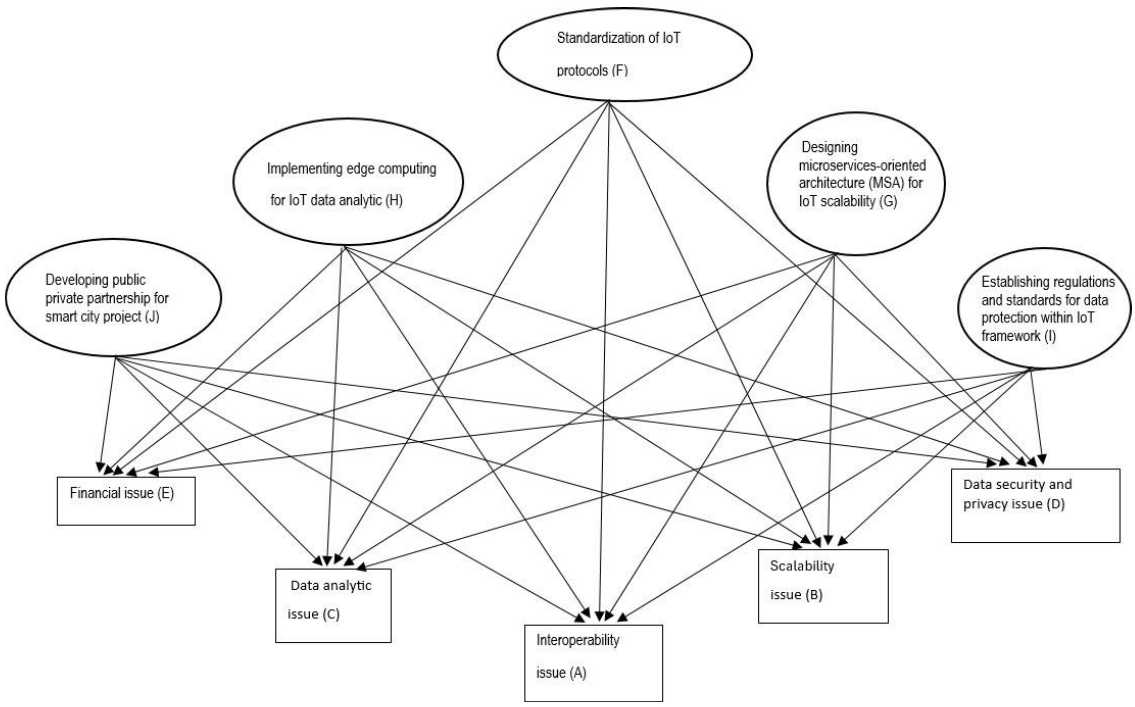

Fig. 6: Relationship diagram of Strategies vs Challenges of IoT Implementation in a smart city

Two patterns are evident. First, all five strategies recorded positive net-relation values, and all five challenges recorded negative net-relation values, confirming that the strategies are perceived collectively to act on the challenges rather than the reverse. Second, standardisation of IoT protocols (F) again recorded the strongest net influence ($R_i - C_j$ = +1.504), followed by PPPs (J, +1.458), regulatory frameworks (I, +1.369), edge computing (H, +1.336), and MSA (G, +1.211).

Tracing the above-threshold paths, standardisation exerts direct perceived influence on all five challenges, with the largest entries flowing to interoperability (A) and financial constraints (E). PPPs likewise reach all five challenges and have the largest perceived effect on financial constraints. Edge computing is most strongly perceived to affect data analytics and data security. Regulatory frameworks are perceived to have the greatest influence on data security and privacy. Across the three analyses, standardisation and PPPs are perceived within this panel as the strategies with the broadest influence, while data security and privacy are perceived as the most influential challenge to address first.

6.0 DISCUSSION

The DEMATEL analyses produced three findings that warrant careful interpretation.

6.1 Prominence versus Net Causality: The Financial-Constraint Paradox

An important feature of DEMATEL is the distinction between prominence ($R_i + C_j$) and net causality ($R_i - C_j$). Financial constraints recorded the highest prominence among challenges, but a near-zero, marginally negative net-relation value. In substantive terms, experts perceive financial pressure as ubiquitous in the system, touching and being touched by every other challenge, yet not as an independent root cause. Financial constraints appear to absorb pressure from upstream issues: weak data security inflates cost through risk management and trust-building, and poor interoperability inflates integration costs. The practical implication is that direct financial interventions, such as budget increases, may yield smaller systemic returns than upstream interventions in security and standardisation, because the financial problem partly reflects costs imposed by those upstream weaknesses. This interpretation is consistent with Popova (2020) and contrasts with simpler accounts that treat finance as a primary independent barrier.

6.2 Data Security and Privacy as a Perceived Driver

Among the five challenges, data security and privacy showed the strongest positive net relation, making it the strongest perceived causal driver in the panel's judgment. This is consistent with the broader literature on socio-technical IoT systems, which argues that trust and risk management shape the conditions under which other components can operate (Al-Turjman et al., 2022; Hussain, 2024; Liu et al., 2024). The result should be read as a recommendation grounded in expert-based DEMATEL findings rather than as an empirical causal law. The panel believes that addressing security and privacy first would relieve pressure elsewhere in the system, and this view is plausible in light of prior work; empirical validation using longitudinal project data would be needed to establish the corresponding causal claim.

6.3 Standardisation and PPPs as Cross-Cutting Strategies

The strategy analyses converge on standardisation of IoT protocols as the strongest perceived driver and PPPs as a strong secondary driver. The convergence is consistent with the socio-technical framework. Standardisation is a technical intervention with organisational consequences: it lowers integration costs (technical), enables shared procurement (financial), and provides a common reference for regulation (organisational). PPPs are an organisational intervention with technical and financial consequences. Both strategies span subsystems, in line with the framework's expectation that cross-cutting interventions exert broader influence. Strategies confined to a single subsystem, such as MSA and edge computing, appear as perceived effects rather than perceived causes.

6.4 Implication for Policy and Practice

The findings imply a sequence rather than a portfolio of equal-weight interventions: standardisation and data-protection regulation should be established early; PPP structures layered next to mobilise capital; and technical strategies such as edge computing and MSA deployed within this stabilised environment. National alignment with international IoT standards, such as ISO/IEC 30141, would support this sequence by reducing fragmentation, and embedding this alignment within Malaysia's existing smart city policy infrastructure would lower the cost of subsequent municipal-level deployments. These implications should be applied with caution outside the Malaysian context: features such as the concentration of expertise, the active role of GLCs, and an established yet still-evolving regulatory base shape the observed influence structure, and other institutional configurations may exhibit different patterns.

6.5 Interpretive Cautions

Three cautions discipline the interpretation. First, DEMATEL outputs are perceived influence structures derived from expert judgment; they are not measured causal effects. Second, the panel is small, predominantly male, and geographically concentrated, so the influence structure should be read as representing the views of senior IoT professionals operating in major Malaysian smart-city hubs rather than the views of all stakeholders. Third, the threshold α is computed as the mean of T; alternative threshold choices would produce slightly different digraphs without changing the prominence or net-relation rankings.

7.0 CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH

This study used DEMATEL to model the perceived causal structure linking five IoT implementation challenges and five strategic responses in Malaysian smart cities, drawing on the judgments of 25 practitioners and a socio-technical conceptual framework. Two patterns stand out. Among challenges, data security and privacy were the strongest perceived causal drivers. At the same time, financial constraints were the most prominent but largely receiving factor, a distinction with direct implications for how interventions are sequenced. Among strategies, standardisation of IoT protocols was the strongest perceived driver, with public–private partnerships acting as a strong secondary lever. Both span technical, organisational, and financial subsystems, consistent with the framework's expectation that cross-cutting interventions have the broadest perceived influence.

The study makes two conservative and specific contributions. First, it provides a Malaysia-focused, expert-based causal mapping of IoT challenges and strategies, a context-specific addition to a literature that has so far treated these factors largely in isolation. Second, it offers a DEMATEL-based prioritisation framework that policymakers, urban planners, and technology providers in similar settings can adapt when allocating limited resources. The framework supports sequencing rather than a uniform portfolio of interventions.

7.1 Limitations

Several limitations qualify the findings. The expert panel is relatively small (n = 25), is skewed toward male respondents from the private sector, and is geographically concentrated in Pulau Pinang, Kuala Lumpur, and Cyberjaya. Although the sample size is consistent with established DEMATEL practice, the demographic and geographic skew constrains generalisation to other

Malaysian states and to other countries. DEMATEL itself produces perceived influence structures rather than empirically tested causal effects, and is sensitive to threshold choice. Cronbach's alpha was used as a supplementary internal-consistency check; it is not a DEMATEL-specific consensus measure. The study analyses five challenges and five strategies; other plausible factors, such as skill shortages, political continuity, and cybersecurity workforce capacity, were excluded to keep the matrices tractable.

7.2 Future Research

Four extensions would strengthen the evidence base. First, the study could be replicated with larger and more demographically balanced expert panels, including public-sector and civil-society representatives, to test the robustness of the influence structure. Second, comparative DEMATEL studies in other countries, such as Indonesia, Vietnam, and the United Arab Emirates, would identify which features of the influence structure are common across contexts and which are Malaysia-specific. Third, fuzzy DEMATEL or grey DEMATEL variants could relax the assumption of crisp expert ratings and accommodate uncertainty in expert judgment. Fourth, mixed-method follow-up studies that combine DEMATEL with longitudinal case studies of specific projects would help distinguish perceived causal structures from empirically observable causal effects.

In sum, the study offers a careful, expert-grounded basis for sequencing IoT interventions in Malaysian smart cities. The findings are not claims about how IoT systems must work everywhere; they are a structured representation of how a panel of experienced Malaysian practitioners currently judges the relationships among the principal challenges and strategies they face.

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CONFLICTS OF INTEREST AND INFORMED CONSENT DECLARATIONS

The authors certify that they have no affiliations with, or involvement in, any organisation or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript. Informed consent was obtained from all participating experts, and responses were anonymised.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author on reasonable request.

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