CHEMICAL ENGINEERING TRANSACTIONS

VOL. 106, 2023

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

**ISBN** 979-12-81206-05-2; **ISSN** 2283-9216

DOI: 10.3303/CET23106118

# Blockchain-based Internet of Things Adoption for Smart Cities in Society 5.0: A Problematique Analysis

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This paper proposes a novel problematique analysis to understand the barriers in adopting blockchain-enabled Internet of Things (IoT) in smart cities. The method integrates the Bayesian best-worst method (BWM) with the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique and Interpretive Structural Modelling (ISM). The BWM is used to rank barriers based on their perceived urgency from the group of experts, while the integrated DEMATEL-ISM approach provides a structural model to capture the problem complexity, showcasing the interrelationships among the identified barriers through causal diagrams and hierarchical digraphs. This combination allows for a comprehensive metric to rank each barrier, considering both its inherent sense of urgency and its importance from strength of influence over other barriers. A numerical example is presented using a case study in Phnom Penh, Cambodia where the respondents highlight crucial barriers such as the inadequate government policy and regulatory framework on wider adoption of blockchain-IoT solutions as it drives interrelated challenges on scalability, interoperability, and integration of these technologies, and sustainability due to lack of financing and private investments. Through this transparent and systematic approach, policymakers and stakeholders can gain valuable insights to develop effective strategies or interventions for successful adoption of blockchain-based IoT in smart cities in line with Society 5.0 vision.

## 1. Introduction

By 2050, about two-thirds of the global population will live in cities (UNEP, 2018) and the rapid pace of urbanization has also brought forth many challenges, ranging from resource management to environmental sustainability. In response to these pressing issues, the concept of smart cities has emerged, which could leverage cutting-edge information and communication technologies (ICT) to create urban ecosystems that are efficient, connected, and sustainable, aiming for a high quality of life for its citizen (Tura and Ojanen, 2022). At the forefront of this transformation lie the Internet of Things (IoT) and blockchain technologies, poised to revolutionize how cities operate and evolve. The Internet of Things (IoT) represents a vast network of interconnected devices, objects, and processes that generate an unprecedented amount of data. In the context of smart cities, the IoT can provide real-time insights into various aspects of urban life, from energy consumption and transportation systems to waste management and public safety (Bellini et al., 2022). This wealth of data has the potential to drive evidence-based decision-making, optimize resource allocation, and enhance the quality of life for citizens. Blockchain technology, on the other hand, serves as a distributed and secure ledger that ensures transparency, privacy, and immutability (Majeed et al., 2021). By leveraging blockchain, smart cities can address critical challenges, such as lacking a transparent and trustworthy platform for citizen participation and collaboration among industries, organizations, and civil societies. Blockchain-based IoT solutions can incentivize active citizen involvement, foster cooperation, and promote sustainable practices in waste management, energy efficiency, and urban planning.

There are barriers and challenges in adopting blockchain-based IoT solutions in smart cities. To successfully integrate these transformative technologies, it is crucial to identify and understand the interrelationship of these barriers that hinder their implementation in the context of Society 5.0. Society 5.0 envisions a future where technology and human society coexist harmoniously, utilizing advanced technologies to overcome societal challenges. In this paradigm, smart cities are vital in achieving sustainability, resilience, and inclusivity. This

Paper Received: 29 May 2023; Revised: 24 July 2023; Accepted: 26 August 2023
Please cite this article as: Promentilla M.A.B., Kuok F., 2023, Blockchain-based Internet of Things Adoption for Smart Cities in Society 5.0: A Problematique Analysis, Chemical Engineering Transactions, 106, 703-708 DOI:10.3303/CET23106118

paper proposes a methodology through problematique analysis to examine these barriers and to shed light on the key barriers that could impede the widespread adoption of blockchain-based IoT solutions in smart cities.

## 2. Methodology

The proposed workflow for problem analysis is illustrated in Figure 1. The problematique is elucidated by identifying the barriers to adopting blockchain-based IoT for smart cities. The Bayesian Best-Worst Method provides the initial rank of the barriers based on their sense of urgency according to the perceptions of multiple stakeholders or experts. The novelty of the proposed problematique analysis allows us to integrate BWM with DEMATEL-ISM which provides a metric to compute the final weight and rank the barrier not only based on its inherent sense of urgency but also its strength of influence over the other barrier. The DEMATEL-ISM approach is used for the structural analysis of the barriers, as depicted in the causal diagram and hierarchical digraph.

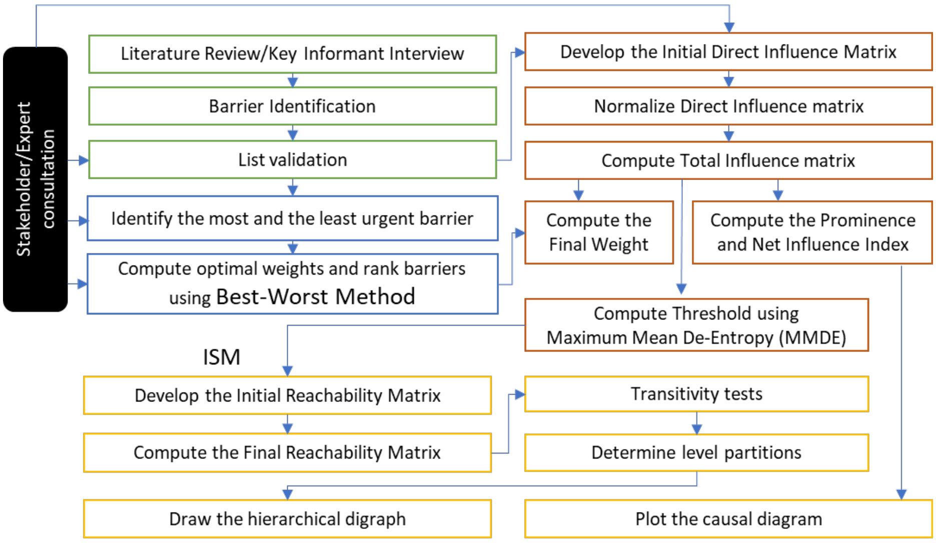


*Figure 1: Workflow for problematique analysis*

### 2.1 Bayesian Best Worst Method

Bayesian Best Worst method computes the priority weights of $n$ elements in a set from multiple decision makers by modelling the aggregated optimal weights as joint probability distribution described in Mohammadi and Rezaei (2020). Each decision maker provides ratings for $2n-3$ reference pairwise comparisons to derive the optimal weights. By first considering the” best” and “worst” element as a reference in the set and then comparing all the other elements, it provides a structure for more reliable pairwise comparisons. A weighted digraph can be used to visualize the credal ranking, which provides a confidence level based on the Dirichlet distribution of the aggregated weight [$w_i$] to measure the extent to which the group prioritizes one element over the other.

### 2.2 DEMATEL and Maximum Mean De-entropy (MMDE) algorithm

Fontela and Gabus (1972) developed the Decision Making Trial and Evaluation Laboratory (DEMATEL) technique to elucidate complex and interrelated problems through structural analysis. For brevity, the details of the procedure for DEMATEL are described elsewhere (e.g., see Kuok and Promentilla, 2021). DEMATEL starts with populating the direct influence matrix based on the aggregated rating of the decision makers (DM). The individual rating uses the 4-point intensity scale,i.e., no influence is zero and very high influence is 4.0. The average influence rating of barrier $i$ to $j$ is used to populate $i$th row and $j$th column of the matrix. The principal diagonal have 0’s since initially the barrier is not influenced by itself. Such initial direct influence matrix ($D$) is normalized by $s$, i.e., the largest row sum or the largest column sum of the matrix, whichever is greater. The total influence matrix accounts for both direct and indirect effects calculated from Eq(1) where $s$ is the normalization parameter, $I$ is the identity matrix and $t_{ij}$ in matrix $T$ describes the total influence of barrier $i$ to barrier $j$.

$$T = \frac{D}{s}\left(I - \frac{X}{s}\right)^{-1} = \begin{bmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{n1} & \cdots & t_{nn} \end{bmatrix} \tag{1}$$

The prominence index and net influence index from *T* are used to plot the causal diagram. The prominence index is the degree of the linkage of barriers in the network of interrelated problems. The sum of the row sum and column sum attributed to the barrier ($R_i + C_i$) is the prominence index while their difference ($R_i - C_i$) is the net influence index. The barrier belongs to the causal group if such a difference is positive. Otherwise, the barrier belongs to the effect group. From the total influence matrix, the threshold is also calculated using the maximum mean de-entropy (MMDE) method described in Li and Tzeng (2009). This threshold identifies the nodes (barriers) that significantly influence others and those significantly influenced by others. The threshold value is then used to generate the initial reachability matrix before developing the hierarchical digraph.

### 2.3 Interpretive Structural Modeling (ISM)

The ISM was developed in the 1970s by Warfield (1974) to draw out the interrelationship among a set of problems that transformed the unclear and poorly articulated mental models into articulated clear structural models. A recent scoping review of the literature by Ahmad and Qahmash (2021) indicates its varied applications in business, engineering, computer science, decision science, and social science, among others. For brevity, the detail of the technique is described elsewhere (e.g., see Ahmad and Qahmash, 2021). The initial reachability matrix describes the significant aggravation pathway from one barrier to another. The final reachability matrix is prepared by checking for transitivity. For example, if A aggravates B, and B aggravates C, then A aggravates C because of such transitive inference. The impact of A may be much greater than might appear as aggravation propagates all the way to B and C. The next step is to calculate the hierarchical level of the elements in the set through level partitioning, which is used to draw the digraph.

## 3. Numerical Example

The ASEAN region, with its burgeoning economic growth and dynamic urban landscapes, could benefit greatly from embracing smart city initiatives. For example, Phnom Penh City is a vibrant commercial hub that envisions integrating IoT and blockchain technologies in its smart city roadmap but adopting these technologies is not without its hurdles. Table 1 summarizes these barriers identified through literature review (Kuok and Promentilla, 2022) and then validated through key informant interview. Tables 2 and 3 provide the sample rating from four respondents, which were used to compute the initial group weights using Bayesian Best Worst Method. The respondents were experts affiliated from government agencies, think tank and academe who are knowledgeable on digital technologies and data management.

*Table 1: Identification of barriers*

| Label | Barriers |
|---|---|
| P01 | Lack of reliable energy supply and sustainable management of clean energy |
| P02 | Lack of industry standards and inadequate network infrastructure for integration and convergence of these technologies |
| P03 | Lack of trust due to data privacy and cybersecurity concerns |
| P04 | Lack of financing and private investments to demonstrate use cases for blockchain-based IoT solutions |
| P05 | Challenges on the market acceptance due to scalability and interoperability issues |
| P06 | Inadequate government policy and regulatory framework to enable the widespread adoption of blockchain-based IoT solutions |
| P07 | Lack of education and awareness of the technologies to encourage technical talent development |

Credal ranking according to the level of urgency the group perceived indicates P06 and P02 as the most and least pressing issues (see Figure 2). Barriers P06, P05, and P04 are ranked as the top three most critical barriers based on the final weights incorporating the total influence scores obtained from DEMATEL (see Table 4). P06 is both an urgent and most important barrier from the integrated BWM-DEMATEL method. Note that the final weight (priority vector $\bar{v}$ ) is computed from Eq(2) where $\bar{T}$ is the column sum-normalized total influence matrix, i.e., each column sum to 1, and *w* is the initial weight vector computed from BWM.

$$\bar{v} = \bar{T} \times w \tag{2}$$

*Table 2: Comparison of the most urgent barrier to the other barriers using a 9-point scale.*

| Respondent | P01 | P02 | P03 | P04 | P05 | P06 | P07 | *Most Urgent* |
|---|---|---|---|---|---|---|---|---|
| DM1 | 1 | 2 | 4 | 4 | 7 | 7 | 6 | P01 |
| DM2 | 9 | 9 | 6 | 3 | 1 | 2 | 1 | P05 and P07 |
| DM3 | 8 | 9 | 6 | 3 | 1 | 2 | 1 | P05 and P07 |
| DM4 | 7 | 9 | 1 | 9 | 8 | 2 | 9 | P03 |

*Table 3: Comparison of the other barriers to the least urgent barrier using a 9-point scale.*

| Respondent | P01 | P02 | P03 | P04 | P05 | P06 | P07 | *Least Urgent* |
|---|---|---|---|---|---|---|---|---|
| DM1 | 7 | 4 | 2 | 2 | 1 | 1 | 1 | P05, P06 and P07 |
| DM2 | 1 | 1 | 3 | 5 | 9 | 7 | 9 | P01 and P02 |
| DM3 | 2 | 1 | 4 | 6 | 9 | 8 | 9 | P02 |
| DM4 | 3 | 2 | 9 | 1 | 2 | 8 | 1 | P04 and P07 |

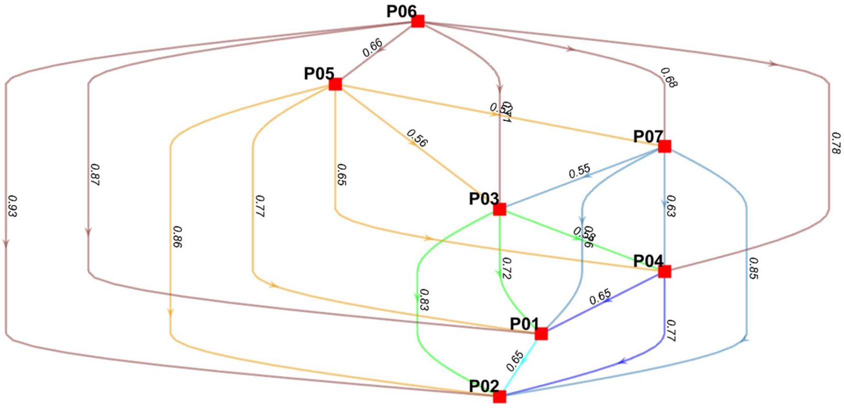


*Figure 2: Credal ranking of barriers from graphical output of Bayesian Best Worst method*

*Table 4: Summary of results from integrated BWM-DEMATEL*

| Label | BWM Weights | Initial Rank | Prominence Rank | Final Weight | Final Rank |
|---|---|---|---|---|---|
| P01 | 0.114 | 6 | 5 | 0.131 | 4 |
| P02 | 0.095 | 7 | 6 | 0.102 | 7 |
| P03 | 0.149 | 4 | 7 | 0.106 | 6 |
| P04 | 0.135 | 5 | 3 | 0.151 | 3 |
| P05 | 0.160 | 2 | 1 | 0.183 | 2 |
| P06 | 0.190 | 1 | 2 | 0.199 | 1 |
| P07 | 0.156 | 3 | 4 | 0.129 | 5 |

The initial direct relation score from the average rating of 4 respondents is shown in Table 5, which was used as input to calculate the total influence matrix (see Table 6) using Eq(1) where $s$ = 18.75. The prominence index and net influence index are also computed based on the values of the total influence matrix, as shown in Table 6.

*Table 5: Initial direct-influence matrix prior to normalization*

|  | P01 | P02 | P03 | P04 | P05 | P06 | P07 |
|---|---|---|---|---|---|---|---|
| P01 | 0.00 | 2.00 | 1.50 | 1.75 | 2.75 | 1.75 | 1.75 |
| P02 | 1.00 | 0.00 | 2.25 | 1.00 | 1.50 | 1.25 | 1.75 |
| P03 | 0.50 | 0.75 | 0.00 | 1.50 | 3.75 | 1.50 | 0.75 |
| P04 | 3.00 | 3.75 | 0.75 | 0.00 | 1.00 | 3.50 | 1.75 |
| P05 | 2.00 | 2.50 | 1.50 | 3.25 | 0.00 | 3.25 | 4.00 |
| P06 | 3.00 | 3.25 | 2.75 | 3.75 | 3.75 | 0.00 | 2.25 |
| P07 | 0.50 | 0.50 | 0.75 | 3.00 | 3.50 | 2.25 | 0.00 |

*Table 6: Total influence matrix for this case study and the computed prominence and net influence index*

| | P01 | P02 | P03 | P04 | P05 | P06 | P07 | R | C | [Ri+Ci][a] | [Ri-Ci][b] | Net Influence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P01 | 0.17 | 0.31 | 0.23 | 0.32 | 0.38 | 0.31 | 0.29 | 2.01 | 1.81 | 3.82 | 0.20 | Causal |
| P02 | 0.17 | 0.15 | 0.23 | 0.23 | 0.27 | 0.23 | 0.24 | 1.51 | 2.25 | 3.76 | -0.74 | Effect |
| P03 | 0.17 | 0.22 | 0.13 | 0.27 | 0.38 | 0.26 | 0.22 | 1.65 | 1.66 | 3.32 | -0.01 | Effect |
| P04 | 0.34 | 0.42 | 0.23 | 0.27 | 0.34 | 0.41 | 0.32 | 2.33 | 2.46 | 4.79 | -0.13 | Effect |
| P05 | 0.34 | 0.41 | 0.29 | 0.48 | 0.35 | 0.46 | 0.47 | 2.79 | 2.65 | 5.44 | 0.14 | Causal |
| P06 | 0.40 | 0.48 | 0.37 | 0.52 | 0.55 | 0.34 | 0.42 | 3.09 | 2.35 | 5.44 | 0.74 | Causal |
| P07 | 0.21 | 0.25 | 0.19 | 0.38 | 0.40 | 0.34 | 0.21 | 1.98 | 2.18 | 4.16 | -0.19 | Effect |

[a]Prominence index [b]Net Influence Index

Figure 3a shows the causal diagram where barriers in quadrants I and II are causal or have a positive net influence index, whereas barriers in quadrants III and IV with negative net influence index are effect barriers. Barriers P06 and P05 are key causal barriers that are strongly linked (QI) in contrast to causal barriers in QII (e.g., P01) that are independent or weakly linked to other barriers. Likewise, the barriers in QIII (e.g., P02, P07, and P03) are effect barriers that are autonomous, while P04 (QIV) is a strongly linked effect barrier. To plot the significant impact relation map for interpretability, a threshold value of 0.4768 is computed from the MMDE algorithm. This method identified the necessary nodes and edges for the digraph attributed to barriers P02, P04, P05, and P06. This threshold value was also used to prepare the initial reachability matrix for ISM. The total relation matrix is filtered and transformed to a binary matrix such that the value is 1 in the $i^{th}$ row and $j^{th}$ column of the matrix if the total influence score is equal to or greater than the threshold value, otherwise, the value is 0. Members of the set that will not be included in creating the digraph are removed, and transitive relations are checked to prepare the final reachability matrix. A reduced conical matrix is also prepared after level partitioning to remove possible edges to improve the interpretability of the final ISM model while maintaining the level and without affecting the structure. Figure 4 describes the process of developing the ISM hierarchical directional structure among barriers in Figure 3b. From the final reachability matrix, level partitioning was done by identifying the members of the reachability set and antecedent sets. The reachability set consists of itself and the barriers it influences, while the antecedent set consists of itself and all the barriers influencing it. The intersection set of reachability and the antecedent set is then identified. Barriers with the same reachability and intersection sets are assigned to Level 1 and are removed from the next iteration. The process is repeated until all barriers are partitioned into levels (see Figure 4d) and used to create the digraph. From the aggregation of poorly articulated mental models of the group, such digraph can be used for an interpretive well-structured, and easily communicated model. Based on such problematique analysis, the top three key barriers are interrelated such that the intervention should focus on inadequate government policy and regulatory framework (P06) as it aggravates the challenges on market acceptance due to scalability and interoperability (P05) and lack of financing and private investments (P04). Policies which promote scalability and interoperability would affect the technical design and implementation of blockchain-driven IoT solutions for smart cities.

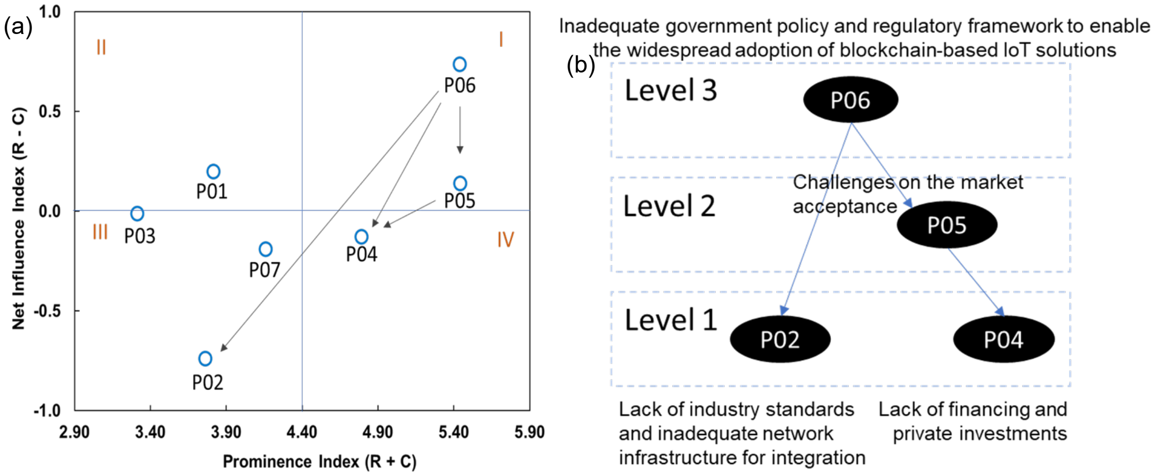
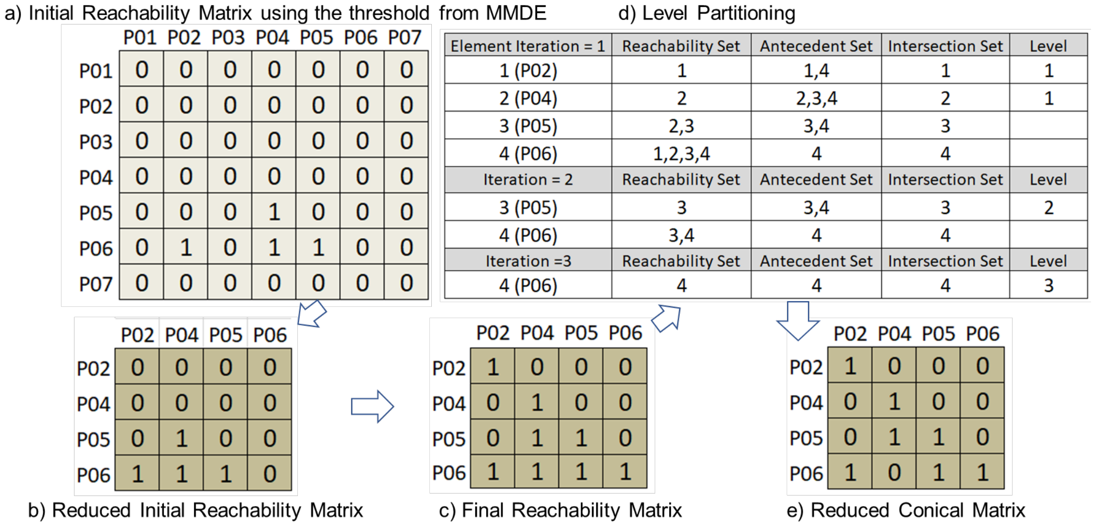


*Figure 3: Graphical output from the integrated DEMATEL-ISM method using MMDE-based threshold (a) Casual diagram from DEMATEL and (b) Hierarchical model from ISM*



a) Initial Reachability Matrix using the threshold from MMDE

| | P01 | P02 | P03 | P04 | P05 | P06 | P07 |
|---|---|---|---|---|---|---|---|
| P01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| P05 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| P06 | 0 | 1 | 0 | 1 | 1 | 0 | 0 |
| P07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

d) Level Partitioning

| Element Iteration = 1 | Reachability Set | Antecedent Set | Intersection Set | Level |
|---|---|---|---|---|
| 1 (P02) | 1 | 1,4 | 1 | 1 |
| 2 (P04) | 2 | 2,3,4 | 2 | 1 |
| 3 (P05) | 2,3 | 3,4 | 3 | |
| 4 (P06) | 1,2,3,4 | 4 | 4 | |
| Iteration = 2 | Reachability Set | Antecedent Set | Intersection Set | Level |
| 3 (P05) | 3 | 3,4 | 3 | 2 |
| 4 (P06) | 3,4 | 4 | 4 | |
| Iteration =3 | Reachability Set | Antecedent Set | Intersection Set | Level |
| 4 (P06) | 4 | 4 | 4 | 3 |

b) Reduced Initial Reachability Matrix

| | P02 | P04 | P05 | P06 |
|---|---|---|---|---|
| P02 | 0 | 0 | 0 | 0 |
| P04 | 0 | 0 | 0 | 0 |
| P05 | 0 | 1 | 0 | 0 |
| P06 | 1 | 1 | 1 | 0 |

c) Final Reachability Matrix

| | P02 | P04 | P05 | P06 |
|---|---|---|---|---|
| P02 | 1 | 0 | 0 | 0 |
| P04 | 0 | 1 | 0 | 0 |
| P05 | 0 | 1 | 1 | 0 |
| P06 | 1 | 1 | 1 | 1 |

e) Reduced Conical Matrix

| | P02 | P04 | P05 | P06 |
|---|---|---|---|---|
| P02 | 1 | 0 | 0 | 0 |
| P04 | 0 | 1 | 0 | 0 |
| P05 | 0 | 1 | 1 | 0 |
| P06 | 1 | 0 | 1 | 1 |

*Figure 4: Sample output from the ISM method to develop the hierarchical digraph.*

## 4. Conclusions

Through a rigorous problematique approach, this study utilizes the Bayesian best-worst method (BWM) to rank the identified barriers based on the perceived sense of urgency from multiple stakeholders. An integrated framework of the DEMATEL method and ISM is applied to analyse the interrelationships among these barriers and their hierarchical structure. By employing a case study in Cambodia, the proposed methodology illustrates practical insights that can inform policy initiatives, driving the widespread adoption of blockchain-based IoT as a platform for sustainable smart cities.

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