ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

Comparison of Asset Management Approaches to Optimize Navigable Waterway Infrastructure

Bukola Oni[1]*, Katherine Madson, Ph.D.[2], Cameron MacKenzie, Ph.D.[3]

[1] *Department of Civil, Construction, and Environmental Engineering, Iowa State University, 394 Town Engineering, 813 Bissell Road, Ames, 50011 IA, USA,* E-mail address: boni@iastate.edu
[2] *Department of Civil, Construction, and Environmental Engineering, Iowa State University, 394 Town Engineering, 813 Bissell Road, Ames, 50011 IA, USA,* E-mail address: kmadson@iastate.edu
[3] *Department of Industrial and Manufacturing Systems Engineering, Iowa State University, 3004 Black Engineering, Ames, 50011 IA, USA,* E-mail address: camacken@iastate.edu

Abstract: An estimated investment gap of $176 billion needs to be filled over the next ten years to improve America's inland waterway transportation systems. Many of these infrastructure systems are now beyond their original 50-year design life and are often behind in maintenance due to funding constraints. Therefore, long-term maintenance strategies (i.e., asset management (AM) strategies) are needed to optimize investments across these waterway systems to improve their condition. Two common AM strategies include policy-driven maintenance and performance-driven maintenance. Currently, limited research exists on selecting the optimal AM approach for managing inland waterway transportation assets. Therefore, the goal of this study is to provide a decision model that can be used to select the optimal alternative between the two AM approaches by considering key uncertainties such as asset condition, asset test results, and asset failure. We achieve this goal by addressing the decision problem as a single-criterion problem, which calculates each alternative's expected value and certain equivalence using allocated monetary values to determine the recommended alternative for optimally maintaining navigable waterways. The decision model considers estimated and predicted values based on the current state of the infrastructure. This research concludes that the performance-based approach is the optimal alternative based on the expected value obtained from the analysis. This research sets the stage for further studies on fiscal constraints that will effectively optimize these assets condition.

Keywords: inland waterways, asset management, single-criterion, decision model.

1. INTRODUCTION

In recent years, there has been a decline in investment in public infrastructure across the U.S., resulting in an estimated gap of more than $176 billion for inland waterway (IWW) infrastructure (including navigable channels, locks, and ports) [1]. These IWWs are one of the nation's critical capital assets that contribute to a sustainable economy [2]. The investment gap has resulted in assets that are more than 50 years beyond their original design life and are severely deteriorating [3]–[5]. If a lack of investment continues, existing IWW infrastructure degradation will continue [5], and shipping delay times will continue to increase [3], [6]. Despite this degradation, IWW usage is increasing daily [7], indicating sufficient demand for these systems and that IWW maintenance should be prioritized. IWW offers shippers benefits such as improved safety over other means of transportation and reduced cargo shipping costs [8].

Developing an appropriate asset management (AM) practice is vital to ensuring the longevity of these IWW assets. AM is the practice of managing infrastructure assets through processes such as decision-making to deliver services that consider present and future needs, risk and opportunity management, and resource optimization [9], [10]. AM can be implemented through a variety of approaches, and the decision-maker (DM) is often left to determine the preferred AM approach, which can be challenging. The DMs on any infrastructure project have to provide answers to questions regarding infrastructure optimization, cost, and the preferred method for achieving maintenance goals. Although effective AM practice is valuable for risk management, building and enhancing resilience, decision optimization, and projects with budget constraints, government agencies have not fully identified the best approach for managing infrastructure assets [9], [11]. Compounding upon this, infrastructure decay and funding constraints pose a major challenge for DMs [7]. Yet, there is no substantial literature to support AM approaches on IWW. Therefore, it is essential to assess maintenance approaches to understand the challenges that come with aging IWW infrastructure and low investment [5], [7], [18].

The primary objective of this study is to analyze the challenge of deciding between two commonly used AM approaches for IWW assets maintenance. The decision analysis comprises the evaluation of two major AM alternatives: Policy-based AM and Performance-based AM. This analysis is done by developing a model in which the problem is viewed as a single-criterion problem that calculates each alternative's expected value and certain equivalence using allocated monetary values.

2. LITERATURE REVIEW

2.1. Decision-making

Decision-making is a key part of infrastructure AM [12], which involves choosing a suitable alternative based on the DM’s values and preferences [13], [14]. According to Arif and Bayraktar [5], assessing maintenance investment decision-making practices (in addition to increased funding) is essential for potential infrastructure improvements. Physical condition is a major decision parameter when considering these investments [5]. Poor condition can lead to needing either maintenance, repair, and rehabilitation [5]. Decision problems can be treated as a single criterion model (e.g., [15]), which are effective as a final decision-making tool for producing an optimal solution based on the objective’s best value and constraints [13] or a multi-objective model (e.g., [2], [16]) for obtaining likely trade-offs [17].

2.2. Utility Function

Utility measures the individual satisfaction derived by consuming goods or services [15], [19]. A utility function then refers to a mathematical method for evaluating preferences [19]. Utility functions depend on the risk attitude of the DM with regard to profit, loss, and risk in quantifying value [13], [20]. The risk attitude of a DM in any decision problem can be risk preferred/risk loving (risk odds[r] <1), risk-averse ($r > 1$), or risk-neutral ($r = 1$) [14], [15]. The value that a risk-averse DM places on an uncertain deal is less than the expected monetary value of that deal [14]. The risk-preferred, risk-averse, and risk-neutral attitude is represented by convex, concave, and linear utility functions, respectively [14]. Multiple utility functions can be employed, such as linear, quadratic, logarithmic, power, and exponential utility [21]. Furthermore, the utility function is used to calculate the expected value of each available alternative and convert it to a monetary value [22]. The monetary value is a certain equivalent (CE), which helps to accurately determine the best alternative based on the estimated cost for each process [22]. Maximizing utility is achieved through decision-making [14]. Thus, assessing uncertainties and associated risk upgrades the quality of decisions despite increasing the decision-making complexity [13].

3. METHODOLOGY AND MODEL DEVELOPMENT

The U.S. IWW system, which is approximately 25,000 miles [3], is operated and maintained by the United States Army Corps of Engineers (USACE) [18], [23]. Construction and maintenance of the locks and dams on the IWW are done by the USACE and are funded on a 50:50 basis from Congress' annual appropriation to the Inland Waterways Trust Fund and from general revenue [5],[15],[16]. According to the United States Government Accountability Office [18], construction projects, including rehabilitation of locks and dams on IWWs, are prioritized using the expected costs and benefits.

In this study, we evaluated two common AM approaches for maintaining IWW infrastructure, such as a lock, on the Illinois Waterway. These included policy-based and performance-based maintenance strategies (see [25] for a full list of AM approaches). In case studies performed and described in [4], the researchers observed that the USACE most commonly adopts a maintenance strategy similar to the policy-based approach. With this knowledge, we developed two scenarios to determine if this is the optimal approach for IWW lock maintenance or if the performance-based approach would be more optimal.

Scenario 1, Policy-Based Approach. Maintenance of the IWW infrastructure occurs at set time intervals, which can vary based on government policies. In this example, a five-year time frame is considered for routine maintenance. At the end of five years, the lock either needs repair or rehabilitation by the end of the time frame, or else preventative maintenance is performed. This approach prioritizes the evaluation of investment costs and subsequent benefits.

Scenario 2, Performance-Based Approach. In this scenario, maintenance of the IWW occurs based on set measures and objectives. These include the results of performance testing (performed at two years intervals) which provides insight into the physical condition of these assets. The decision maker can either conduct maintenance or delay that maintenance based on condition.

3.1. Assumptions and Preferences

Preferences help to accurately depict what the DM wants and how the DM would fulfill their demand [14]. The preferences of the USACE and assumptions made in this study are outlined below. These include:

i. Asset condition is constant over a period based on the present condition of infrastructure and does not improve without external control [26].
ii. The probability of asset failure within a given time interval increases based on asset age [26].
iii. DM has a risk-averse attitude [3] which describes how they prioritize projects.

3.2. Uncertainties

AM methods are affected by three major uncertainties: asset condition, test results, and asset failure [26]. When considering IWW components, we recognize that various uncertainties abound that can influence decision-making [27]. Hence, we consider two of these major uncertainties, including asset condition and asset failure. In this study, the performance test results provided insight into the asset condition.

Asset Condition. When evaluating an IWW asset via performance testing, the test results are used to determine the condition of an asset. This condition enables some level of operational productivity. The condition can be either good (productivity level <80%), fair (productivity level 50% - 79%), or poor (productivity <50%).

Asset Failure. Catastrophic failure can occur at any point, even when the infrastructure is in good condition. In this circumstance, this could be a result of an unexpected accident. The risk increases as the condition rating decreases from good to poor. Based on continual testing, the risk of failure is re-evaluated every two years within this model.

3.3. Case study

We frame the decision problem as a decision tree simplified in Figure 1. The DM has to decide whether to invest in maintenance or wait depending on the asset condition. Furthermore, the DM has to decide between repairing and rehabilitating the asset if a failure occurs.

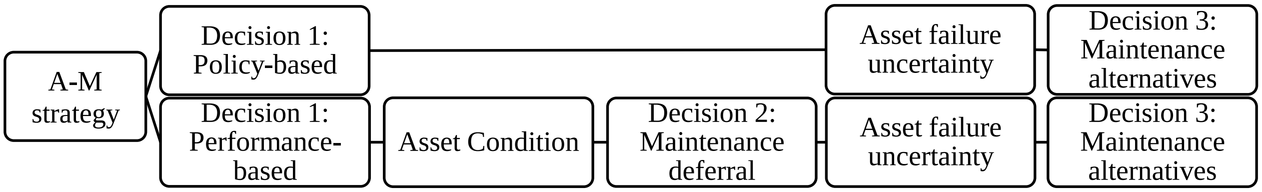

Figure 1. Decision Tree

We can calculate the expected utility value (*E(u))* of each decision path by inputting cost values (x) into a utility function. The utility function was developed by incorporating the alternatives, uncertainties, and the DM's risk attitude [13], shown in equations (1) – (3). To determine the extent of their risk tolerance, we then determined the point at which the DM is indifferent at 'q' chance of gaining 'm' and '$1-q$' chance of losing 'm' (equation 2). The risk attitude of the DM was then assessed using the risk odds, r (equation 2) to calculate the risk aversion coefficient (γ) obtained from (2), towards choosing the optimal alternative between the AM approaches. In this case, a risk-averse DM is unwilling to risk \$100 million if the loss odds are greater than 5%, as shown in Table 1. This means that the DM is indifferent for an uncertain deal with a 95% (q) chance of earning \$100M (m) and a 5% chance of losing \$100M. This is also equivalent to a DM being indifferent between gaining \$0 with 100% certainty and a 50% chance of gaining \$34M (risk tolerance) and a 50% chance of losing \$17M.

$$E(U) = 1 - exp(-\gamma x) \tag{1}$$

$$\gamma = ln\,(r) = ln\left[\frac{q}{1-q}\right]^{1/m} \tag{2}$$

$$E(U) = 1 - exp(0.0294x) \tag{3}$$

Table 1. Decision Parameters

Parameters	Values
m (\$)	100,000,000
q	95%
Risk odds (r)	1.03
Risk tolerance	33,960,000

To determine the total cost on each path (x in equation 3), the cost of each action the DM could take had to be determined. These were obtained from [28] and [29] and included: traditional maintenance cost of \$113,110,000, repair cost of \$240,000,000, and rehabilitation cost of \$200,000,000. Testing to determine the asset condition costs \$200,000 each time. We assumed that the test results would show a 58% chance of performing up to expectation (good condition), a 30% chance of being in fair condition, and a 12% chance of not functioning well (poor condition) (Table 2). These probabilities were chosen based on the assumptions that there is a direct proportionality of the probability of asset failure to the ages of the asset [26], that locks on Illinois waterway have exceeded their lifespan, and that maintenance was done recently [4]. Additionally, other outcomes with probabilities indicated in Table 2 are assigned strategically using Bayes' theorem and based on the asset condition. For instance, a good condition indicates a low chance of asset failure. In this research, we assume that failure of the lock is most likely to occur from miter gate failure. Dang et al. [30] determined that there is a 4% chance of failure for a miter gate that is 50 years old. We then assume a gate of this age is in fair condition. Once the utility function and associated costs were defined, and the probabilities were established, the decision tree could be evaluated. This was done by rolling back the decision tree, where the optimal decision was made by calculating from the opposite direction and selecting the most economic option. Recognizing the speculation in these probabilities, we performed a sensitivity analysis to determine the impact of changing risk attitude and uncertainty on the optimal decision.

Table 2. Probabilities of Outcomes

Alternatives	Condition	P(u) (%)	Alternatives	Asset Failure Potential and Probability P(u) (%)
Policy-based				Failure (4%) / No failure (96%)
Performance-based	Good	57.8	*Maintain*	Failure (0.014%) / No Failure (99.99%)
			Wait	Failure (0.3%) / No Failure (99.7%)
	Fair	30	*Maintain*	Failure (0.2%) / No Failure (99.8%)
			Wait	Failure (4%) / No Failure (96%)
	Poor	12.2	*Maintain*	Failure (1.6%) / No Failure (98.4%)
			Wait	Failure (21.3%) / No Failure (78.7%)

4. RESULTS AND DISCUSSION

The results in Table 3 indicate the optimal decision for optimizing IWW assets under each scenario and whether the USACE should repair, rehabilitate, or wait depending on if assets fail or not. Based on the aforementioned conditions, the CE represents the total cost of each AM approach if it were employed. The policy-based AM requires a higher maintenance cost of approximately $126 million for maintaining the assets every five years. Under the policy-based approach, results show that assets should be rehabilitated if assets fail, and scheduled maintenance conducted if there is no failure.

The optimal alternative for the decision model is the performance-based AM, which has a minimum CE of roughly $93 million expended on maintenance of infrastructure assets. Based on these conditions, the performance-based AM approach should be adopted for infrastructure assets management as it requires the lowest cost. The cost of adopting this approach is 26% lower than the cost incurred using the policy-based AM, which is attributed to being able to determine the condition of the asset prior to maintenance events. In the policy-based approach, the USACE has to rehabilitate or maintain irrespective of failure since the maintenance schedule should not be delayed. Furthermore, the lower value of the performance-based approach depicts that the assets should be maintained if the test condition is fair or poor, and the USACE can wait to invest in the infrastructure if the results show a good condition. As expected, results indicate that the assets should be further rehabilitated upon failure regardless of the condition.

Table 3. Summary of results obtained from the decision analysis

Decision 1	Condition	Decision 2	Asset Failure	Decision 3	CE($M)
Policy-based	-	-	Failure	Rehabilitate	126
			No Failure	Maintain	

Performance-based	Good	Wait	Failure	Rehabilitate	93
			No Failure	Wait	
	Fair	Maintain	Failure	Rehabilitate	
			No Failure	Wait	
	Poor	Maintain	Failure	Rehabilitate	
			No Failure	Wait	

5. SENSITIVITY ANALYSIS

We conducted a series of sensitivity analyses to determine the impact of our assumptions on the model to better understand the relationship between the input and the output of our model [7]. These included evaluating the risk aversion and the probability of asset failure.

Risk attitude. To determine the impact of assuming a risk-averse DM, results for the risk-neutral scenario were also tabulated. The expected costs of the policy-based and performance-based AM approaches are approximately $116 million and $8 million, respectively. As such, the optimal alternative is still the performance-based AM. Therefore, if the DM is more risk-neutral, the recommended approach is the performance-based A-M approach with lower maintenance cost due to cost savings on the maintenance process when the recommended decision is to wait.

Probability of asset failure. The probability of failure for the performance-based and the policy-based AM approach can be assumed to be equal when the DM waits to maintain an asset in fair condition. Therefore, the probability of failure at this point can be directly compared.

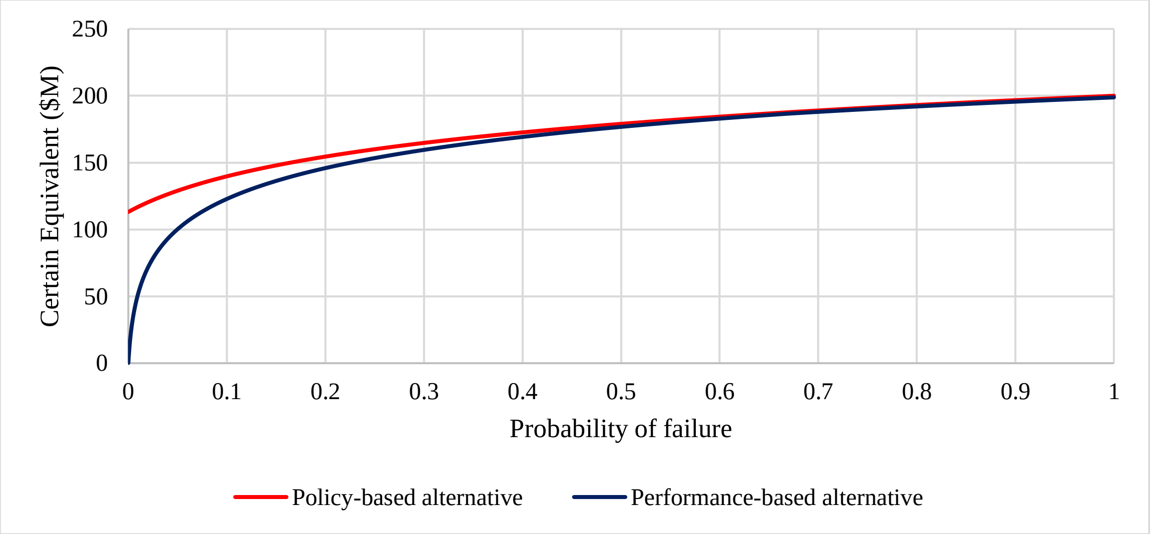

Figure 2. Sensitivity to the probability of failure

Figure 2 shows the sensitivity of the AM approaches to changes in the probability of failure. In this case, if the probability of failure is greater than 60%, either approach can be adopted. However, the performance-based approach still proves to be the optimal choice with a lower cost.

6. CONCLUSION AND RECOMMENDATIONS

This study aimed to compare two AM approaches, including policy-based and performance-based maintenance. The developed model considers estimated and predicted values based on the current state of the infrastructure as obtained from existing literature. This model is significant in the decision-making process because it provides the optimal approach to maintenance when considering the uncertainties involved and the risk attitude of the DM. Furthermore, the expected value obtained represents the appropriate maintenance decisions made repeatedly over time for a risk-neutral DM.

From the analysis in this study, the authors recommend that tests be conducted before maintenance, as seen in the performance-based approach. These tests help determine the extent of degradation of these assets and consequently enable the DM to incur a lower cost of maintenance.

Based on both risk-neutral and risk-averse scenarios, the performance-based approach is beneficial through reduced cost, improved condition of assets, reduced risk, and indirect increased protection. This research contributes to the body of knowledge supporting the need for performance-based maintenance approaches. Further research is needed to better identify the risk odds considered in this study, and more in-depth scenarios could be run to determine how to integrate this across the entire IWW system.

REFERENCES

[1] ASCE, “A Comprehensive Assessment of America’s Infrastructure,” American Society of Civil Engineers (ASCE), 2021.

[2] C. A. MacKenzie, K. Barker, and F. H. Grant, “Evaluating the Consequences of an Inland Waterway Port Closure with a Dynamic Multiregional Interdependence Model,” *IEEE Trans Syst Man Cybern A*, vol. 42, no. 2, pp. 359–370, 2012.

[3] American Society of Civil Engineers (ASCE), “2017 Infrastructure Report Card,” ASCE, 2017.

[4] B. Oni and K. Madson, “Improved Project Planning Strategies for Transportation Assets: The Necessity of Early Stakeholder Involvement,” presented at the CI and CRC Joint Conference, Virginia, 2022.

[5] F. Arif and M. E. Bayraktar, “Current Practices of Transportation Infrastructure Maintenance Investment Decision Making in the United States,” *J. Transp. Eng. Part Syst.*, vol. 144, no. 6, p. 04018021, 2018.

[6] S. Zhang, H. Lee, and R. Homer, “Dynamic Decision Modeling for Inland Waterway Disruptions,” University of Arkansas, 2017.

[7] Z. Dowd, A. Y. Franz, and J. S. Wasek, “A Decision-Making Framework for Maintenance and Modernization of Transportation Infrastructure,” *IEEE Trans. Eng. Manag.*, vol. 67, no. 1, pp. 42–53, 2020.

[8] H. Baroud, K. Barker, J. E. Ramirez-Marquez, and C. M. Rocco S., “Importance measures for inland waterway network resilience,” *Transp. Res. Part E Logist. Transp. Rev.*, vol. 62, pp. 55–67, 2014.

[9] Alberta Municipal Affairs, “Building community resilience through asset management: a handbook & toolkit for Alberta municipalities,” Municipal Affairs, Edmonton, Guide, 2015.

[10] ASCE, “Changing the Infrastructure Equation: Using Asset Management to Optimize Investments,” American Society of Civil Engineers (ASCE), 2019. [Online]. Available: www.asce.org/govrel

[11] J. M. Giglio, J. H. Friar, and W. F. Crittenden, “Integrating lifecycle asset management in the public sector,” *Bus. Horiz.*, vol. 61, no. 4, pp. 511–519, 2018.

[12] L. Chen and Q. Bai, “Optimization in Decision Making in Infrastructure Asset Management: A Review,” p. 30, 2019.

[13] V. Liubchenko, “Risk-Oriented Approach in Multi-Criteria Decision- Making,” p. 11, 2020.

[14] S. Devi, M. M. Nayak, and S. Patnaik, “A Study on Decision Making by Estimating Preferences Using Utility Function and Indifference Curve,” in *Intelligent and Cloud Computing*, Singapore, 2021, vol. 194, pp. 373–385.

[15] L. Ye, J. Yao, X. Ouyang, X. Zhu, and S. Yang, “Risk Analysis and Utility Function-Based Decision-Making Model for Spinning Reserve Allocations,” *IEEE Access*, vol. 9, pp. 18752–18761, 2021.

[16] F. Arif, M. E. Bayraktar, and A. G. Chowdhury, “Decision Support Framework for Infrastructure Maintenance Investment Decision Making,” *J Manage Eng*, vol. 32, no. 1, 2016.

[17] A. Cheaitou, M. Gardoni, and S. Hamdan, “A decision-making framework for environmentally sustainable product design,” *Concurr. Eng.*, vol. 27, no. 4, pp. 295–304, 2019.

[21] U.S. Government Accountability Office, “Inland Waterways: Actions Needed to Increase Budget Transparency and Contracting Efficiency,” Report to Congressional Requesters, 2018.

[19] Q. Brabant, M. Couceiro, D. Dubois, H. Prade, and A. Rico, “Extracting decision rules from qualitative data via Sugeno utility functionals,” Cadiz France, Jun. 2018, pp. 253–265.

[20] D. R. Anderson, D. J. Sweeney, and T. A. Williams, *An Introduction to Management Science: Quantitative Approaches to Decision Making*. Thomson/South-Western, 2003.

[21] R. Kaas, M. J. Goovaerts, J. Dhaene, and M. Denuit, Eds., *Modern actuarial risk theory: Using R*, 2. ed., corr. 2. print. Berlin Heidelberg: Springer, 2009.

[22] W. Winston and S. C. Albright, *Practical management Sciences (Rev)*, Third. Mason, OH: Thomson/South-Western, 2009.

[23] USACE, *Inland waterway navigation (value to the nation)*. Institute for Water Resources, 2000.

[24] Task Committee on Inland Navigation of the Waterways Committee of the COPRI, *Inland Navigation: Environmental Sustainability*. Reston, VA: American Society of Civil Engineers, 2019.

[25] T. F. Fwa and J. Farhan, “Optimal Multiasset Maintenance Budget Allocation in Highway Asset Management,” *J. Transp. Eng.*, vol. 138, no. 10, pp. 1179–1187, 2012.

[26] C. Feinstein and P. Morris, “The role of uncertainty in asset management,” *Methods Asset Ma*, 2010.

[27] D. B. Ashley, K. Uehara, and B. E. Robinson, “Critical Decision-making during Construction,” *J Constr Eng Manage*, vol. 109, no. 2, pp. 146–162, 1983.

[28] Civil Works, “Budget of the U.S. Army Corps of Engineers,” Department of the Army Office, Washington DC, 2019.

[29] Congressional Research Service, “Inland Waterways: Financing and Management Options in Federal Studies,” For Members and Committees of Congress, 2013.

[30] T. V. Dang, P. G. Morato, Q. A. Mai, and P. Rigo, “Optimal inspection and repair scheduling for mitre lock gates,” *Proc. Inst. Civ. Eng. - Marit. Eng.*, vol. 172, no. 3, pp. 95–103, Sep. 2019, doi: 10.1680/jmaen.2019.10.