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Optimal Management of Energy Storage Systems in Hospitals with Quantum Spherical Fuzzy Decision-Making Modelling

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ABSTRACT

This study aims to identify prioritized strategies to increase the effectiveness of energy storage investments in hospitals. High energy consumption in hospitals increases the importance of energy storage investments. For this purpose, 5 literature-based criteria affecting hospital energy storage investments are identified. These criteria are weighted by the quantum spherical fuzzy DEMATEL method. On the other side, 4 different renewable energy alternatives are identified. The performance of these alternatives is ranked with the quantum spherical fuzzy TOPSIS approach. It is determined that storage capacity is the most critical factor in increasing the effectiveness of the energy storage systems in the hospital. Similarly, technological infrastructure is another key issue for the development of this process. However, it is also seen that security issues, legal effectiveness, and financial situations have lower weights. In addition, the ranking results demonstrate that wind energy is the most appropriate renewable energy type for the energy storage performance of hospitals. Geothermal energy can also be considered for this situation. On the other hand, solar and hydropower energy types perform at lower levels in this framework.

1. Introduction

Hospitals are businesses that need to provide 24/7 service. Accordingly, the dependence of hospitals on uninterrupted energy draws attention. Continuity of health services and ensuring patient safety are directly related to uninterrupted electrical energy [1]. Therefore, energy storage systems used in hospitals are of increasing importance day by day. Energy storage systems are vital during possible interruptions or when the energy demand is high due to service intensity [2]. The use of energy storage systems in hospitals is important in many ways. There are many advantages of using energy storage systems in hospitals. It is of great importance in terms of ensuring energy security for hospitals [3]. It contributes to the uninterrupted operation of important medical devices during possible energy losses. They also have a significant positive impact on energy efficiency. Furthermore,

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these systems make it possible to reduce the carbon footprint as they facilitate the integration of renewable energy. It is important to ensure operational continuity against emergencies [4].

The sustainability of healthcare services is critical in modern societies. The safety, quality, and efficiency of healthcare services are directly related to sustainable healthcare [5]. For sustainable healthcare, uninterrupted energy is indispensable. Therefore, it is expected that energy storage investments in hospitals will increase [6]. However, there are many factors affecting this issue. One of these factors is the adequacy of technological infrastructure [7]. The success of energy storage systems depends on their compatibility with the hospital's technological infrastructure. Furthermore, the flexibility of the existing infrastructure is important for its long-term effectiveness in adapting to evolving technology [8]. In addition, attention should be paid to the need for qualified personnel to use this technology [9]. Apart from this, another important factor affecting energy storage investments in hospitals is financial considerations. The initial investment cost of energy storage investments is high. This can prolong the payback period of investments. Besides, these technologies bring with them advanced maintenance and repair costs [10].

Another important factor affecting these investments is the adequacy of government incentives [11]. Government support in providing financial support contributes to increasing energy storage investments [12]. Moreover, renewable energy investments require advanced technology. It would be appropriate for the government to implement R&D incentive policies for this purpose [13]. Therefore, it is obvious that government policies and support are needed to increase energy storage investments in hospitals [14]. Qualified personnel are another important factor affecting energy storage investments in hospitals [15]. Energy storage investments incorporate advanced technology. This brings with it the need for continuous maintenance and technical knowledge. Thus, it is important to have qualified personnel to sustain energy storage investments. Skilled personnel who can use this advanced technology contribute to the efficient, reliable, and sustainable operation of the system [16].

When the literature is examined, it is understood that energy storage systems have an important impact on the sustainability of healthcare services. In addition, it can be said that the factors affecting energy storage have been examined separately. However, there are limited studies on energy storage investments in hospitals. Accordingly, this study aims to identify prioritized strategies to increase the effectiveness of energy storage investments in hospitals. The research question of the study is which are the most effective strategies to ensure the effectiveness of energy storage investments in hospitals. For this purpose, 5 literature-based criteria affecting energy storage investments in hospitals are identified. These criteria are weighted by the Quantum Spherical Fuzzy Modelling method. The need for energy storage investments in hospitals constitutes the main motivation of this study. Multi-criteria decision-making models are utilized to provide this motivation. However, there are many criticisms of the methods used. The main contribution of this research to the literature is to propose a new model that meets these criticisms.

Methodology, analysis results and conclusions are presented in the following sections of the study.

2. Methodology

This section provides detailed information about the method. In this study, Quantum Spherical Fuzzy Sets with Golden Cut, the extension of DEMATEL and the extension of TOPSIS methods are utilized. Quantum theory is used in different science [17]. This methodology is very successful to make future estimation [18]. With the help of this benefit, in this model, it is used for decision-making analysis. This situation has a positive contribution to handle uncertainty in this process [19]. Therefore, more effective findings can be reached. In this proposed model, this theory is integrated with spherical fuzzy sets [20]. The main superiority of this sets is that a wide range of data can be taken into consideration [21]. Membership, non-membership hesitant degrees are considered in these sets [22, 23]. In addition to this issue, golden ratio is also used in this study to compute the degrees [24]. This situation helps to provide methodological originality of this study. On the other hand, to calculate the weights of the criteria, DEMATEL methodology is taken into consideration. This is one of the most popular weighting techniques in the literature [25]. The main superiority of DEMATEL is that causal directions between can be taken into consideration. This condition has a positive influence on the accuracy of the findings. Finally, selected alternatives are ranked with TOPSIS approach. This technique is also preferred in the literature for different purposes. In this framework, the distances to both positive and negative ideal solutions are considered in the evaluation process [26]. This condition is accepted as the main superiority of this technique.

3. Results

The findings are presented in this section.

3.1 Criteria and Alternative List

The literature-based criteria set is given in Table 1.

Table 1: Criteria List

Criteria	Codes
Storage capacity	C1
Technological improvements	C2
Security issues	C3
Legal effectiveness	C4
Financial issues	C5

The list of alternatives identified is given in Table 2.

Table 2: Alternatives List

Alternatives	Codes
Solar energy	A1
Wind energy	A2
Hydropower	A3
Geothermal energy	A4

The linguistic frequentist and cut-based quantum spherical fuzzy numbers used to make the analysis results more consistent are given in Table 3.

Table 3: Linguistic scales and golden cut-based quantum spherical fuzzy numbers

Linguistic Scales for Criteria	Linguistic Scales for Alternatives	Possibility Degrees	QSFNs
No influence (n)	Weakest (w)	0.40	$[\sqrt{0.16}e^{j2\pi.0.4}, \sqrt{0.10}e^{j2\pi.0.25}, \sqrt{0.74}e^{j2\pi.0.35}]$
somewhat influence (s)	Poor (p)	0.45	$[\sqrt{0.20}e^{j2\pi.0.45}, \sqrt{0.13}e^{j2\pi.0.28}, \sqrt{0.67}e^{j2\pi.0.27}]$
medium influence (m)	Fair (f)	0.50	$[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.60}e^{j2\pi.0.19}]$
high influence (h)	Good (g)	0.55	$[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.51}e^{j2\pi.0.11}]$
very high influence (vh)	Best (b)	0.60	$[\sqrt{0.36}e^{j2\pi.0.6}, \sqrt{0.22}e^{j2\pi.0.37}, \sqrt{0.42}e^{j2\pi.0.03}]$

There are many criticisms of multi-criteria decision-making techniques in the literature that expert evaluations are taken equally. The characteristics of the experts in this study, in which the method developed in response to these criticisms is used, are given in Table 4.

Table 4: Specifications of the Experts

Specifications	Expert 1	Expert 2	Expert 3	Expert 4
Experience (years)	15	17	22	18
Education level	Master-Engineering	Bachelor- Engineering	Master- Finance	PHD-Economics
Title	Manager	Head of Department	Project Manager	CEO
Expertise/Field	Energy	Production	Economics	Economics

Expert evaluations for criteria are given in Table 5.

Table 5: Expert opinions for the criteria

	C1	C2	C3	C4	C5
Expert 1					
C1		VH	H	H	H
C2	VH		H	H	M
C3	M	S		M	M
C4	H	VH	M		M
C5	VH	M	H	M	
Expert 2					
C1		H	H	M	M
C2	VH		H	H	M
C3	M	M		M	M
C4	H	VH	M		M
C5	H	M	H	M	
Expert 3					
C1		VH	H	VH	H
C2	VH		H	H	S
C3	M	S		M	M
C4	H	VH	M		S
C5	VH	S	H	M	
Expert 4					
C1		VH	VH	H	VH
C2	VH		H	H	M
C3	M	S		S	H
C4	H	VH	S		H
C5	VH	M	H	M	

The mean values of quantum spherical fuzzy numbers for the criteria are presented in Table 6.

Table 6: Average values of quantum spherical fuzzy numbers for the criteria

	C1	C2	C3	C4	C5
C1		$\begin{bmatrix}\sqrt{0.35}e^{j2\pi.0.59},\\ \sqrt{0.21}e^{j2\pi.0.36},\\ \sqrt{0.44}e^{j2\pi.0.06}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.32}e^{j2\pi.0.57},\\ \sqrt{0.20}e^{j2\pi.0.35},\\ \sqrt{0.48}e^{j2\pi.0.09}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.31}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.13}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.31}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.13}\end{bmatrix}$
C2	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.60},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.42}e^{j2\pi.0.03}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.24}e^{j2\pi.0.48},\\ \sqrt{0.14}e^{j2\pi.0.30},\\ \sqrt{0.62}e^{j2\pi.0.22}\end{bmatrix}$
C3	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.22}e^{j2\pi.0.47},\\ \sqrt{0.13}e^{j2\pi.0.29},\\ \sqrt{0.65}e^{j2\pi.0.25}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.24}e^{j2\pi.0.48},\\ \sqrt{0.14}e^{j2\pi.0.30},\\ \sqrt{0.62}e^{j2\pi.0.22}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.26}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.20}\end{bmatrix}$
C4	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.60},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.42}e^{j2\pi.0.03}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.24}e^{j2\pi.0.48},\\ \sqrt{0.14}e^{j2\pi.0.30},\\ \sqrt{0.62}e^{j2\pi.0.22}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$
C5	$\begin{bmatrix}\sqrt{0.35}e^{j2\pi.0.59},\\ \sqrt{0.21}e^{j2\pi.0.36},\\ \sqrt{0.44}e^{j2\pi.0.06}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.24}e^{j2\pi.0.48},\\ \sqrt{0.14}e^{j2\pi.0.30},\\ \sqrt{0.62}e^{j2\pi.0.22}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$	

Table 7 shows the score function of the criteria for quantum global fuzzy sets.

Table 7: Score function of the criteria for quantum spherical fuzzy sets

	C1	C2	C3	C4	C5
C1	0.000	1.863	1.759	1.709	1.709
C2	1.920	0.000	1.705	1.705	1.453
C3	1.500	1.356	0.000	1.453	1.553
C4	1.705	1.920	1.453	0.000	1.507
C5	1.863	1.453	1.705	1.500	0.000

The normalized relationship matrix is shown in Table 8.

Table 8: Normalized relation matrix

	C1	C2	C3	C4	C5
C1	0.000	0.265	0.250	0.243	0.243
C2	0.273	0.000	0.242	0.242	0.206
C3	0.213	0.193	0.000	0.206	0.221
C4	0.242	0.273	0.206	0.000	0.214
C5	0.265	0.206	0.242	0.213	0.000

The total relationship matrix is in Table 9.

Table 9: Total relation matrix

	C1	C2	C3	C4	C5
C1	2.893	2.974	2.974	2.883	2.832
C2	3.025	2.688	2.891	2.807	2.734
C3	2.666	2.542	2.389	2.485	2.451
C4	2.945	2.844	2.808	2.555	2.683
C5	2.928	2.770	2.803	2.702	2.479

The weightings of the criteria formed as a result of the analysis are shown in Table 10.

Table 10: Influence and Weights of the Criteria

	D	E	D+E	D-E	Weighting results	Impact directions
C1	14.555	14.458	29.013	0.097	0.2110	C1→(C2,C3,C4,C5)
C2	14.145	13.818	27.963	0.327	0.2034	C2→(C1,C3,C4)
C3	12.533	13.864	26.398	-1.331	0.1920	-
C4	13.835	13.431	27.267	0.404	0.1983	C4→(C1,C2,C3)
C5	13.683	13.179	26.862	0.503	0.1954	C5→(C1,C2,C3)

Table 10 explains that storage capacity is the most critical factor to increase the effectiveness of the energy storage systems in the hospital. Similarly, technological infrastructure is another key issue for the development of this process. However, it is also seen that security issues, legal effectiveness and financial situations have the lower weights. The evaluations given by the experts for the alternatives are given in Table 11.

Table 11: Expert opinions for the alternatives

Expert 1					
	C1	C2	C3	C4	C5
A1	B	G	P	F	F
A2	G	F	G	B	G
A3	B	F	G	G	G
A4	B	G	G	G	G
Expert 2					
	C1	C2	C3	C4	C5
A1	B	B	G	F	F
A2	G	F	G	B	G
A3	G	G	G	G	G
A4	B	G	G	G	G
Expert 3					
	C1	C2	C3	C4	C5
A1	G	G	F	F	F
A2	G	F	G	B	G
A3	G	G	G	G	F
A4	G	G	G	G	G
C5	G	G	F	F	F
Expert 4					
	C1	C2	C3	C4	C5
A1	G	G	F	F	F
A2	G	F	G	B	G
A3	B	F	G	F	F
A4	G	F	G	F	G

The average values of quantum spherical fuzzy numbers for the alternatives identified based on the literature are shown in Table 12.

Table 12: Average values of quantum spherical fuzzy numbers for the alternatives

	C1	C2	C3	C4	C5
A1	$\begin{bmatrix}\sqrt{0.33}e^{j2\pi.0.58},\\ \sqrt{0.20}e^{j2\pi.0.36},\\ \sqrt{0.47}e^{j2\pi.0.08}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.32}e^{j2\pi.0.57},\\ \sqrt{0.20}e^{j2\pi.0.35},\\ \sqrt{0.48}e^{j2\pi.0.09}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$
A2	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.60}e^{j2\pi.0.19}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.60},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.42}e^{j2\pi.0.03}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$
A3	$\begin{bmatrix}\sqrt{0.33}e^{j2\pi.0.58},\\ \sqrt{0.20}e^{j2\pi.0.36},\\ \sqrt{0.47}e^{j2\pi.0.08}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.28}e^{j2\pi.0.52},\\ \sqrt{0.16}e^{j2\pi.0.32},\\ \sqrt{0.58}e^{j2\pi.0.19}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.29}e^{j2\pi.0.54},\\ \sqrt{0.18}e^{j2\pi.0.33},\\ \sqrt{0.53}e^{j2\pi.0.13}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.28}e^{j2\pi.0.52},\\ \sqrt{0.16}e^{j2\pi.0.32},\\ \sqrt{0.58}e^{j2\pi.0.19}\end{bmatrix}$
A4	$\begin{bmatrix}\sqrt{0.33}e^{j2\pi.0.58},\\ \sqrt{0.20}e^{j2\pi.0.36},\\ \sqrt{0.47}e^{j2\pi.0.08}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.29}e^{j2\pi.0.54},\\ \sqrt{0.18}e^{j2\pi.0.33},\\ \sqrt{0.53}e^{j2\pi.0.13}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.29}e^{j2\pi.0.54},\\ \sqrt{0.18}e^{j2\pi.0.33},\\ \sqrt{0.53}e^{j2\pi.0.13}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.51}e^{j2\pi.0.11}\end{bmatrix}$

The normalized decision matrix obtained for the alternatives as a result of the analysis is Table 13.

Table 13: Normalized decision matrix

	C1	C2	C3	C4	C5
A1	0.507	0.539	0.455	0.444	0.460
A2	0.478	0.460	0.514	0.568	0.523
A3	0.507	0.491	0.514	0.490	0.492
A4	0.507	0.507	0.514	0.490	0.523

The weighted decision matrix for the alternatives is in Table 14.

Table 14: Weighted decision matrix

	C1	C2	C3	C4	C5
A1	0.107	0.110	0.087	0.088	0.090
A2	0.101	0.093	0.099	0.113	0.102
A3	0.107	0.100	0.099	0.097	0.096
A4	0.107	0.103	0.099	0.097	0.102

The ranking of the alternatives criteria is shown in Table 15.

Table 15: Ranking results

Alternatives	D+	D+	RCi	Ranking
A1	0.030	0.017	0.367	4
A2	0.017	0.030	0.633	1
A3	0.019	0.018	0.486	3
A4	0.017	0.022	0.569	2

Table 15 gives information that wind energy is the most appropriate renewable energy type with respect to the energy storage performance of the hospitals. Geothermal energy can also be considered for this situation. On the other hand, solar and hydropower energy types have lower performance in this framework.

4. Conclusions

In this study, it is aimed to define prioritized strategies to increase the effectiveness of energy storage investments in hospitals. Within this scope, 5 literature-based criteria affecting energy storage investments in hospitals are identified. These criteria are weighted by the quantum spherical fuzzy DEMATEL method. On the other side, 4 different renewable energy alternatives are determined. The performance of these alternatives are ranked with quantum spherical fuzzy TOPSIS approach. It is identified that storage capacity is the most critical factor to increase the effectiveness of the energy storage systems in the hospital. Similarly, technological infrastructure is another key issue for the development of this process. However, it is also seen that security issues, legal effectiveness and financial situations have the lower weights. In addition to them, the ranking results demonstrate that wind energy is the most appropriate renewable energy type with respect to the energy storage performance of the hospitals. Geothermal energy can also be considered for this situation. On the other hand, solar and hydropower energy types have lower performance in this framework. Therefore, it would be appropriate for decision makers to develop strategies by taking into account the results of this study.

Author Contributions

Conceptualization, H.D. and Y.G.; methodology, H.D. and Y.G..; software, H.D. and Y.G..; validation, H.D. and Y.G..; formal analysis, H.D. and Y.G..; investigation, H.D. and Y.G.; resources, H.D. and Y.G.; data curation, H.D. and Y.G.; writing—original draft preparation, H.D. and Y.G.; writing—review and editing, H.D. and Y.G.; visualization, H.D. and Y.G.; supervision, H.D. and Y.G.; project administration, H.D. and Y.G.; funding acquisition, H.D. and Y.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

There is no data in this study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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