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MCDM approach to select IoT devices for the reverse logistics process in the Clinical Trials supply chain

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***Abstract**: Clinical trials companies are increasingly digitalising their reverse logistics flow supply chains to increase visibility and monitoring of their specimens using Internet of Things (IoT) devices, however the large number and diverse range of IoT solutions make it difficult to select the most appropriate one for the closed-loop supply chain of clinical trials which operates in reverse logistics flow. This paper identifies the criteria with which to evaluate IoT devices for the reverse logistics flow of clinical trials supply chains and proposes Analytic hierarchy process (AHP) combined with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach for the evaluation and selection of the best alternative. The approach is demonstrated on a real case and a sensitivity analysis and comparison to the AHP method validates the robustness of the solution.*

Keywords: MCDM, IoT, Reverse Logistics, Clinical trials supply chains, AHP-TOPSIS.

1. INTRODUCTION

Digitalisation in logistics improves competitive advantage (Gunasekaran et al., 2017), promotes smooth transition between multi-modal logistics (Harris et al., 2015), and increases the environmental, economic, and social impacts of transport (Sarkis et al., 2020). The increased organization that can be brought about by digitisation provides significant advantages to Health supply chains in terms of flexibility and agility (Seyedghorban et al., 2020). However, the context of the reverse logistics flow in the clinical trials supply chain is unlike the common understanding of 'reverse logistics' which usually entails a product's end of life, and includes the dispatch of kits to, and the pick-up of samples from investigations. Moreover, medical samples for clinical trials must be transported under controlled conditions as they are sensitive to elements of the external environment and require monitoring throughout the supply chain. In this context, Internet of things (IoT) devices can not only improve the real-time tracking and tracing of shipments but also to transmit information on real-time temperature and humidity in the shipment. Companies working in the clinical trial ecosystem are faced with selecting the most appropriate IoT device for the unique reverse logistics flow of the clinical trials closed-loop supply chain due to the large number of IoT devices on the market which have different functionalities and operational systems. Consequently, the objective of this paper is to develop a multi-criteria decision-making (MCDM) method to evaluate and select the best IoT device for reverse clinical trials supply chains. Section 2 presents the state of the art in this area followed by the proposed MCDM approach to evaluate and select IoT devices for reverse logistics in section 3. A real case is tested using the methodology in section 4 and the results are discussed. Section 4 also includes a sensitivity analysis and benchmarking of the approach. The paper is concluded in section 5.

2. STATE OF THE ART

IoT devices are already used in the clinical trials industry to recruit patients for clinical trials, for medical follow-up and health monitoring systems (Angeletti et al., 2017; Ngayua et al., 2021; Swaroop et al., 2019). However, only one paper has considered IoT devices, in conjunction with blockchain, regarding the complex

reverse logistics process in the closed-loop supply chain for clinical trials. Badulescu and Cheikhrouhou (2021) develop a framework integrating both IoT and blockchain in the clinical trials supply chain in order to allow for an increased level of traceability and visibility, and greater efficiency in managing issues that arise in the reverse logistics process.

There has been some research regarding IoT devices in reverse logistics outside of the scope of clinical trials. The main issues in reverse logistics include the lack of information management systems to deal with the complexity and stochastic nature of the reverse logistics flow in a closed loop supply chain, the absence of real-time logistics data and the uncertainty of logistics demand (Xu et al., 2011). Liu et al. (2018) propose a framework for the use of real-time IoT sensing data in the reverse logistics flow, used by logistics companies to improve the sustainable utilisation of their logistics resources. Thürer et al. (2019) develop a framework for an IoT-driven Kanban system to collect waste in the reverse logistics process which allows to handle data more rapidly than the traditional Kanban visual approach as well as transforming the reverse logistics process from push to pull, based on the requirements of waste collection.

IoT solutions for logistics have become plentiful in recent years, however the specific nature of the reverse logistics flow for the clinical trials supply chain creates additional novel requirements when selecting the best IoT solution. The traceability of clinical trials kits and samples makes it possible to ensure the quality control of the samples which directly influences the results of analyses and allows permanent monitoring of the product's logistics flow. The World Health Organisation recommends that temperature monitoring data be recorded and available for auditing purposes in the medical industry (*WHO Fifty-fifth report*, 2021). Grida et al. (2020) evaluate and compare the performances of several companies with IoT-based supply chains using a Plithogenic BWM and VIKOR approach. Similarly, Wibowo and Grandhi (2018) use a fuzzy TOPSIS approach to evaluate IoT-based supply chains and identify six main evaluation criteria which are expanded upon by Grida et al. (2020), and include financial cost, service quality, functionality, technological infrastructure, reliability and security. Kondratenko et al. (2018) use different MCDM methods to evaluate and select IoT platforms and identify seven main criteria from surveys: device management, integration level, level of safety and reliability, protocols for data collection, variety of data analytics, usefulness of visualization and database functionality.

So far, there are no studies that investigate or propose an approach for the selection of an IoT solution for the reverse logistics process in the clinical trials supply chain, nor which distinguish the criteria with which to evaluate the various IoT solutions. Consequently, this paper identifies the criteria for evaluation of IoT devices for reverse logistics in the clinical trials supply chain and proposes an Analytic hierarchy process (AHP) combined with a Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach as in (Kara and Cheikhrouhou, 2014) to evaluate and select an IoT solution in this context based on the specific criteria. The AHP has some limitations according to Kara and Cheikhrouhou (2014): It is time-consuming since it is necessary to perform mathematical calculations and several pairwise comparisons that increases along with the number of criteria and alternatives; Decision makers must revise their evaluations when the number of alternatives or criteria changes; and the rank of the alternatives depends on the number of alternatives. The addition or deletion of alternatives leads to substantial changes in the final order. Therefore, to overcome the limitations of AHP in terms of ranking robustness, the approach proposed uses AHP to determine the criteria weights, while ranking of alternatives will be carried out by using the TOPSIS method. Indeed, TOPSIS is a robust ranking method that evaluates alternatives based on their geometric distance from the positive-ideal and negative-ideal solution. Accordingly, the best alternative is the one with the shortest distance to the positive-ideal solution, and with the greatest distance from the negative-ideal solution.

3. THE CASE AND THE PROPOSED METHODOLOGY

3.1 Clinical trials reverse logistics supply chain problem description and identification of evaluation criteria

We consider a clinical trials reverse flow supply chain consisting of a clinical trials company, investigators or doctors and transporters as drawn in Figure 1. The clinical trials company dispatches the empty medical kits and logistics documents to the investigators. The investigators collect the required samples from participating subjects and request a pick-up directly to the transporter. The samples are picked up including the associated medical information and necessary transportation documentation. The shipments arrive to the clinical trials company. The location of the shipments during transportation are unknown to the clinical trials company. In addition, the contents of incoming shipments are unknown until the boxes are open and the documents are read. These two reasons provide a room for IoT integration and use. In fact, an IoT device that is linked to a shipment will provide information on its localisation, its routing and on the details of the contents of the shipment. The information obtained through the sensors embedded in the IoT device are sent through the communication systems (GPS, Sigfox network, Lora network, etc.) to the clinical trials company to track and trace the shipment along the supply chain and to plan the medical/clinical activities before receiving the shipment. The criteria and their sub-criteria used to evaluate IoT devices are identified by the decision-makers in clinical trials companies on the basis of a list of criteria depicted from the literature and shown in Table 1.

Table 1: Evaluation criteria for IoT devices

Criteria & Sub-criteria		**Sources**
Financial Cost	**C1**	(Grida et al., 2020)
Hardware Costs	C2	
Software / usage costs	C3	
Implementation costs	C4	
Maintenance costs	C5	
Service Quality	**Q1**	(Grida et al., 2020)
Service level	Q2	
System reliability	Q3	
Distribution network quality	Q4	
Functionality	**F1**	(Grida et al., 2020)
Technical compliance of device	F2	
Operational feasibility of device	F3	
Ability to define acceptable logistics route	F4	Experts from Clinical trials company
Real-time track and trace	F5	
Rapid identification and reporting of issues	F6	
Temperature range	F7	
Humidity measurement	F8	
Vibration or shocks	F9	
Real time Temperature measurement	F10	
Additional functionalities	F11	
Technological infrastructure	**T1**	(Grida et al., 2020; Kondratenko et al., 2018)
Interoperability with other systems	T2	
Security	**S1**	(Grida et al., 2020)
Level of device verification	S2	
Level of encryption	S3	
Level of safety and reliability	S4	(Kondratenko et al., 2018)
Clinical Trials SC Requirements	**R1**	Experts from Clinical trials company
Weight	R2	
Dimensions / size	R3	
Battery life	R4	

3.2 AHP-TOPSIS approach for selection of IoT solution

A combined AHP-TOPSIS methodology is proposed for the context of IoT device selection for the reverse logistics closed loop supply chain of clinical trials. Combining TOPSIS with AHP avoids the rank-reversal issue when a non-optimal alternative is introduced (Sipahi and Timor, 2010). AHP on the other hand provides an easy approach to define weights for criteria in a hierarchical structure with more than one hierarchical levels, TOPSIS does not (Tao et al., 2012). Moreover, as the evaluation criteria for IoT devices (Table 1) includes both quantitative and qualitative information, AHP enables decision-makers to compare the responses of each criterion pairwise between alternatives using linguistic variables and Saaty's 1-9 scale.

Figure 2 shows the AHP-TOPSIS decision-making methodology consists of three phases for the problem described in section *3.1*. In the first phase, the experts are selected, the alternative IoT solutions are identified, and the criteria to evaluate the alternatives are selected from Table 1.

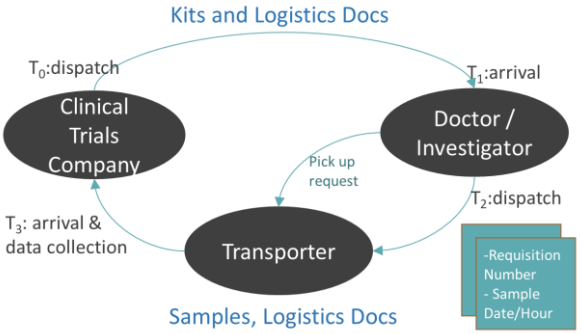

Figure 1. Reverse logistics flow of a Clinical Trials supply chain

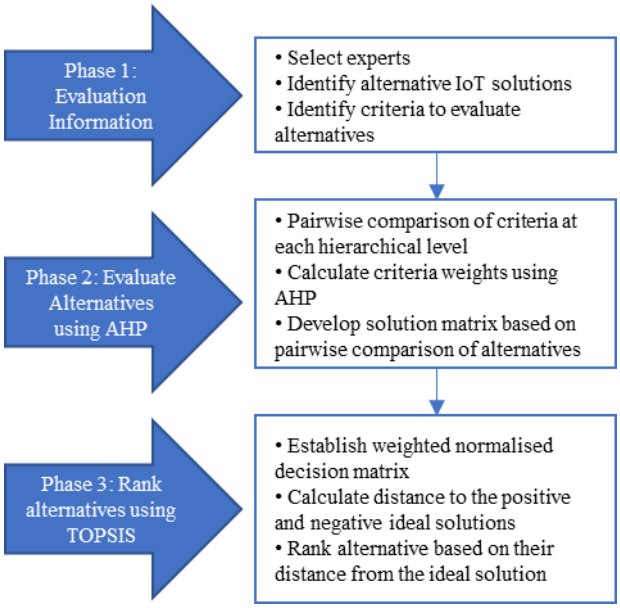

Figure 2. AHP-TOPSIS approach for selecting the best IoT device for the RL of a Clinical Trials SC

Phase 2 concerns the evaluation of the alternative IoT devices based on the selected criteria using the AHP approach. AHP allows deriving priorities among criteria considering their hierarchal structure. The experts perform pairwise comparison using the Saaty 1-9 scale between firstly the highest hierarchical level of criteria (C1, Q1, F1, T1, S1, R1), followed by pairwise comparison of the sub-criteria to create a pairwise comparison matrix (*M*). The normalised weight vector (*w*) is then obtained by determining the maximum

eigenvalue λ_{max} of the comparison matrix (M) and finding the solution to Eq. (1).

$$Mw = \lambda_{max} w \quad \text{(Eq.1)}$$

The evaluation criteria consist of quantitative and qualitative criteria. In the case of the qualitative criteria, a pairwise comparison to compare the relative importance of each alternative with each other per criteria to create a comparison matrix similar to *M*. Then the normalised weight vector is calculated for each alternative per criteria using Eq. 1. The weight vectors for each alternative per criterion are assembled in the solution matrix A, where a_{dc} is the information of criterion c based on alternative IoT device d. Phase 3 consists of ranking the IoT solutions from best to worst using TOPSIS. Assuming that n is the number of criteria, the TOPSIS procedure consists of the following steps:

Step 1: Determine the normalised decision matrix. Each normalised value r_{dc} is calculated as:

$$r_{dc} = \frac{f_{dc}}{\sqrt{\sum_{d=1}^{D} {a_{dc}}^2}}, \quad d = 1, 2, 3 \dots D \quad \text{(Eq. 2)}$$

Where *D* is the total number of alternatives.

Step 2: Determine the weighted normalised decision matrix. Each weighted normalised value v_{dc} is calculated as:

$$v_{dc} = w_d \times r_{dc} \quad \text{(Eq. 3)}$$

For $d = 1, 2, 3, \dots, D \quad and \quad c = 1, 2, 3, \dots, n$

Where w_c is the weight of the c^{th} criterion and $\sum_{c=1}^{n} w_c = 1$.

Step 3: Determine the ideal and negative ideal solutions, respectively $B^+ \; and \; B^-$.

$$B^+ = \{v_1^+, \dots, v_c^+\} = \{(max_d \; v_{dc} | c \in I'), (min_d \; v_{dc} | c \in I")\} \quad \text{(Eq. 4)}$$

$$B^- = \{v_1^-, \dots, v_c^-\} = \{(min_d \; v_{dc} | c \in I'), (max_d \; v_{dc} | c \in I")\} \quad \text{(Eq. 5)}$$

Where I' is associated with the benefit criteria, and $I"$ is associated with cost criteria.

Step 4: Calculate the distances from the positive and negative ideal solutions using the n-dimensional Euclidean distance. The distance of each potential partner from the positive ideal solution is given as:

$$K_d^+ = \sqrt{\sum_{c=1}^{n} (v_{dc} - v_c^+)^2} \quad d = 1, 2, 3, \dots, D \quad \text{(Eq. 6)}$$

Similarly, the distance from the negative ideal solution is given as:

$$K_d^- = \sqrt{\sum_{c=1}^{n} (v_{dc} - v_c^-)^2} \quad d = 1, 2, 3, \dots, D \quad \text{(Eq. 7)}$$

Step 5: Calculate the relative closeness CC^+ to the ideal solution. The relative closeness of the potential partner A_d is defined as:

$$CC_d^+ = \frac{K_d^-}{K_d^+ + K_d^-} \qquad d = 1, 2, 3, \dots, D \quad \text{(Eq. 8)}$$

Step 6: Rank the alternative solutions from the best (closest, largest CC^+) to worst (farthest, smallest CC^+).

4. CASE DEVELOPMENT AND RESULTS

The decision-making approach is validated on a real case of a clinical trials company in the process of digitalising their reverse logistics flow which is described in section *3.1*. The company is considering 7 alternative IoT devices (A_1 to A_7) to accompany their shipments in reverse logistics flow within the closed-loop supply chain. There is one decision-maker which selects the criteria to be used for evaluation and the relative importance of each criterion using pairwise comparison. The expert selects 14 criteria: C2, Q4, F5, F6, F7, F8, F9, F10, F11, T2, S3, R2, R3 and R4. Firstly, the weights are determined for the first level criteria: {C1, Q1, F1, T1, S1, R1} which are {0.09, 0.09, 0.35, 0.05, 0.16, 0.26}, respectively. F1, 'functionality' which refers to the range of operations available per IoT solution has the highest relative importance, followed by R1 which include the 'other requirements' identified by the clinical trials company, and S1, regarding 'security' which is a major concern in the clinical trials industry. Only two of the main criteria include sub-criteria which are selected by the expert, under F1 and R1, the weightings for those are also determined via the AHP process. These are {0.3, 0.3, 0.13, 0.03, 0.13, 0.05, 0.07} for {F5, F6, F7, F8, F9, F10, F11}, and {0.2, 0.2, 0.6} for {R2, R3, R4}, respectively. The final sub-criteria weights, ω_c, are determined by multiplying the sub-criteria weights with the criteria weights and seen in Table 2. The criteria with the greatest relative importance is S3, "Level of encryption" and R4, "Battery Life", followed by F5 and F6, "Real-time track and trace" and "Rapid identification and reporting of issues", respectively. This appropriately reflects the perceived importance of criteria evaluated by the expert whose main concern is the level of security of the information as the medical industry is based on patient privacy protection, and the longevity of the IoT devices themselves represented by the battery life to minimise re-ordering devices and maintenance. Moreover, the functionalities of the IoT devices are essential to track and trace the shipments and quick identify issues and reporting them. The weighted normalised decision matrix is established using Eq. 2 and 3, and the positive and negative ideal solutions per criterion is determined based on Eq. 4 and 5, which are used to calculate the distances (K^- and K^+) of each solution using Eq. 6 and 7. The relative closeness (CC^+) is determined using Eq. 8 and these are shown in Table 3. The final ranking of alternative IoT solutions, A_1 to A_7, are based on their relative closeness to the ideal solution, $\mathbf{CC}^+$. The larger the number, the closer they are to the ideal solution. Therefore, alternative A_1 is ranked as the best IoT solution based on the MCDM approach proposed in this paper. The top 3 ranked alternative IoT solutions are A_1, A_3 and A_2, in order. Although A_1 is the most expensive alternative, the weight of the criteria in which they perform the best are the criteria which are regarded with

greater importance by the experts. A_1 performed the best in the criteria F5, F6, F10, F11, and S3, which proved advantageous for A_1 as the criteria with the highest weights include S3, F5 and F6. A_1 performed the worst in C2, F8 and F9, relative to the other alternatives. This approach allows for the best alternative to be selected based on the judgment of the experts that will be using the solutions and avoids selecting the subjectively 'wrong' IoT device.

Table 2: Criteria weights and solutions matrix for alternative IoT devices A_1 to A_7

Criteria		Solutions for alternatives per criterion						
c	ω_c	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C2	*0.09*	0.03	0.06	0.09	0.12	0.29	0.12	0.29
Q4	*0.09*	0.12	0.25	0.12	0.25	0.03	0.03	0.19
F5	*0.10*	0.18	0.18	0.18	0.12	0.08	0.08	0.18
F6	*0.10*	0.23	0.23	0.23	0.11	0.07	0.07	0.07
F7	*0.05*	0.10	0.21	0.39	0.02	0.13	0.13	0.02
F8	*0.01*	0.08	0.08	0.08	0.54	0.08	0.08	0.08
F9	*0.05*	0.03	0.03	0.23	0.03	0.23	0.23	0.23
F10	*0.02*	0.19	0.19	0.19	0.03	0.19	0.19	0.03
F11	*0.02*	0.29	0.29	0.03	0.07	0.14	0.14	0.05
T2	*0.05*	0.13	0.30	0.13	0.30	0.05	0.05	0.05
S3	*0.16*	0.29	0.13	0.29	0.13	0.07	0.07	0.02
R2	*0.05*	0.09	0.14	0.05	0.05	0.29	0.05	0.34
R3	*0.05*	0.13	0.13	0.03	0.05	0.29	0.06	0.32
R4	*0.16*	0.16	0.16	0.03	0.03	0.16	0.29	0.16

Table 3: Final ranked alternatives

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
K^-	0.02	0.02	0.02	0.03	0.02	0.03	0.03
K^+	0.02	0.02	0.02	0.01	0.02	0.02	0.02
CC^+	0.56	0.49	0.50	0.35	0.42	0.43	0.43
Rank	**1**	**3**	**2**	**7**	**6**	**4**	**5**

4.1 Comparison to AHP benchmark method

To analyse the robustness of this approach, the ranking results using AHP-TOPSIS are compared to using only the AHP method. The results in Table 4 show that using the AHP method without TOPSIS generates A_2 as the best alternative IoT solution followed by A_1 and A_3, whereas the AHP-TOPSIS method ranked A_1 as the best IoT device, with A_2 ranked only third. This is because the TOPSIS approach takes into account not only the distance from the ideal positive solution K^-, in which A_2 is 3% further than A_1 from K^-, but it also considers the distance from the ideal negative (worst) solution K^+, in which A_2 is 19% closer to the worst solution relative to A_1. This mapping between the ideal positive and negative solutions allows to rank the alternatives relative more appropriately to each other. Whereas the AHP approach simply multiplies the normalised priority weights per criterion with those of the alternatives and does not consider how close each alternative is to an ideal solution per specific criterion. Moreover, when comparing the criteria of A_1 and A_2, although A_1 is 76% more expensive than A_2, it runs on a distribution network preferred by the experts, and works on a GSM network versus an integrated antenna for A_2, which means the trucks don't need to be equipped with a transmitter. Moreover, A_1, has a 50% longer battery life than A_2, making it the preferred solution for the clinical trials company in question.

Table 4: Alternative A_1 to A_7 priority weights using AHP

Alternative	A_1	A_2	A_3	A_4	A_5	A_6	A_7
Weight	0.16	0.17	0.16	0.11	0.14	0.12	0.15
Rank	**2**	**1**	**2**	**7**	**5**	**6**	**4**

4.2 Sensitivity Analysis

To analyse the robustness of the final ranking using AHP-TOPSIS, a sensitivity analysis is performed to determine the effect of the criteria weighting on the final ranking of results. Therefore, simulations are run in which the weighting of one main criterion is increased by 50% and the weighting of the remaining criteria is reduced proportionally. Table 5 shows the ranking based on the relative closeness of the alternatives for six scenarios and the original for comparison purposes.

Table 5: Ranking of alternatives based on sensitivity analysis

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
Original	*1*	*3*	*2*	*7*	*6*	*4*	*5*
+50% C1	1	5	2	7	4	6	3
+50% Q1	1	2	3	6	7	5	4
+50% F1	2	3	1	7	6	4	5
+50% T1	1	2	3	7	6	4	5
+50% S1	1	3	2	5	6	4	7
+50% R1	2	4	6	7	5	1	3

In all scenarios, except two, A_1 is consistently ranked the best alternative IoT device even if the criteria weights increase by 50%. However, when the weights of the F1 and R1 criteria are increased, so do the sub-criteria {F5, F6, F7, F8, F9, F10, F11} and {R2, R3, R4}. A_1 is the worst wrt. F8 and F9. Moreover, A_6 has a battery life which is more than double the next longest battery life for A_1 and considering the weight for R4 becomes 24%, this criterion is given a very large importance relative to the other criteria.

5. CONCLUSION

This paper presents an approach that aids in selecting an IoT solution for the reverse logistics flow of the clinical trials supply chain. Demonstration using a real case of a clinical trials company, which are in the process of digitalising their reverse logistics, shows that using this approach successfully selects the best IoT device based on the expertise of the decision-maker and helps the company avoid selecting an inappropriate or worse alternative. The AHP-TOPSIS approach proposed in the work provides a consistent decision and shows a strong robustness compared to AHP, which is considered as a state-of-the-art technique.

This paper has two main contributions: 1) the identification of the criteria to evaluate IoT devices for transportation of packages in a closed loop supply chain in reverse flow, and 2) a validated method to select the best IoT device for the reverse logistics of the clinical trials supply chain. Future research directions will address the challenges faced in adopting IoT devices in clinical trials supply chains, which needs the use of appropriate MCDM approaches such as combined Total Interpretive Structural Modelling with DEMATEL.

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