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A New Replacement Model under Trapezoidal Fuzzy Number Environment

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Abstract

In today's dynamic world, the replacement of machinery and facilities is a permanent and complicated issue due to rapid technical growth and globalization, which is a shared concern in the minds of the owners of any business. Maintenance is a scheduled procedure to ensure that equipment, systems, or facilities remain normal to perform their intended purpose correctly without risking the loss of service time due to their failure. To maintain a certain degree of consistency, protection, and performance maintenance activities for systems and facilities in good working conditions are indispensable. The repair operation helps to preserve and increase the operating performance of machinery and facilities and thus adds to revenues. So if an entity or corporation needs to continue its competitive market, it is important to verify if the operating and repair costs are to be sustained with the old equipment or replaced by it. For that, the decision parameters such as maintenance cost, resale value, capital cost, and rate of interest should be known exactly. But it is not possible in reality, as reality is uncertain and complex. This uncertainty is competently governed and controlled by fuzzy set theory. This work aims to discuss equipment replacement in a fuzzy environment. In this fuzzy replacement model, all inaccurate costs are represented by trapezoidal fuzzy numbers (TFNs). The suggested technique finds the best replacement time for a fuzzy replacement problem without converting to a crisp one and is supported by an illustrative numerical example.

Keywords: Fuzzy Number, Fuzzy replacement model, Midpoint of fuzzy number, Operations on fuzzy numbers, Ranking of fuzzy numbers, Width of fuzzy number.

Introduction

Machines, instruments, equipment, and technical standards must be replaced strategically and economically in today's challenging industrial and commercial environment. As a result, the decision to replace is important to the company's success, as it is largely irreversible, requiring a substantial amount of cash and resources. Therefore a quick replacement decision could generate major challenges for the company's working capital and hence it is very important to decide the optimal period for replacement. Conventionally, the replacement of equipment has been done mostly in a deterministic and crisp manner. But in day-to-day applications, uncertainty and vagueness are dealt with in the form of money, time etc., due to many reasons. As a result, a tolerable range rather than a precise number should be used to determine the best time to replace equipment. Zadeh proposed the concept of fuzzy set

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Baghdad Science Journal

theory[1], which may be a useful tool for dealing with such scenarios.

Lotka[2] originated the problem of replacement in industries in 1939, using the concept of renewal theory. Further, several authors discussed the replacement models in classical nature. Kai-Yuan and Chuan-Yuan[3] realized that all costs involved in the real-world replacement model are not precise in nature and hence introduced a fuzzy environment in the street-lighting system. Tolga, Demircan, and Kahraman[4] used the fuzzy analytic hierarchy method to approach the replacement model.

Biswas and Pramanik[5] El-Kholy and Abdelalim[6] employed fuzzy ranking approaches to evaluate the economic life of equipment by transforming fuzzy replacement models (FRMs) into classical models. The authors have described them in general. Balaganesan and Ganesan[7, 8] examined the economic life of equipment as its monetary value changed and also, they discussed the same under intuitionistic fuzzy sense. On using the ranking concept, Mitlif RJ[9] obtained the solution for the fuzzy fractional programming problem. Mitlif, Hussein [10] solved a fuzzy multiple objective programming problem in a crisp manner after converting the TFNs into their crisp form. Singh, Chinta [11, 12] discussed the individual and group replacement models under an intuitionistic fuzzy environment. Anees et al[13] analyzed the FRM without shortages. A technique for random sampling has been proposed by Kesemen et al[14] that offers a switch between choosing samples with and without replacement. Jueming et. al[15] formulated the optimization of maintenance under uncertainty as a Markov Decision Process problem, which they addressed with a modified version of Reinforcement Learning. It takes an infinite horizon into account for both constrained deterministic and stochastic maintenance scheduling. Dong et al[16] studied the best preventative replacement schedule for a single unit system that experiences both external shocks and stochastic deterioration. Biswas, Pramanik[17] discussed the replacement model by considering the present worth factor. Cruz-Suárez et al[18,19] analyzed the discounted and advanced Markov decision processes under a fuzzy environment.

The majority of the researchers transformed the provided problem into a crisp one and they derived the crisp answer. The goal of this article is to give a mathematical method for expressing vagueness in replacement analysis without changing it into its precise form.

Novelties of the Work

Fuzzy set theory is a useful tool for understanding technical disciplines and issues related to decision-making in an uncertain circumstance. The primary objective of this research is to address the fuzzy replacement problem in the following manner:

1. Parametric representation is used to express the trapezoidal fuzzy numbers (TFNs).
2. Developing arithmetic operations for TFNs based on core and spread ideas, including addition, subtraction, division, and multiplication of two fuzzy numbers.
3. Finding a method to achieve optimality is the most crucial step in transforming a fuzzy replacement model into a crisp one. It is necessary to confirm the validity of the solution because the fuzzy model's equivalent crisp model might not solve the original problem. The optimization model's fuzzy nature is not effectively captured by the crisp model. Therefore the numerical example discussed in this paper has been solved without converting into a crisp one.

The content of this work is arranged as follows. Section 2 covers the fundamentals of fuzzy sets, trapezoidal fuzzy numbers, and related arithmetic operations. Section 3 describes the suggested model's algorithm. In section 4, the replacement model is explained using a real-life scenario. Section 5 concludes this paper.

Materials and Methods

Definition 1: Let X be a universe of discourse. A fuzzy set $\tilde{A}$ in X is given by $\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) : x \in X\}$. Where $\mu_{\tilde{A}}(x) \to [0,1]$ represents the degree of belongingness of the element $x \in X$ in $\tilde{A}$.

Definition 2: A fuzzy set $\tilde{A}$ defined on the set of real numbers $\mathcal{R}$ is said to be a fuzzy number, if its membership function $\tilde{A}: \mathcal{R} \to [0,1\}$ has the following characteristics

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1. $\tilde{A}$ is convex, (i.e.) $\tilde{A}(\lambda x_1 + (1-\lambda)x_2) \geq \min\{\tilde{A}(x_1), \tilde{A}(x_2)\}, \lambda \in [0,1], for\ all\ x_1, x_2 \in \mathcal{R}$.
2. $\tilde{A}$ is normal, (i.e.) there exists $x \in \mathcal{R}$ such that $\tilde{A}(x) = 1$.
3. $\tilde{A}$ is piecewise continuous.

Definition 3: A fuzzy number $\tilde{a}$ is a trapezoidal fuzzy number denoted by $\tilde{a} = (p, q, r, s)$, where p, q, r and s are real numbers is given by

$$\mu_{\tilde{a}}(x) = \begin{cases} \dfrac{x-p}{q-p} & if\ \ p \leq x \leq q \\ 1 & if\ \ \ q \leq x \leq r \\ \dfrac{s-x}{s-r} & if\ \ \ r \leq x \leq s \\ 0 & otherwise \end{cases}$$

And its diagrammatic representation is given in Fig 1.

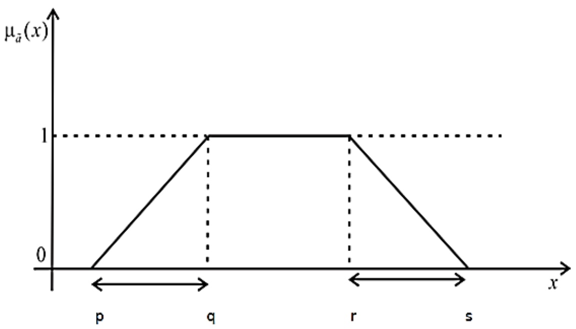

Figure 1. Trapezoidal fuzzy number $\tilde{a} = (p, q, r, s)$

This article portrays the trapezoidal fuzzy number $\tilde{a} = (p, q, r, s) = ([q, r], g, h) = (e, f, g, h)$, where $e = \left(\frac{q+r}{2}\right)$ and $f = \left(\frac{r-q}{2}\right)$ are the midpoint and width of the core [q, r] respectively. Also $g = (q-p)$ denotes the left spread and $h = (s-r)$ denotes the right spread of the trapezoidal fuzzy number.

Arithmetic Operations on Trapezoidal Fuzzy Numbers

Based on[20], the arithmetic operations between $\tilde{a} = (e_1, f_1, g_1, h_1)$ and $\tilde{b} = (e_2, f_2, g_2, h_2)$ are given by:

Addition:

$$\tilde{a} + \tilde{b} = (e_1, f_1, g_1, h_1) + (e_2, f_2, g_2, h_2)$$

$$= \left(e_1 + e_2, \max(f_1, f_2), \max(g_{1,} g_2), \max(h_1, h_2)\right)$$

Subtraction:

$$\tilde{a} - \tilde{b} = (e_1, f_1, g_1, h_1) - (e_2, f_2, g_2, h_2)$$

$$= \left(e_1 - e_2, \min(f_1, f_2), \min(g_{1,} g_2), \min(h_1, h_2)\right)$$

Multiplication:

$$\tilde{a} \times \tilde{b} = (e_1, f_1, g_1, h_1) \times (e_2, f_2, g_2, h_2)$$

$$= \left(e_1 \times e_2, \max(f_1, f_2), \max(g_{1,} g_2), \max(h_1, h_2)\right)$$

Division:

$$\tilde{a} \div \tilde{b} = (e_1, f_1, g_1, h_1) \div (e_2, f_2, g_2, h_2)$$

$$= \left(e_1 \div e_2, \min(f_1, f_2), \min(g_{1,} g_2), \min(h_1, h_2)\right)$$

Here g and h are following the lattice rule. The ranking function is used to compare the fuzzy numbers based on the graded mean.

Replacement Model with Trapezoidal fuzzy numbers

The objective of the work is to determine the optimal time to replace an equipment whose service (running) cost increases with time while the price level stays unchanged and time is a discrete variable. Here,

$\tilde{R}_n$ - Fuzzy running cost for n hours.
$\tilde{C}$ - Fuzzy capital cost (FCC) for the item.
$\tilde{S}_n$ - Fuzzy scrap value (FSV) of the item in n time duration.

Then[7] helps to conclude the replacement time,

i.e. $\tilde{R}_{n+1} > \frac{\tilde{P}_n}{n} > \tilde{R}_n$ (or) $\tilde{R}_{n+1} > \tilde{W}(n) > \tilde{R}_n$

Theorem: Optimum Replacement Policy[21]

1. If the succeeding period fuzzy maintenance cost is less than the fuzzy average total cost of the preceding period, replacement is not required.
2. If the succeeding period fuzzy maintenance cost is greater than the fuzzy average total cost of the preceding period, replace the old equipment with a new one.

Proof:

Let $\tilde{R}_n$, $\tilde{C}$ and $\tilde{S}_n$ be fuzzy running cost, fuzzy capital cost, and fuzzy scrap value respectively. Here n is the discrete variable.

Annual cost for n hours $\approx \tilde{R}_n + \tilde{C} + \tilde{S}_n$.

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The total cost incurred on the item is $\tilde{P}_n \approx \sum_{t=1}^{n} \tilde{R}_t + \tilde{C} - \tilde{S}_n$.

Therefore, the average total cost is $\tilde{w}(n) \approx \frac{\tilde{P}_n}{n}$.

Now, $\tilde{w}(n)$ is minimum if $\Delta\tilde{w}(n-1) \prec 0 \prec \Delta\tilde{w}(n)$ is satisfied.

As it is known that, $\Delta\tilde{w}(n) \approx \tilde{w}(n+1) - \tilde{w}(n)$

$$\approx \left[\frac{\sum_{t=1}^{n+1} \tilde{R}_t}{n+1} + \frac{\tilde{C} - \tilde{S}_{n+1}}{n+1}\right] - \left[\frac{\sum_{t=1}^{n} \tilde{R}_t}{n} + \frac{\tilde{C} - \tilde{S}_n}{n}\right] \approx \frac{\tilde{R}_{n+1}}{n+1}\left[\frac{\sum_{t=1}^{n} \tilde{R}_t}{n(n+1)} + \frac{\tilde{C} - [(n+1)\,\tilde{S}_n - n\tilde{S}_{n+1}]}{n(n+1)}\right]$$

For minimum $\tilde{w}(n) \Rightarrow \Delta\tilde{w}(n-1) \prec 0 \prec \Delta\tilde{w}(n)$

$$\Rightarrow \frac{\tilde{R}_{n+1}}{n+1} \succ \frac{\sum_{t=1}^{n} \tilde{R}_t}{n(n+1)} + \frac{\tilde{C} - [(n+1)\,\tilde{S}_n - n\tilde{S}_{n+1}]}{n(n+1)}$$

$$\Rightarrow \tilde{R}_{n+1} \succ \frac{\sum_{t=1}^{n} \tilde{R}_t}{n} + \frac{\tilde{C} - [(n+1)\,\tilde{S}_n - n\tilde{S}_{n+1}]}{n}$$

$$\Rightarrow \tilde{R}_{n+1} \succ \frac{\sum_{t=1}^{n} \tilde{R}_t}{n} + \frac{\tilde{C} - \tilde{S}_n}{n}$$

$$\Rightarrow \tilde{R}_{n+1} \succ \frac{\tilde{P}_n}{n}.$$

Similar proof is needed to prove the next part also.

$$\tilde{R}_n \prec \frac{\tilde{P}_n}{n}.$$

Therefore $\tilde{R}_{n+1} \succ \frac{\tilde{P}_n}{n} \succ \tilde{R}_n$, which leads to the proof of the theorem.

Procedure to find the trapezoidal fuzzy equipment replacement time

Step 1. By using midpoint, width, and spread concepts, rewrite the given TFNs in the form of

$$\tilde{a} = (e, f, g, h)$$

Step 2. Find the cumulative maintenance cost $\sum \tilde{R}_n$ for n = 1,2,3,…

Step 3. Find $\tilde{C} + \sum \tilde{R}_n$

Step 4. Subtract the scrap value from the result obtained in the previous step to calculate $\tilde{C} - \tilde{S}_n + \sum \tilde{R}_n$

Step 5. Compute the average cost $\widetilde{W}(n)$ by dividing $\tilde{C} - \tilde{S}_n + \sum \tilde{R}_n$ with the respective years.

Step 6. Use the graded mean concept to find the weighted average cost.

Step 7. Apply the replacement policy $\tilde{R}_{n+1} > \widetilde{W}(n) > \tilde{R}_n$ to determine the optimum time of replacement of the equipment.

Flowchart to find the trapezoidal fuzzy equipment replacement time

Fig 2 shows the framework of the proposed method.

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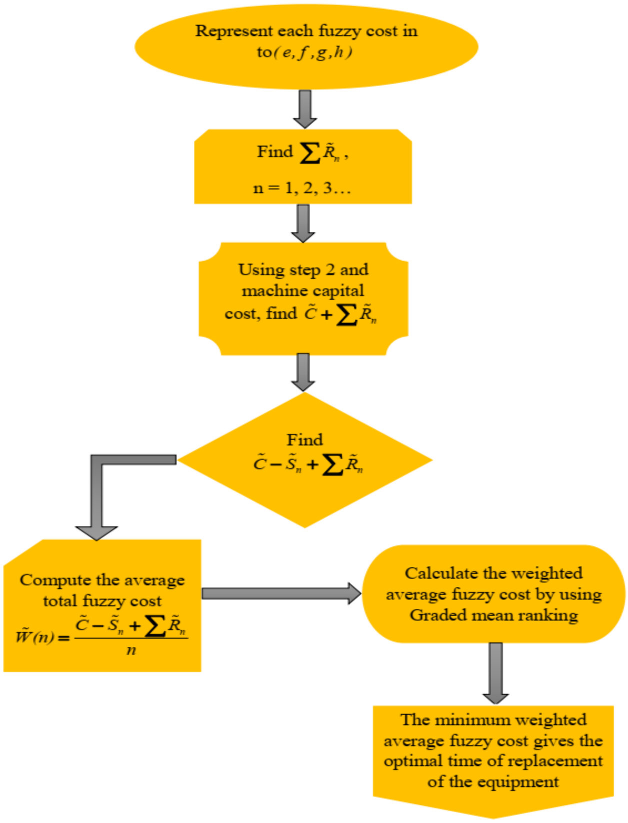

Figure 2. Steps to determine the fuzzy equipment replacement time

Numerical Simulation

A real-life numerical example is considered from[5]. A construction company introduced a new sort of loader with a fuzzy cost, $\tilde{C}$ = (61000, 613000, 617000, 62000), and the scrap value $\tilde{S}$ = (4200, 4250, 4300, 4350) in Rupees. After survey, company officials noticed that the fuzzy running cost in Rupees is found from experience (Table 1, take Rs. 100 = 1 unit). When should the company officials recommend that the loader be replaced?

Table 1. Fuzzy maintenance cost and its alternative representation (Here Rs.100 = 1 unit)

Time (n)	$\tilde{R}_n$
1	(12, 13.5,14,14.5)
2	(25,26,27.5,29)
3	(35,37,38.5,40)
4	(45,46.5,48,50)
5	(60,65,67,68)
6	(80,82,84.5,88)
7	(105,110,125,140)
8	(160,170,185,200)

Table 2 gives the parametric form of $\tilde{R}_n$ and $\tilde{S}_n$.

Table 2. Parametric form of $\tilde{R}_n$ and $\tilde{S}_n$

Time (n)	$\tilde{R}_n$	$\tilde{S}_n$
1	(13.75,0.25,1.5,0.5)	(42.75,0.25,0.5,0.5)
2	(26.75,0.75,1,1.5)	(42.75,0.25,0.5,0.5)
3	(37.75,0.75,2,1.5)	(42.75,0.25,0.5,0.5)
4	(47.25,0.75,1.5,2)	(42.75,0.25,0.5,0.5)
5	(66,1,5,1)	(42.75,0.25,0.5,0.5)
6	(83.25,1.25,2,3.5)	(42.75,0.25,0.5,0.5)
7	(117.5,7.5,5,15)	(42.75,0.25,0.5,0.5)
8	(177.5,7.5,10,15)	(42.75,0.25,0.5,0.5)

The optimum replacement time is obtained by using the proposed method which is given in detail in Table 3.

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Table 3. Table determining the optimal replacement time

Year (n)	$\sum \tilde{R}_n$	$\tilde{C} - \tilde{S}_n + \sum \tilde{R}_n$	$\tilde{W}(n) = \frac{\tilde{P}_n}{n}$	$R[\tilde{W}(n)]$
1	(13.75,0.25,1.5,0.5)	(586,0.25,0.5,0.5)	(586,0.25,0.5,0.5)	586
2	(40.5,0.75,1.5,1.5)	(612.75,0.25,0.5,0.5)	(306.375,0.25,0.5,0.5)	306.375
3	(78.25,0.75,2,1.5)	(650.5,0.25,0.5,0.5)	(216.833,0.25,0.5,0.5)	216.833
4	(125.5,0.75,2,2)	(697.75,0.25,0.5,0.5)	(174.438,0.25,0.5,0.5)	174.438
5	(191.5,1,5,2)	(763.75,0.25,0.5,0.5)	(152.75,0.25,0.5,0.5)	152.75
6	(274.75,1.25,5,3.5)	(847,0.25,0.5,0.5)	(141.167,0.25,0.5,0.5)	141.167
7	(392.25,7.5,5,15)	(964.5,0.25,0.5,0.5)	**(137.786, 0.25, 0.5, 0.5)**	**137.786**
8	(569.75,7.5,10,15)	(1142,0.25,0.5,0.5)	(142.75,0.25,0.5,0.5)	142.75

Results and Discussion

Without disturbing the fuzzy environment, the proposed algorithm helps to conclude that the loader needs to be replaced after the seventh year. The minimum average annual cost in that year is Rs. (13703.6, 13753.6, 13803.6, 13853.6). But Biswas and Pramanik[5] analyzed that, the loader needs to be changed at the end of the 7th year and the average annual cost is Rs. 13792.8 in crisp nature. Fig 3 gives a comparison of results.

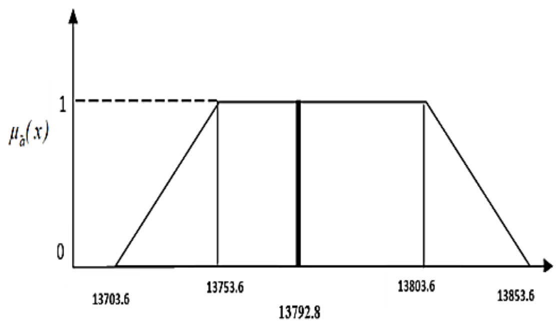

Figure 3. Comparison of results

Conclusion

Due to unknown elements, ambiguity plays a crucial role in all replacement decisions in our real-life challenges. This paper presents a numerical example for considering fuzziness in replacement analysis without transferring to its accurate form, which is simple to follow and determine the equipment strength and durability. Many authors approached the replacement problems in a fuzzy way, but their results were crisp. A mathematical model is developed to demonstrate that the ambiguity in the outcome using our suggested technique does not alter the imprecise quality. This research could be extended to a trapezoidal intuitionistic fuzzy replacement model with a constant money value that does not fluctuate over time.

Authors' Declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for re-publication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at College of Engineering and Technology, SRM Institute of Science & Technology, Kattankulthur, Tamil Nadu, India.

Authors' Contribution Statement

This work was carried out in collaboration between all authors. MB, Conceptualization, and writing - original draft. EMV, data curation. GK review, editing and supervision. All authors read and approved the final manuscript.

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نموذج بديل جديد في بيئة الأرقام شبه المنحرفة الضبابية

بالاجانيسان م ، ميليتا فينوليا إي، كريشنافيني جي

قسم الرياضيات، كلية الهندسة والتكنولوجيا، معهد SRM للعلوم والتكنولوجيا، كاتانكولثر، تاميل نادو، الهند.

الخلاصة

في عالم اليوم الديناميكي، يعد استبدال الآلات والمرافق مسألة دائمة ومعقدة بسبب النمو التقني السريع والعولمة، وهو اهتمام مشترك في أذهان أصحاب أي عمل تجاري. الصيانة هي إجراء مجدول للتأكد من أن المعدات أو الأنظمة أو المرافق تظل طبيعية لأداء الغرض المقصود منها بشكل صحيح دون المخاطرة بخسارة وقت الخدمة بسبب فشلها. للحفاظ على درجة معينة من الاتساق والحماية، ولا غنى عن أنشطة صيانة الأداء للأنظمة والمرافق في ظروف عمل جيدة. فهو يزيد من تكاليف التشغيل عن طريق تقليل وتحسين فعالية الإنتاج وفوائده. تساعد عملية الإصلاح في الحفاظ على الأداء التشغيلي للآلات والمرافق وزيادته، وبالتالي زيادة الإيرادات. لذلك، إذا احتاج كيان أو شركة إلى مواصلة سوقها التنافسي، فمن المهم التحقق مما إذا كان سيتم تحمل تكاليف التشغيل والإصلاح بالمعدات القديمة أو استبدالها بها. ولهذا السبب، يجب أن تكون معلمات القرار مثل تكلفة الصيانة وقيمة إعادة البيع وتكلفة رأس المال وسعر الفائدة معروفة بدقة. لكن ذلك غير ممكن في الواقع، فالواقع غير مؤكد ومعقد. يتم التحكم في حالة عدم اليقين هذه بكفاءة من خلال نظرية المجموعات الضبابية. يهدف هذا العمل إلى مناقشة استبدال المعدات في بيئة ضبابية. إن التقنية الأساسية للتأكيد على معلمات الضبابية التي تشارك في العديد من مواقف العالم الحقيقي هي نظرية المجموعات الضبابية. في نموذج الاستبدال الضبابي هذا، يتم تمثيل جميع التكاليف غير الدقيقة بأرقام ضبابية شبه منحرفة (TFNs). تجد التقنية المقترحة أفضل وقت استبدال لمشكلة استبدال ضبابي دون التحويل إلى مشكلة واضحة ومدعومة بمثال عددي توضيحي.

الكلمات المفتاحية: الرقم الضبابي، نموذج الاستبدال الضبابي، نقطة المنتصف للرقم الضبابي، العمليات على الأعداد الضبلبية، ترتيب الأعداد الضبابية، عرض الرقم الضبابي.