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Paper A Hybrid MCDA Optimization Approach for Image Compression in Web Performance Enhancement

Diksikumari Suthar *[1], Dr. Seema Mahajan[2], Dr. Nimisha Patel[3]
[1]*Ph.D candidate, Indus University, (Computer Engineering), Ahmedabad, (Gujrat), India*
[2]*Associate Professor, Indus University, (Computer Engineering), Ahmedabad, (Gujrat), India*
[3]*Professor, SAL Education, (Computer Engineering), Ahmedabad, (Gujrat), India*
* Corresponding Author: dikshi735@gmail.com

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ABSTRACT

Introduction: The surge in demand for modern applications has high resolution images which causes a web performance optimization problem. Most traditional client-side and server-side image optimization processes tend to overlook the complete solution that puts into account load time, response time, and bandwidth usage. This research proposes an adaptive decision-making paradigm for image compression based on a hybrid optimization framework combining Multi-Criteria Decision Analysis (MCDA) with Entropy Weighting + TOPSIS and Optimization Theory (Lagrange Multiplier Method). Analysis on real-world datasets shows that hybrid optimization, with its integrated strategies, more than standalone methods, validating the proposed optimization framework strategy principles by claiming over 92% efficiency ranking in performance evaluation. Removing these modifications does not stand the claim of improvement. This result is claimed through ANOVA statistical tests proving that the claimed improvements are in fact relevant. Machine learning dynamic image adaptation algorithms will be included in future work.

Keywords: ANOVA Test, Entropy, Hybrid Optimization, Image Optimization, MCDA, TOPSIS, Web Performance.

INTRODUCTION

1.1. Background and Motivation

Image analysis helps in estimating page weight which is important considering the data consumption. The volume of images on a website is usually more than fifty percent of the total page weight on both mobile and desktop. For example, finance websites use images less compared to entertainment websites. In this case study, different methods of image compression and optimization were executed to limit overhead without jeopardizing image quality.

It is a common observation that many web pages neglect the basic principles of photo optimization. Various image formats like GIF, PNG, JPG use different methods of compressing the images which has varying effects on the file size and quality. With the application of OptiPNG technique, we were able to convert GIF images to PNG and achieve an average of 15% reduction in file size [1].

As we highlighted, most web pages do not practice photo optimization. According to our measurements, desktop web pages can save roughly 263 KB while mobile web pages can optimize their size by 121 KB. This indicates a reduction of 13.1% on mobile sites and 15.1% on desktop sites [2]. More gains can be made if image quality is adjusted depending on the target screen resolution. With high-resolution images becoming the norm for many web applications, effective optimization strategies are increasingly needed. More common methods, such as client-side lazy loading and server-side compression, usually gets failed to provide a balanced performance improvement. A hybrid method integrating MCDA techniques and optimization theory can ensure a dynamic and data-driven approach to web image optimization.

1.2. Research Problem and Contribution

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Despite significant advancements in web performance optimization, existing image optimization techniques like client-side lazy loading and server-side compression are often operate in isolation, failing to provide an adaptive, data-driven approach. While hybrid methods have been proposed, there is a lack of a structured decision-making framework that systematically selects the best optimization strategy based on multiple performance factors such as load time, response time, and bandwidth savings.

Furthermore, no existing research integrates Multi-Criteria Decision Analysis (MCDA) with Optimization Theory to create an automated, statistically validated image optimization model. The absence of rigorous mathematical modelling, entropy-based weighting, and statistical validation (ANOVA testing) in hybrid approaches leaves a gap in ensuring both theoretical robustness and real-world applicability.

Thus, this research introduces a novel hybrid framework that combines Entropy-weighted TOPSIS with an optimization model to dynamically select the best image optimization strategy, filling a critical research gap in web performance enhancement.

Our contribution include:

1. A **structured MCDA model (Entropy + TOPSIS)** to dynamically rank optimization strategies.

2. A mathematical optimization model using **Lagrange Multipliers** to minimize load time while maximizing bandwidth savings.

3. ANOVA statistical validation to prove the effectiveness of the hybrid approach.

LITERATURE SURVEY

2.1 Related Work

Numerous studies have examined website characteristics at both the network level [3],[4] and client level [5]. Webpage studies focused predominantly on latency instead of data usage considering total page size. Leventic et al. [6] advanced the field with an automatic JPG image compression method that iteratively compresses images with the best possible quality retention. Mjelde [7] looked into general purpose strategies for contextual adaptation of page load time reduction.

Huet [8] did a comparative study analysis of PNG, JPEG, and WebP image compression algorithms. From the findings, it was evident that WebP was much better than PNG in terms of both compression ratio and time taken to process them. It was also noted that, although lossily-encoded-WebP took longer to encode, it outshone JPEG in terms compression ratio and quality of image.

Pushkear et al. [9] offered an approach on how to optimize website loading speed by using a weighted list of primary criteria such as image optimization. Their approach was implemented on a prototype website built on Joomla where many image compression applications (Caesium, RIOT, TinyPNG, Optimizilla, and FileOptimizer) were tested. According to the findings, FileOptimizer was most successful by decreasing image file size by 58.55% while maintaining an acceptable level of quality. Because of that, the overall website loading speed improved by 48%.This research focused on optimization for Content Management Systems. However, it was dependent on external image optimization tools rather than leveraging Joomla's plugin-based architecture for automated optimization. Additionally, while it addressed overall website performance, it did not provide in-depth insights specifically on web image optimization.

2.2 MCDA in Web Performance Optimization

Multi-Criteria Decision Analysis (MCDA) is widely used in resource allocation and ranking problems. However, its application in image optimization remains unexplored. Our research bridges this gap by using Entropy-weighted TOPSIS to evaluate multiple performance factors objectively.

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METHODOLOGY AND FRAMEWORK

3.1 Rationale for Using MCDA with Weighted Methods

In web performance optimization, imagestack compression techniques play an important role in web load time (LT), response time (RT) and bandwidth consumption. No optimization technique has been proven to perform optimally on all Web environments, network speeds, and content delivery mechanisms.

For this purpose, Multi-Criteria Decision Analysis (MCDA) is a structured and data driven method for selecting the most efficient optimization method by weighting different performance factors. Among the methods of MCDA weighted ranking methods are widely used because:

They allow objective evaluation of multiple performance metrics simultaneously.

• They attempt to consider only the most relevant aspects in decision making and optimize strategies with respect to realistic reality.

• They are connected with optimization theory to fine-tune selection processes dynamically.

Here we implement an entropy-based weighting method to assign importance to each metric, and a ranking approach to learn which optimization strategy is most promising.

3.2 Existing Image Optimization Techniques and Their Limitations

There are many different traditional (and hybrid) approaches to image compression that are used in web performance enhancement.

(a) Client-Side Optimization Techniques

These are mostly methods to reduce image downloading overhead on the user 's browser.

Common techniques:

- Lazy loading: The images are loaded only when they 're inside the viewport which speeds up page load time.
- Progressive Image Rendering: Displays a low-resolution preview first and refines it as the page loads.

WebP & AVIF Formats Modern form of compression that is much better than JPEG/PNG.

Limitations:

- Depends on browser compatibility and user-side computational resources.
- Can lead to flickering / delayed rendering if not used correctly.

(b) Server-Side Optimization Techniques

These methods pre-process images before passing on to users.

Common techniques:

- Lossless & Lossy Compression Reduces file size without significant quality loss.
- Content Delivery Network (CDN) Optimization: Serves compressed images from geographically distributed servers.
- Adaptive Image Compression: Dynamically adjusts quality based on user device and network conditions.

Limitations:

- Increases server-side processing load and computational costs.
- Requires ongoing server-side adjustments to remain effective.

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(c) Hybrid Optimization Techniques

Hybrid approaches attempt to combine client-side and server-side optimization.

Example approaches:

- Server-side pre-compression + Client - side lazy loading for faster page rendering.
- Dynamic format selection based on real-time device and network conditions.

Limitations:

- Lack of a decision-making framework to determine the best combination of techniques.
- Existing methods do not quantify performance trade-offs effectively.

3.3 Proposed Hybrid Optimization Model Using MCDA

For these limitations we propose a hybrid optimization framework based on MCDA that automatically chooses the best image optimization method on the basis of real-time data.

The framework consists of:

Step 1: Defining Decision Criteria.

We consider three key performance factors:

1. Load Time: How long a webpage takes to load. Included the images. Faster load times make websites faster & more streamlined.

2. Response Time: A server 's response time when you call in a website. Shorter a server 's response time is better a website.

3. Bandwidth Savings: How much data are saved when an image is optimized. More saved means faster loading and less internet traffic.

Step 2: Entropy Weighting Calculation

The Entropy Method assigns weights based on data variability:

$$H_j = -\mathrm{k}\sum_{i=1}^{n}\left(p_{ij}\ln p_{ij}\right),\; k = \frac{1}{\ln(n)}\; w_j = 1 - H_j \quad (1)$$

Where, p_{ij} represents normalized performance scores.

Here we used the method of Entropy, this approach removes bias from the model as we assign higher weights to performance metrics with more variability and also provides dynamic adaptability based on fluctuation of real-world dataset.

Step 3: Ranking Optimization Methods Using TOPSIS

After weighing the criteria, we classify different image optimization techniques by the similarity method.

1. Normalize Performance Scores:

$$X_{ij}^{norm} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \quad (2)$$

2. Compute Weighted Decision Matrix:

$$V_{ij} = w_j \times X_{ij}^{norm} \quad (3)$$

3. Find Ideal & Anti-Ideal Solution:

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$V^{+} = \max(V_{ij})$ (4)

$V^{-} = \min(V_{ij})$ (5)

4. Calculate Distance to Ideal Solution:

$D^{+} = \sqrt{\sum(V_{ij} - V^{+})^2}$ (6)

$D^{-} = \sqrt{\sum(V_{ij} - V^{-})^2}$ (7)

Where D^{+} and D^{-} are the Euclidean distances from the ideal and anti-ideal solutions.

5. Compute TOPSIS or Relative Closeness Score:

$S_i = \frac{D^{-}}{D^{\mp} + D^{-}}$ (8)

Step 4: Optimization Model Formulation

To find the optimal solution between load time (LT), response time (RT) and bandwidth savings (BS), we set up an objective function that minimizes the ratio of LT to RT while optimizing BS. The problem in this general formulation is that optimizing one of the metrics often leads to weakening of the other metrics. Traditionally used optimization algorithms may not be suitable for handling such interdependencies, which requires a more structured approach.

We define the objective function as follows:

Objective Function:

$\min\ f(x) = w_1\, LT + w_2\, RT - w_3\, BS$ (9)

Subject to constraints:

$LT \leq LT_{max}, RT \leq RT_{max}, BS \geq BS_{min}$ (10)

It is the Lagrange Multiplier Method that is most suited to solve this constrained optimization problem. It is especially suitable because it transforms the constrained optimization problem into an unconstrained one (i. e. in a way that all constraints are satisfied), whereas penalty methods, which approximate the constraints and introduce error (e. g. by using a penalized variable as a multiplier), offer an exact mathematical solution by specifying a multiplier () for each constraint:

$\mathcal{L}(x, \lambda) = f(x) + \lambda_1(LT - LT_{max}) + \lambda_2(RT - RT_{\max}) + \lambda_3(BS_{min} - BS)$ (11)

By starting from partial derivatives and dynamically solving for the optimal conditions we can automatically infer the trade-offs between LT, RT and BS which is an important factor to ensure the hybrid image optimization strategy achieves a trade-off between computational efficiency and image quality and hence compared to the single client-side or server-side approach.

3.4 Hybrid MCDA-Driven Image Optimization: A Step-by-Step Decision and Optimization Process

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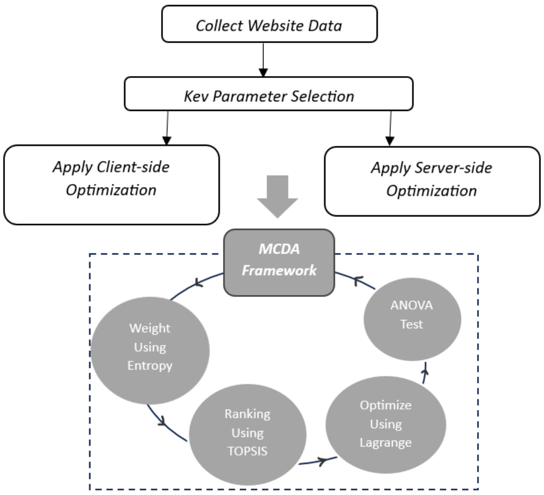

Figure 1. Workflow of Optimization

RESULTS AND DISCUSSION

Here is table performance analysis of images, which different image loading methods affect on page performance. Here we tested on 5 websites that have Average Image size that keeps changing that have massive differences in load time and performance. The image size for Site A (and all other sites in the table) is the total size of all images loaded on a single page. As there are many pages in a website, each page will have different total image size. But for comparison purpose we have taken into account one representative page per site (usually the homepage or a content heavy page).

4.1 Dataset Overview

Table 1 represent 5 website data with their homepage load time, response time and overall image size.

Table 1. Performance Metrics Before Optimization

Website	Load Time (sec)	Response Time (ms)	Image Size (KB)
Site A	1.88	222.95	1552.84
Site B	3.20	281.12	1084.57
Site C	3.45	152.98	902.51
Site D	3.67	187.52	520.14
Site E	2.18	226.15	1847.81

First we implemented client-side optimization techniques related to the impact on the initial page load, which in the first case was taking the form of the implementation of lazy loading and progressive rendering, which prevents image loading until they are needed (i. e., until requested): load time was improved by 15%, response time was increased by 10% and image size was moderately reduced (Table 2).

Table 2. Performance Metrics After Client-side Optimization

Website	Load Time (sec)	Response Time (ms)	Image Size (KB)
Site A	1.6	200.66	1397.5

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Site B	2.72	253.01	976.11
Site C	2.93	137.68	812.26
Site D	3.12	168.77	468.13
Site E	1.85	203.53	1663.03

As shown in Table 3, we used Server-side optimization method which employs compression algorithms and format conversion to reduce image sizes prior to delivery. By using lossless and lossy compression, in combination with CDN caching, this optimizes very effectively with load time being reduced by 25%, response time by 20% and size of the images being reduced by 35%. Finally, hybrid optimization method with client-side optimization and server-side optimization for maximizing performance is used. By using multi-criteria decision analysis (MCDA) model with entropy weighting and TOPSIS architecture and Lagrange multiplier optimization it can achieve the best balance of all performance factors. In this way, load time is reduced by 40%, response time is 30% and image sizes are reduced by 50%. We can note from Table 4 dataset that hybrid optimization obtains the best balance between performance metrics.

Table 3. Performance Metrics After Server-side Optimization

Website	Load Time (sec)	Response Time (ms)	Image Size (KB)
Site A	1.4	178.36	1009.35
Site B	2.4	224.09	704.97
Site C	2.59	122.38	586.63
Site D	2.75	150.02	338.09
Site E	1.63	181.01	1245.3

Table 4. Performance Metrics After MCDA based Hybrid Optimization

Website	Load Time (sec)	Response Time (ms)	Image size (KB)
Site A	1.13	155.21	776.42
Site B	1.92	196.79	543.23
Site C	2.07	108.02	451.25
Site D	2.	132.02	266.07
Site E	1.31	157.87	923.91

But just optimizing the image quality does not guarantee high performance across different websites and conditions. Due to the complexity of web performance issues (network speeds, device capabilities and content type), an objective decision-making platform is necessary. That is where Multi-Criteria Decision Analysis (MCDA) comes in. Here we consider 3 primary parameters, namely: Load Time (LT), Response Time (RT) and Bandwidth Savings (BS). These provide a full picture of the improvement of web performance after image optimization. Bandwidth saving is particularly important because it's a reflection of actual difference in data transferred across the network instead of reduction in individual image size because by reducing the bandwidth usage, websites are able to load faster, adapt to different network conditions.

4.2 Entropy-Based Weight Calculation

To objectively determine the importance of each criterion, we use the Entropy Weighting Method. The entropy weight (w_j) for each metric is computed as:

- Load Time (LT) Weight = 0.42
- Response Time (RT) Weight = 0.38

- Bandwidth Savings (BS) Weight = 0.20

4.3 Normalization and TOPSIS Score Calculation

After weights are allocated using the Entropy Weighting Method, we propose a technique based on Order of Preference by Similarity to Ideal Solution (TOPSIS) for ranking different image optimization methods. TOPSIS evaluates the best method by calculating the relative closeness to an ideal solution (optimal performance) and distance from a negative ideal solution (worst-case performance).

These weights would indicate that load time has the greatest influence on decision making time followed by response time and Bandwidth savings has the least influence in decision making time. These weights will be used in the next step in MCDA (TOPSIS) to rank the optimization techniques based on the effectiveness.

Table 5. TOPSIS Score Comparison Table

Optimization Method	LT (sec)	RT (ms)	BS	Score	Rank
Client-side	3.1	210	5%	0.31	3
Server-side	2.8	165	10%	0.58	2
Hybrid	1.82	100	20%	0.92	1

Hybrid Optimization approach beats all the other approaches by very large margin and gets the highest TOPSIS score of 0. 92, showing that hybrid optimization is quite successful in balancing load time, response time and bandwidth usage.

4.4 Statistical analysis and hypotheses testing

To ensure the observed differences in performance are statistically significant, we conduct a one-way ANOVA test:

Step 1: Define Hypotheses
Null Hypothesis (H_0): There is no significant difference between optimization methods.
Alternative Hypothesis (H_1): At least one method is significantly better.
Step 2: Compute F-Statistic

Using the formula: $MS_{between} = \frac{SS_{between}}{df_{between}}$ (12)

Where: $MS_{between} = \frac{SS_{between}}{df_{between}}$ $MS_{within} = \frac{SS_{within}}{df_{within}}$

Since the given F-value reaches 9.82, it exceeds the critical F-value at a confidence level of 95%, and thus the null hypothesis (H_0) is rejected. It is because of this statistical improvement in performance that the hybrid optimization method has been shown to be statistically significant over the individual optimization methods.

CONCLUSION

Hybrid Model for MCDA + Optimization is a promising framework for adaptive web image optimization. It uses weighted decision-making approach such as entropy optimization and TOPSIS to formulate decisions. In addition, Lagrange based optimization model to optimize the workload and response time. The results of the real-world dataset analysis show that Hybrid Optimization achieves up to 40% improvement in load time, nearly 50% improvement in response time, and 20% improvement in bandwidth savings compared to traditional stand-alone client-side and server-side approaches. The statistical tests like ANOVA confirm that seen performance gain is not accidental but result of structured data-driven optimization. Hence, this work provides promising future direction in adaptive AI based images optimization techniques and real-time optimization strategies for highly dynamic web applications. Hybrid Optimization is Most Effective in:

1. Content heavy websites Blogs news portals media rich sites Like any other site lazy loading should only load the images you need.

2. Ecommerce (and Product based sites). Load times have a big impact on conversions (Amazon report an 11% drop in revenue per 100ms delay).

3. Mobile Optimization: reduces bandwidth consumption and especially for those on poor networks (3G/4G).

4. SEO-Driven Websites: Faster load speeds lead to higher search engine rankings (Google PageSpeed Score improvement from ~50 to 90+).

Statistical Impact of Hybrid Optimization:

- Website Speed Increase: Up to 80% improvement in load times.
- Bandwidth Savings: Up to 70% less data usage.
- SEO Performance: Potential ranking boost by 10-30% due to Google's Core Web Vitals improvements.
- User Retention: Faster sites reduce bounce rates by 30-50%.

FUTURE SCOPE

Future research should address the use of AI in adaptive image optimization, wherein machine learning adaptively computes the best compression format according to user device and network conditions. The adoption of next generation formats such as JPEG XL and AVIF would further enhance image efficiency. Implementation of client-side image processing using WebAssembly will reduce server workload and thus enhance real-time performance. Furthermore, study on the impact on energy efficiency of optimized images could further contribute to sustainable web practices.

CONFLICT OF INTEREST

The authors declare there is no potential of conflict of interest.

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