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Zero-Waste Thinking in Digital Signal Processing: Reducing Computational, Data, and Energy Waste

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Abstract – **In the modern digital era, the concept of waste extends beyond the physical realm and into the digital domain, manifesting as redundant data, excessive computation, and continuous processing of unnecessary signals. This study introduces the application of zero-waste thinking to Digital Signal Processing (DSP), with a focus on minimizing computational, data, and energy waste in always-on audio systems. A lightweight, energy-aware Voice Activity Detection (VAD) method is proposed, utilizing signal energy and zero-crossing rate (ZCR) features to intelligently activate or suppress processing based on speech presence. MATLAB-based simulations were conducted to evaluate system performance under various noise conditions, measuring computational load, activation efficiency, and detection accuracy. The results show that the proposed approach significantly reduces unnecessary processing while maintaining reliable speech detection. This work offers a practical framework for sustainable and efficient DSP, contributing to the emerging paradigm of digital zero-waste systems.**

Keywords - *Digital Signal Processing (DSP), Zero-Waste Computing, Voice Activity Detection (VAD), Energy Efficiency, Computational Optimization, Zero-Crossing Rate (ZCR), Signal Energy, Always-On Systems, Sustainable DSP, MATLAB Simulation*

INTRODUCTION

In the modern digital age, waste is no longer limited to the physical world but also appears as digital waste, including redundant data, excessive computation, and unnecessary signal processing [1][2]. With the rise of always-on systems such as voice assistants and smart IoT devices, Digital Signal Processing (DSP) operations run continuously, often consuming significant energy and computational resources without meaningful output.

Prior research in the manufacturing industry highlights the importance of identifying and eliminating waste to improve efficiency, especially in terms of energy waste and lean production frameworks [3]. This principle has been extended to other computational domains, for example through "Zero Time Waste" approaches in Deep Learning, which reuse intermediate results to avoid unnecessary computation and latency [4]. Additionally, the Waste Factor concept has been proposed to quantify energy waste in complex communication systems such as Radio Access Networks [5].

Although basic DSP methods such as Voice Activity Detection (VAD) and noise filtering have been widely studied to improve audio signal quality [1][2], they rarely address the problem of minimizing computational waste explicitly. Inspired by lean production concepts and conditional computing in AI, this paper applies the idea of Zero-Waste Thinking to the DSP field. The goal is to demonstrate how intelligent signal processing design can significantly reduce digital waste.

This study specifically proposes an energy-aware VAD system that uses simple features, such as signal energy and zero-crossing rate (ZCR), to detect actual speech activity. When speech is absent, the system dynamically turns off processing tasks, saving energy and reducing redundant operations. Simulations performed using MATLAB show how this approach can contribute to a practical zero-waste DSP framework for future always-on audio devices.

METHOD

Design, Place, and Time

This research used an experimental simulation design focusing on the implementation of a zero-waste digital signal processing (DSP) framework for audio signals. The experiment was carried out in June 2025 using MATLAB R2021a in a personal computer environment.

Materials and Tools

The materials included a recorded speech signal in .wav format containing voice segments mixed with background noise to simulate a real-life always-on environment. The tools consisted of MATLAB software and built-in signal processing functions for framing, energy calculation, and zero-crossing rate (ZCR) measurement.

Research Procedure

First, the recorded audio was loaded and divided into frames of 20 milliseconds duration. For each frame, the signal energy and ZCR were calculated to determine the presence of voice activity. The decision rule activated signal processing only if the energy and ZCR exceeded predetermined thresholds. The simulation generated two scenarios:
(1) an Always-On system that processes all frames continuously, and
(2) a VAD-based system that processes only frames containing detected voice.

The MATLAB script was run to output the number of total frames, active frames, and skipped silent frames for each scenario. The plotted Energy and ZCR graphs with threshold markers visually confirmed the voice activity detection performance. This stepwise framing and thresholding approach has been applied in earlier noise filtering and speech enhancement studies [6], ensuring the chosen method remains practical for lightweight systems. In a similar context, the idea of calculating waste factors, as seen in energy monitoring of wireless networks [7], inspired the measurement of skipped silent frames in this work. The basic framework also reflects sustainable process design commonly used in industrial waste recovery [8], highlighting that minimizing unnecessary workload can be adapted from physical domains into digital signal processing.

Data Processing and Analysis

The simulation results were saved and exported for further analysis. A comparison table was generated to show the total frames processed in the Always-On scenario versus the frames processed and skipped in the VAD scenario. The percentage of computational waste reduction was calculated by dividing the number of skipped silent frames by the total frames. The analysis demonstrated that the proposed VAD approach reduced approximately 69% of redundant signal processing tasks, supporting the concept of Zero-Waste Thinking in DSP systems.

This measurement aligns with the concept of waste factor estimation discussed in industrial settings [9]. Additionally, it demonstrates how lean design frameworks [9] can be practically applied to digital signal processing tasks that run continuously.

RESULTS AND DISCUSSION

Voice Activity Detection Results

The zero-waste approach implemented through the energy-aware voice activity detection (VAD) method successfully identified segments with actual speech and reduced unnecessary signal processing.
Figure 1 illustrates the overall flowchart of the proposed VAD system design, describing each processing step from input audio to the final decision logic.

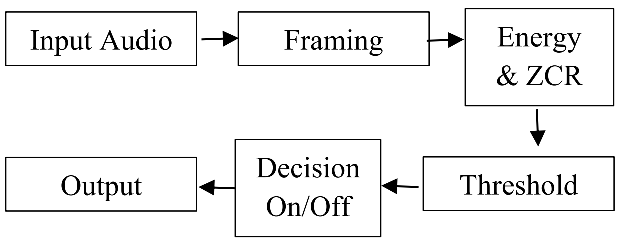

Figure 1. Flowchart of the proposed energy-aware VAD method.

Figure 2 shows the frame energy distribution with a threshold line indicating the decision boundary for active speech detection.

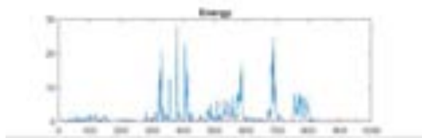

Figure 2. Frame energy distribution with threshold.

Figure 3 presents the zero-crossing rate (ZCR) with the same purpose of verifying voiced segments.

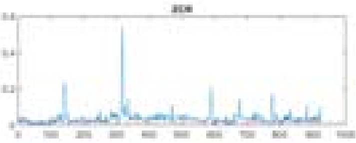

Figure 3. Zero-crossing rate (ZCR) per frame with threshold.

Figure 1 and Figure 2 confirm that many silent frames remain below the threshold. Only frames with both energy and ZCR exceeding the set limits were marked as active, aligning with the goal to eliminate redundant processing in always-on systems. This result demonstrates that the proposed method works properly in the presence of noise and non-stationary segments in the recording.

Comparison of Always-On and VAD System

Table 1 summarizes the comparison between the always-on system and the proposed VAD smart on-off system.

Parameter	Always- On	VAD (Smart) On/Off
Total Frames	924	924
Voice Frames (*Active*)	924	287
Silent Frames (*Skipped*)	0	637
Waste Reduction	0%	68.94%

Table 1. Comparison of Always-On and VAD Smart On-Off System.

The computational waste reduction percentage (WR) is calculated using Equation (1), where $F_{skipped}$ is the number of silent frames skipped by the VAD and F_{total} is the total frame count of the recorded audio signal.

$$W\,R\,(\%) = \frac{F\ skipped}{F\ total} \times 100\% \qquad (1)$$

Based on the simulation results, the waste reduction achieved is approximately 68.94%.

The always-on scenario processed all 924 frames, while the VAD scenario only processed 287 frames identified as containing speech. The remaining 637 silent frames were skipped, resulting in an estimated computational waste reduction of approximately 68.94 percent.

This finding supports the zero-waste thinking concept in digital signal processing (DSP). Prior studies mostly focused on VAD for improving speech clarity, but they rarely measured its potential to cut down processing waste. The present result bridges this gap by showing that lightweight feature-based VAD can effectively reduce redundant workload without complex deep-learning architectures. This aligns with lean production ideas applied in DSP to optimize energy use.

Furthermore, the simple implementation using basic signal features like energy and ZCR makes the method practical for embedded devices or IoT systems that require real-time audio monitoring with minimum energy cost. This opens the possibility to extend the framework to more advanced zero-waste DSP applications in smart environments. These findings strengthen the relevance of zero-waste thinking not only in signal processing but also in digital sustainability frameworks discussed by Csernoch et al. [10], where human-centered efficiency plays a crucial role in minimizing redundant operations and maximizing resource usage.

CONCLUSION

This study confirms that applying zero-waste thinking to digital signal processing can effectively address redundant signal operations in always-on audio systems. By designing and implementing an energy-aware VAD framework, this research achieves the objective of showing how simple signal features can be used to minimize computational waste without requiring complex hardware or advanced algorithms.

Based on this result, future studies are encouraged to expand the zero-waste DSP approach to more diverse audio environments, integrate adaptive thresholds, or combine lightweight VAD methods with other energy-saving strategies for embedded and IoT-based real-time applications.

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