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Optimizing blade design for MSW bag opener machines using FEA

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Abstract. The management of municipal solid waste (MSW) presents a significant challenge worldwide, with potential health and environmental hazards if not properly recycled or disposed of. A promising approach to address this issue is the mechanical-biological treatment (MBT), which can process MSW and minimize landfill deposits. The efficacy of MBT is highly reliant on the bag opener machine's ability to efficiently extract waste from bags. Thus, enhancing the bag opener's performance is crucial for the MBT system's overall effectiveness. This study introduces a set of four innovative blade designs for waste bags opening equipment, aimed at achieving optimal efficiency, minimal power usage, reduced maintenance overhead, and prolonged operational lifespan. These designs were crafted using the 3-D modelling software SOLIDWORKS. Additionally, the paper outlines the primary calculations of the bag opening equipment, derived from a synthesis of MSW characterization research. The robustness, functionality, and longevity of the blades were evaluated through finite element analyses (FEAs) (static/fatigue) at 1 MPa applied pressure. The results indicate that the new design can handle approximately 30 tons per hour, consuming only 22 kW of power. The blade designs reveal that the maximum Von Mises stress and the minimum factor-of-safety (FOS) across models A, B, C, and D, are 14.74, 14.32, 14.16, and 13.46 MPa, and 15.18, 18.66, 19.21, 19.43, and 20.44, respectively. Fatigue stress analysis indicates a lifespan of (10^6) cycles for all models. Model D is determined to be superior in terms of strength, FOS, and durability.

Keywords: Bag Opener; Pre-Shredder; FEA; Fatigue; SOLIDWORKS

Abbreviations

DIN	Deutsches Institut für Normung (German institute for standardization).
FEA	Finite element analysis.
FOS	Factor-of-safety.
MBT	Mechanical/biological treatment.
MSW	Municipal solid waste.
RDF	Refused derived fuel
RVM	Reverse vending machine.
SRF	Solid recovered fuel

1. Introduction

The composition of the municipal solid waste (MSW) comprises a variety of non-hazardous substances produced by urban populations, such as leftover fabric, food, certain plastics, and paper [1],[2],[3]. The effective management of MSW is a significant challenge for environmental sustainability, complicated by the difficulty in regulating its production and the intricate processes involved in its treatment and disposal. Additionally, changes in demographics, economics, and societal factors further complicate the management of MSW, placing more demands on waste management services [4].

Among the methods for managing waste, mechanical treatment is a popular approach for extracting valuable elements from waste [5],[6],[7]. This technique includes downsizing, segregating, sorting, and reclaiming materials and energy from assorted waste [8],[9]. Benefits of mechanical treatment include less waste sent to landfills and incinerators, higher recycling rates, production of solid recovered fuel (SRF) or refuse-derived fuel (RDF) from non-recyclable refuse, and preparing the organic portion of waste for further biological processing [10].

The bag opener of MSW, also known as a pre-shredder, plays a crucial role in breaking open and emptying bags filled with mixed waste [9]. Its importance in mechanical treatment of waste stems from its ability to improve the quality and efficiency of subsequent separation and sorting, increase the recycling and recovery of valuable materials, reduce moisture and contamination in organic waste, and cut down on the operational and maintenance expenses of the treatment facility [10],[11],[12].

Characterization data of MSW is vital for the bag opening equipment design, influencing the dimensions, form, material, velocity, and power of the shearing elements (i.e., cutting blades). The density, composition, moisture, and size distribution of the waste define its physical and chemical characteristics, such as toughness, abrasiveness, stickiness, and energy content. These traits affect blade wear, machine power usage, and the quality of the shredded material [13], [14].

Various bag opener machines for MSW exist, like pre-shredders with single or twin shaft design, each one has its own set of pros and cons in terms of capacity, energy use, efficiency, and maintenance costs in opening bags [5], [15], [16].

Designing a bag opener for MSW is a complex task influenced by many factors [17]. Blade design is paramount, significantly affecting the machine's ability to efficiently break and empty waste bags [18],[19]. Factors such as blade shape and size, material and surface coating, and their arrangement and spacing are crucial for blade design [20]. Enhancing the configuration of blades is crucial for achieving maximum efficiency in opening bags, low energy consumption, minimal maintenance costs, and extending the machine's lifespan [18],[19]. Different bag opener models may include distinctive blade configurations to handle various types of waste materials/bags [17].

Shredders are available in various configurations, including single, double, and quadruple shaft designs, each with its own set of strengths and weaknesses in terms of capacity, energy efficiency, upkeep costs, and operational effectiveness [21]. The design and functioning of these machines depend on several factors, such as the type of material being processed, the desired end-product shape, subsequent processing stages, and the conditions under which they operate.

While numerous studies have explored the limitations and advancements of existing shredder models, such as the counter-rotating twin-shaft shredder [22] and the landfill compactor shredder attachment [23], A research void still exists concerning the specific design features and functional efficiency of MSW bag opening equipment. These machines are specially designed to tear open and empty bags containing a mix of materials.

Shredders are employed for a variety of waste types, including agricultural refuse [24], household garbage [25], and polyethylene terephthalate (PET) bottles [26]. Research has been conducted to develop shredders that convert waste into useful byproducts like fertilizer, small pieces, and components for Reverse Vending Machines (RVM). These studies highlight the benefits of using shredders for reducing waste, enhancing recycling, and recovering energy. Nonetheless, the specific challenges and potential of shredders in handling MSW—a complex and varied waste stream requiring advanced and efficient shredding solutions—have not been fully addressed.

The technical aspects of shredders, such as the number of cutter shape, cutting edges, material, and surface coating, significantly impact their operational efficiency and lifespan. Some research has focused on optimizing these technical details through various methods, including the use of blade reversal [27], Time-dependent finite element analysis [28], and careful selection of materials and hardening techniques [29]. These studies provide valuable insights for selecting the best blade designs for shredders. However, they often overlook the unique properties and needs of MSW, which differ from other waste types due to its variable density, composition, moisture content, and size distribution.

Present studies indicate knowledge gap concerning the design and efficiency of MSW bag opening machinery. While there is extensive study on shredders for different waste types and aspects, the particular performance and design of bag opening equipment have not been the focus. More research is needed on blade design for these machines to enhance their performance and longevity, thereby improving the quality and efficiency of downstream separation and sorting processes.

The innovative bag opening machines' blade design for MSW treatment is presently in the theoretical research phase. Finite element analysis provides preliminary insights into how various design parameters influence blade performance and durability. In light of these results, various blade designs will be fabricated and integrated into a prototype rotor of a bag opener for subsequent empirical assessment of blade efficacy and durability.

2. Methodology

This study aims to improve the bag-opening mechanisms within waste processing plants around the world. Adopting a mixed-methods approach, it seeks to evaluate and develop a new blade design for MSW bag opening equipment. The research focuses on three main questions: the blade's stresses and forces and their components, the best materials and sizes for these blades and components, and the electrical power needed for the operating mechanism of the equipment.

The research is organized into three phases for a thorough investigation. Initially, the design of a blade is created using SOLIDWORKS software. Then, the blade's strength, functionality, and longevity are assessed through FEA (static/fatigue). Finally, the operational power required for the bag-opener is determined using force and torque calculations. This structured approach provides a detailed analysis of the operating mechanism of the equipment, offering significant contributions to enhancing waste treatment plant operations.

2.1 Bag opener blade design methodology

2.1.1 Design criteria

The cutting blades design in a bag opener is crucial for its efficient and dependable functioning. This paper will concentrate on the blade design, providing a main calculation for the MSW bag opener. Key considerations for crafting the blade design include the dimensions, form, composition, velocity, and energy requirements [30].

2.1.2 Assumptions for calculations of the bag opener

The effectiveness of pre-shredded waste in later treatment phases hinges on opened waste bags lump size, which must be adequate to conserve recyclable materials. The operations of Municipal Solid Waste Treatment (MSWT) facilities are tailored to a particular fragment size, determined by the waste's morphological and size analysis. The throughput of MSWT facilities is influenced by various factors, including waste's bulk density and the bag opener machine's efficiency and velocity. Table 1 outlines the foundational bag opener machine assumptions. The performance and productivity of the machine are significantly affected by the design of the bag opener drum and the configuration of the blades. With a drum diameter of 800 mm [31], the blades are set in a spiral arrangement to enhance each blade's impact, prevent material entanglement, and guarantee consistent cutting patterns and durability [32]. The cutting chamber, where blades disjoin the waste from the bags, is designed to maximize bag opening efficacy, material flow, energy efficiency, and minimize noise [33],[34]. It primarily comprises the drum with blade assembly and fixed cutters (comb or mesh), strategically placed to refine mesh sizing and improve the process of opening bags, as depicted in Figure 1.

Table 1. Main assumptions of the bag opener.

Parameter	Value	Reference
Output lump size [mm]	0:300	[32]
Mesh gap size [distances of fixed cutters] [mm]	100	[35]
Diameter of the drum (D [mm])	800	[31]
Length of the Drum (L [m])	2	-
Longitudinal number of blades (BL_L)	17	-
Circumferential number of blades (BL_D)	2	-
Gross number of blades (BL_T)	34	-
Acting force mean radius (R_m [mm])	650	-
Number of acting cutting edges (BL_A)	3	-
Bag opener efficiency (η [-])	0.8	[34]
Drum revolution (N [rpm])	20	[33]

2.1.3 Design of blade shape and dimensional specifications

Four blade models have been developed for the MSW bag opener in this paper, each featuring distinct cutting edge angles as illustrated in Figure 2. Despite varying angles, all blades share identical dimensions with a cutting edge length of 180 mm and a thickness of 20 mm. The meshing interaction between the stationary comb and the rotating blades in the cutting chamber necessitates a specific range of cutting edge angles for both the moving and fixed blades to ensure optimal cutting performance. The angles are set as follows: Model A at 60 degrees, Model B at 50 degrees, Model C at 45 degrees, and Model D at 30 degrees. Each blade model is designed with a dual cutting direction capability to enhance efficiency and facilitate self-cleaning. The blade material, chosen based on waste characterization findings, is DIN

1.0044 (S275JR) or ST-44, known for its wear resistance, with its mechanical properties detailed in
Table 2.

Table 2. Mechanical properties for DIN 1.0044 material (or S275JR equivalent).

Parameter	Value
Elastic Modulus [N/mm²]	210,000.00
Poisson's Ratio [-]	0.28
Shear Modulus [N/mm²]	79,000.00
Density [kg/m³]	7,800.00
Tensile Strength [N/mm²]	410.00
Yield Strength [N/mm²]	275.00

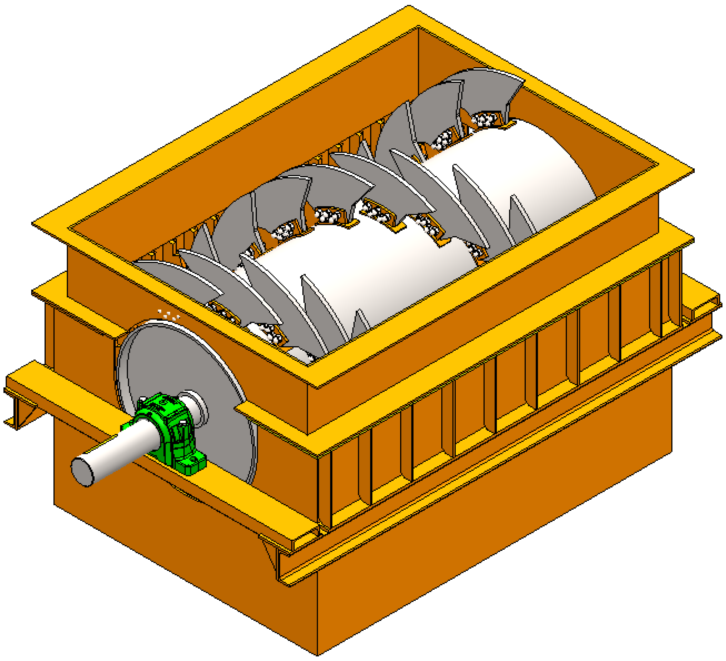


Figure 1. Blades arrangements with drum design assembled with the cutting chamber.

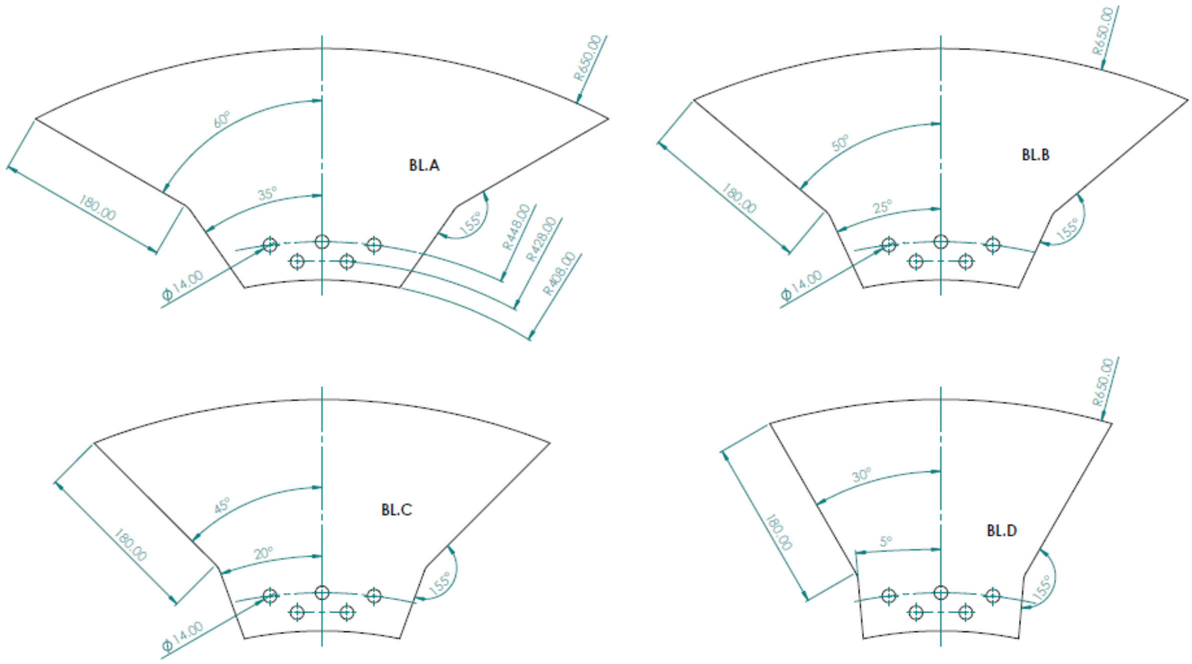


Figure 2. Types of blade models.

2.1.4 Capacity calculation for the bag opener

To determine the capability of the bag opener, proceed with the following instructions:

1. Surface Speed of the Drum (v) = π × N × D
2. Throughput (T) = v × L × η
3. Capacity by Volume (V)= T × Thickness of the Blade
4. Capacity by weight (Q_m)= V × ρ × 60 min/hr.

2.1.5 Power calculation

While the shear strength of MSW is noted at 250 kPa [36], a pressure of 1 MPa is applied to the blade's cutting edge in calculations to account for unforeseen operational scenarios, such as the presence of foreign materials. The steps to determine the power consumption are as follows:

1. Cutting Force (F [N]) = BL_A × P (Pressure)× A (Cutting Area)
2. The Required Torque (T [N.m) = F × r (Radius)
3. The Required Power (P [kW]) = (1/1000) × (T× ω)
4. Selected Motor Power (P_m [kW]) = P/ η_m

2.2 Finite element analysis

Finite Element Analysis (FEA) is a computational technique used to design and refine the blades of MSW bag openers, which face operational pressures and stresses. To pre-empt failure and schedule maintenance, the lifespan of each blade is determined through static and fatigue FEA evaluations. Static FEA assesses the blades' von Mises stress, deformation, safety margin, and strain when under stress. Fatigue FEA predicts the blades' endurance and resilience, drawing on data from static FEA.

2.2.1 Mesh generation

An effective mesh accurately represents the system's structure and dynamics, minimizing errors in the analysis. The study employs a blended curvature mesh, with a standard of 16 Jacobian points for quality, a minimum of 8 elements per circle, and an element size growth ratio of 1.4 across all mesh sizes.

2.2.2 Boundary Conditions

A standard pressure of 1 MPa is applied to the blades' cutting edges. The system is modelled as isotropic. Blades are secured using five bolts per hole (fixed faces), with a roller fixture supporting the faces, as depicted in Figure 3.

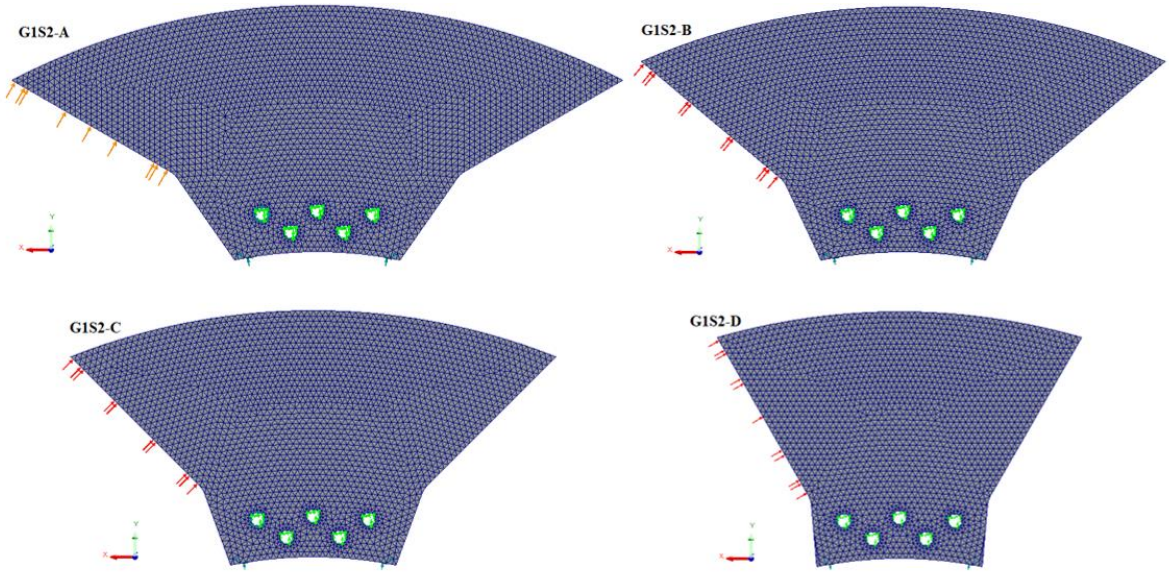


Figure 3. Boundary conditions with mesh applied to each blade model.

3. Results and discussion

3.1 Main calculation results of the bag opener

The performance data presented in Table 3 showcases the MSW bag opener's robust processing capabilities. The machine's Drum Surface Speed (v) is determined to be 50.27 meters per minute, showcasing its rapid operational pace. The Throughput Calculation (T) stands at 80.42 square meters per minute, indicating a notable processing capacity within each time frame. The Volume Processed Per Minute (V) is assessed at 1.61 cubic meters, highlighting the machine's efficiency in handling a considerable volume of waste. Lastly, the Mass Processed Per Hour (Q_m) is calculated to be 28.95 tons, underscoring the machine's proficiency in swiftly managing a large quantity of waste.

Table 3. Calculations of the capacity.

Parameter	Value
The Surface Speed of the Drum (v [m/min])	50.27
Throughput (T [m^2/min.])	80.42
Capacity per Volume (V [m^3/min.])	1.61

Parameter	Value
Capacity per Weight (Q_m [ton/hr.])	28.95

Table 4 outlines the power requirements and consumption for the MSW bag opener's design. It indicates that the design requires a significant power input to operate efficiently. For example, the operation of spinning the drum and tearing open the bags requires about 15 kW. The motor's efficiency is noted to be 0.8, meaning that 80% of the electrical energy is converted into mechanical action. The estimated power needed by the motor is approximately 18.38 kW, suggesting the motor must supply more power than what is used by the bag opener. Consequently, the chosen standard power rating for the motor is 22 kW, aligning closely with the estimated power requirement.

Table 4. Power calculations.

Parameter	Values
Single Blade Force (F_B [N])	3,600.00
Gross Cutting Force (F_T [N])	10,800.00
Required Torque (T [N.m])	7,020.00
Required Power (P [kW])	14.70
Efficiency of the Motor (η_m [-])	0.80
Required Motor Power (P_W [kW])	18.38
Motor Power Standard Selection (P_{motor} [kW])	22.00

3.2 Static FEA assessment

In this analysis, the static FEA outcomes, generated using SOLIDWORKS, are examined. The stress distribution across the four blade models when subjected to pressure is depicted in Figure 4. Stress and strain reflect the internal forces and the extent of deformation in the blades, with lower levels indicating a blade's better resistance to pressure and its ability to retain shape. As shown in Figure 5 Model D registers the lowest maximum stress (13.46 MPa) and strain ($5.018x10^{-5}$), in contrast to model A, which records the highest stress (14.74 MPa) and strain ($5.404x10^{-5}$). Models B and C show relatively similar stress (14.32 MPa and 14.16 MPa, respectively) and strain ($5.242x10^{-5}$ and $5.194x10^{-5}$, respectively), with the highest strain and stress localized near the blade's cutting edge closest hole.

The Factor of Safety (FOS) and displacement for each blade model under pressure are also shown in Figure 6 model D has the highest minimum FOS (20.44) and the lowest maximum displacement ($8.409x10^{-3}$ mm), whereas model A has the lowest FOS (18.66) and the highest displacement ($1.756x10^{-2}$ mm). Models B and C have comparable FOS (19.21 and 19.43, respectively) and displacement ($1.307x10^{-2}$ mm and $1.147x10^{-2}$ mm, respectively). The minimum FOS is found in the same regions as the maximum stress and strain, while the maximum displacement is distributed around the blade's cutting edge.

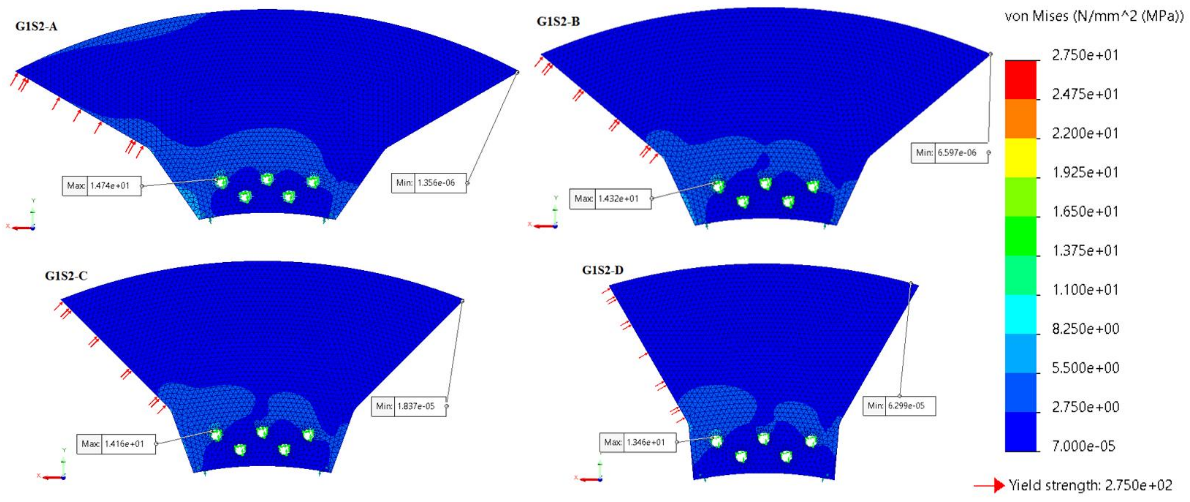
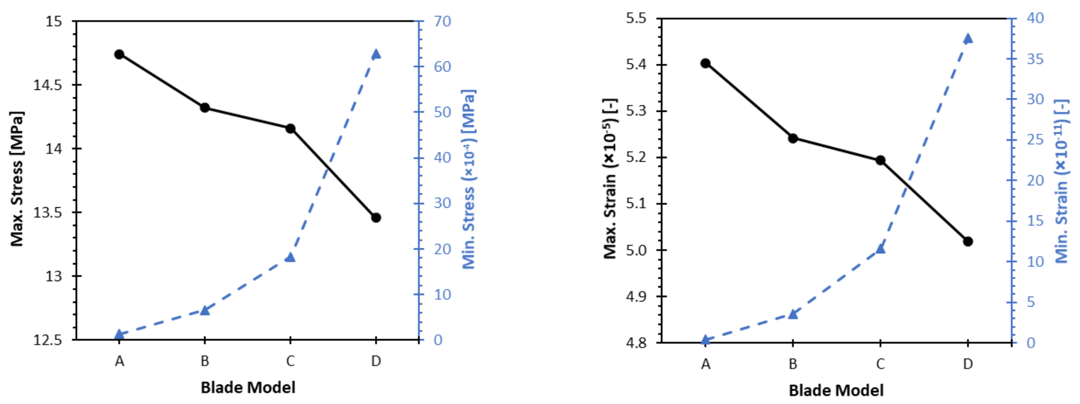


Figure 4. The stress distribution for Von Mises.



(a) Von Mises stress (b) Strain

Figure 5. The maximum and minimum strain and stress of each blade model.

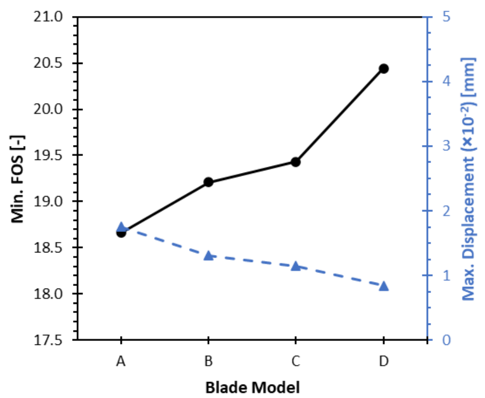


Figure 6. The maximum displacement and minimum FOS of each blade model.

3.3 Fatigue assessment

In this section, the fatigue (FEA) outcomes for four blade designs subjected to cyclic pressure. Fatigue FEA evaluates the load factor and lifespan, aiding in assessing blade robustness and efficiency, and guiding the selection of the most suitable blade for the (MSW) bag opening machinery.

Figure 7 illustrates the distribution of fatigue load factors for the blade models under cyclic pressure. This factor serves as a safety gauge, indicating the allowable stress increase before failure. A greater fatigue load factor equates to enhanced blade safety. According to Figure 7, models D and A boast the highest minimum fatigue load factors, at 10.99 and 10.27, respectively. Conversely, models B and C exhibit lower values, at 6.954 and 7.795, respectively.

Despite all models sharing a minimum fatigue life of 10^6 cycles, signifying their ability to withstand at least 10^6 cycles of cyclic pressure, this does not imply uniform strength, efficacy, or longevity. The maximum stress endured by each blade remains beneath the fatigue endurance threshold—the stress point below which blades can sustain an indefinite cycle count without failure. Nonetheless, the fatigue load factor indicates that model D maintains a superior safety margin compared to its counterparts.

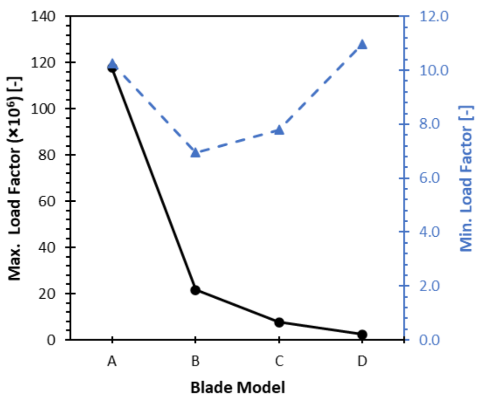


Figure 7. The maximum (left – black solid line with circles) and minimum (right – blue dash-line with triangles) load factor for the four models of blades under investigation.

Resulting from the FEA (static/ fatigue) data, this study identifies the last blade model (i.e., model D) to be the superior blade choice for the bag opening device in MSW treatment. This model exhibits the minimal stress and deformation levels, coupled with the highest Factor of Safety (FOS) in static evaluations, and the most favourable fatigue load factor, while maintaining a fatigue life comparable to other models in fatigue assessments. Conversely, model A is deemed the least suitable, with the highest recorded stress and deformation, and the lowest FOS and fatigue load factor, despite sharing an equivalent fatigue life with other designs. Models B and C rank as intermediate options, sharing similar attributes of strength, functionality, and longevity, yet falling short of model D's standards. The study further correlates the fatigue FEA findings with aspects such as blade shape and structure, material composition and surface treatment, as well as the operational potency and efficacy of the bag opening apparatus, while also addressing the outcomes' implications and constraints.

4. Conclusion

This investigation addressed the challenge of designing and optimizing blades for bag opening equipment used in Municipal Solid Waste (MSW) treatment facilities, necessary for the efficacy of waste management systems. The research posited the question: "Which cutting edge angle optimizes the blade of a waste bag opening equipment?" The study substantiated that the blade model assigned as “D”, having a cutting edge angle of 30°, stands as the optimum design for the cutting blade, as determined by an exhaustive design and evaluation process.

The findings elucidated the resolution to the research inquiry, affirmed the prevailing theories of blade design, and enriched the corpus of knowledge surrounding MSW bag opener machines. The study delineated the ramifications of these discoveries for the design and functionality of MSW bag opening equipment, underscoring their potential to enhance the efficiency, efficacy, and waste management practices sustainability.

Acknowledging the research's constraints, such as its narrow focus, the modest scale of the MSW survey, the assumptions and simplifications within the FEA models, and the variability of the input data, the paper discussed how these factors might influence the validity and applicability of the results. It proposed avenues for future research to surmount these limitations.

Future research directions were recommended, spurred by the identified research gaps and challenges. The paper suggested exploring the impact of varying blade geometries, dimensions, and materials on MSW bag opening equipment performance, optimizing coatings and lubrication of the blades, as well as comparing different machine types. It advocated for methodologies such as field studies, multi- criteria optimization, and LCA (Life Cycle Analysis) for future inquiries.

The paper concluded by accentuating its contributions, encapsulating the research with a potent statement that underscored its novelty and importance. It imparted a definitive message: The paper introduced an innovative, thorough methodology for the design and assessment of the ideal blade for MSW bag opening equipment. Model D, with a cutting edge angle of 30°, emerged as the premier choice, corroborated by FEA (static/fatigue) results. These results demonstrated that model D has a Von Mises stress with the lowest value of 13.46 MPa, while it has the highest FOS of 20.44, alongside a prolonged operational lifespan of 10^6 cycles for all models. The research augmented existing knowledge in the domain of MSW bag opening equipment, providing actionable insights and optimization strategies to enhance the design and functionality of these machines, thereby advancing the waste management process.

References

[1] L. A. Guerrero, G. Maas, and W. Hogland, “Solid waste management challenges for cities in developing countries,” Waste Manag., vol. 33, no. 1, pp. 220–232, 2013, doi: 10.1016/j.wasman.2012.09.008.
[2] J. Namias, “THE FUTURE OF ELECTRONIC WASTE RECYCLING IN THE UNITED STATES : Obstacles and Domestic Solutions,” no. July, 2013.
[3] N. Bamb, I. Bahade, and M. Jawale, “Best Practices of Solid Waste Management and Its Application to Nashik City,” Lect. Notes Civ. Eng., vol. 430 LNCE, pp. 1–20, 2024, doi: 10.1007/978-981-99-4186-5_1.
[4] W. Cox, “Demographia World Urban Areas, 18th Annual Edition: July 2022,” Demograpgia, vol. 18, 2022, [Online]. Available: http://www.demographia.com/db-worldua.pdf
[5] S. K. Ghosh, U. V. Parlikar, and K. H. Karstensen, Sustainable Management of Wastes Through Co-processing. 2022. doi: 10.1007/978-981-16-6073-3.
[6] T. H. Christensen, “Solid Waste Technology and Management, 2 Volume Set.” [Online]. Available: https://www.wiley.com/en-us/Solid+Waste+Technology+and+Management,+2+Volume+Set-p-9781405175173

[7] S. Mandal, A. Bandyopadhyay, and A. Bhadra, “Performance Evaluation of MBT, OBIA and PBRF Method for High-Altitude Water Body Mapping: A Case Study of Mago River Basin of Arunachal Pradesh,” J. Indian Soc. Remote Sens., vol. 51, no. 11, pp. 2187–2200, 2023, doi: 10.1007/s12524-023-01759-0.
[8] S. H. Schneider, “Municipal solid waste,” Energy Conversion, Second Ed., pp. 73–79, 2017, doi: 10.1201/9781315374192.
[9] G. C. Fitzgerald, “Technical and Economic Analysis of Pre-Shredding Municipal Solid Wastes Prior to Disposal,” Columbia Univ., no. September, 2009, [Online]. Available: http://www.seas.columbia.edu/earth/wtert/sofos/Garrett_Fitzgerald_MS_Thesis.pdf
[10] Defra, Mechanical Biological Treatment of Municipal Solid Waste. 2007. [Online]. Available: https://webarchive.nationalarchives.gov.uk/20130403153720/http://archive.defra.gov.uk/environment/waste/residual/newtech/documents/mbt.pdf
[11] T. Theodoridis and J. Kraemer, “Value market research.” [Online]. Available: https://www.valuemarketresearch.com/pressreleases/biostimulant-market
[12] IEA BIOENERGY, Sorting technologies Case study about a MSW sorting facility in Norway. 2022. [Online]. Available: https://www.ieabioenergy.com/wp-content/uploads/2022/06/Task-36-case-studies-sorting-technologies_IVAR-final.pdf
[13] V. R. S. Cheela, S. Goel, M. John, and B. Dubey, “Characterization of municipal solid waste based on seasonal variations, source and socio-economic aspects,” Waste Dispos. Sustain. Energy, vol. 3, no. 4, pp. 275–288, 2021, doi: 10.1007/s42768-021-00084-x.
[14] H. Ramli, H. A. Aziz, and Y.-T. Hung, “Practices of Solid Waste Processing and Disposal,” 2021, pp. 625–673. doi: 10.1007/978-3-030-84180-5_10.
[15] T. Theodoridis and J. Kraemer, “Shredder for Municipal Solid Waste (MSW) | Residual Waste from WEIMA.” [Online]. Available: https://weima.com/en/shredders-municipal-solid-waste-msw/
[16] “M&J PreShred 4000S.” [Online]. Available: https://mjrecycling.com/shredders/m-j-stationary-pre-shredders/m-j-preshred-4000s/
[17] Farotimi Femi and Ogunsajo Oluwole, “Management of Municipal Solid Waste ,” Academia, 2013, [Online]. Available: https://www.academia.edu/4254191/Management_of_Municipal_Solid_Waste
[18] T. Theodoridis and J. Kraemer, “MSW SORTING.”
[19] T. Theodoridis and J. Kraemer, “EUREC SHREDDERS.” [Online]. Available: https://www.eurec.de/en/shredders
[20] “SPR GROUP.” [Online]. Available: https://www.grupo-spr.com/en/products/trituration/bag-opener-spr/#None
[21] A. Arockiarajan, M. Duraiselvam, and R. Raju, Advances in industrial automation and smart manufacturing. 2019.
[22] S. M. Auti, J. Sheth, P. Tulasyan, A. Gaikwad, and P. Bagwe, Design of Shredder Machine for ELV Tyres. 2020. doi: 10.1007/978-981-15-4485-9_64.
[23] S. Escudero, “Design of a shredder attachment for a waste compactor,” 2015. [Online]. Available: http://uvadoc.uva.es/handle/10324/16899
[24] S. Nithyananth, L. Samuel, N. Mathew, and S. Suraj, “Design of Waste Shredder Machine,” Int. J. Eng. Res. Appl., vol. 4, no. 3, pp. 487–491, 2014.
[25] N. Ferronato and V. Torretta, “Waste mismanagement in developing countries: A review of global issues,” Int. J. Environ. Res. Public Health, vol. 16, no. 6, 2019, doi: 10.3390/ijerph16061060.
[26] N. H. A. Rahim and A. N. H. M. Khatib, “Development of pet bottle shredder reverse vending machine,” Int. J. Adv. Technol. Eng. Explor., vol. 8, no. 74, pp. 24–33, 2021, doi: 10.19101/IJATEE.2020.S2762167.
[27] R. M. Hill, “Three Types of Low Speed Shredder Design.,” Proc. Natl. Waste Process. Conf., pp. 265–274, 1986.
[28] Y. Cristian Pedraza, M. A. Pelegrina Romero, and G. J. Pertúz Martínez, “Analysis by Means of the Finite Element Method of the Blades of a PET Shredder Machine with Variation of Material and Geometry ,” Contemp. Eng. Sci., vol. 11, no. 83, pp. 4113–4120, 2018.
[29] S. Ravi, “Utilization of upgraded shredder blade and recycling the waste plastic and rubber tyre,” Proc. Int. Conf. Ind. Eng. Oper. Manag., vol. 2018, no. JUL, pp. 3208–3216, 2018.
[30] S. N. F. Zakaria, H. A. Aziz, Y.-T. Hung, A. Mojiri, and E. A. Glysson, “Mechanical Volume Reduction,” 2021, pp. 297–343. doi: 10.1007/978-3-030-84180-5_5.
[31] Eggersmann, “Bag Opener BRT HARTNER BOS | Eggersmann GmbH.” [Online]. Available: https://www.eggersmann-recyclingtechnology.com/en/brt-hartner/products/bag-opener-brt-hartner-bos/
[32] T. Theodoridis and J. Kraemer, “COPARM.” [Online]. Available: https://www.coparm.net/waste_bag_openers.html

[33] "CP ' s MSW BAG OPENER Efficiency by the Leader CP ' s MSW BAG OPENER Multi Functional for Multi Materials."

[34] T. Theodoridis and J. Kraemer, "UNTHA Shredding municipal solid waste." [Online]. Available: https://www.untha-america.com/en/applications/msw

[35] T. Theodoridis and J. Kraemer, "Matthiessen." [Online]. Available: https://www.bagsplitter.com/

[36] N. Shariatmadari, M. Asadi, and M. Karimpour-Fard, "Investigation of fiber effect on the mechanical behavior of municipal solid waste by different shearing test apparatuses," Int. J. Environ. Sci. Technol., vol. 14, no. 10, pp. 2239–2248, Oct. 2017, doi: 10.1007/s13762-017-1297-z.