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SELECTION OF CRUSHER DESIGN CONCEPTS AS A SUSTAINABLE PRODUCT USING WEIGHTED DECISION MATRIX METHOD

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ABSTRACT

For many years, crusher design concepts have been invented worldwide that purposely crush the used beverage containers to reduce their volume and increase storage bins. However, the developed crusher design concepts present the invention without considering sustainability concerns regarding the three pillars; environment, economic and social impact throughout the product life cycle. Therefore, this paper proposes a study on how crusher design concepts are selected regarding sustainable perspective using the Weighted Decision Matrix (WDM) approach. The WDM analysis has been conducted on previous researchers' three crusher design concepts: motor-operated crusher, mechanical crusher, and pneumatic crusher. This study shows that the pneumatic crusher scored the highest rating compared to the other design concepts and was suggested as a potential sustainable product for future development. This selection method serves as helpful information for product designers to select suitable design concepts based on multiple criteria and verifies the suggested sustainable crusher product.

Keywords: sustainable product, crusher design concept, weighted decision matrix.

INTRODUCTION

For many years, solid waste has been one of the global major environmental problems, especially in developing countries. The government has encouraged the 3R (Reduce, Recycle, and Reuse) programme to manage solid waste in Malaysia since landfill is not a long-term solution. It will cause pollution towards the environmental issue.

People have to keep or store the beverage containers after use and send them to the nearest recycling centre for the recycling approach. However, the used beverage containers require ample space, especially aluminium cans and plastic bottles, which generally overflow a dustbin and consume a lot of space, increasing the total amount of solid waste. The transportation cost also may be high for moving such a huge number of cans or bottles. Due to this situation, many researchers from all countries have invented the crusher machine to crush the used beverage containers [1].

The crusher machine's cans or bottles is one of the most aidable machines that many researchers widely invent. Johnjoshua *et al.* [2] proposed a new motorized beverage crusher that would make it easier to bring anywhere and more accessible to crush the cans or bottles. Husain and Sheikh [3] designed a crusher machine using a scotch yoke mechanism having multi or two-side crushing abilities. Uresh et al. [4] fabricated a compact tin crusher that can be operated manually. Meanwhile, Kumar et al. [5] developed a pneumatic crusher operated by air pressure and manually controlled by a valve. Kathe [6] proposed a crusher with the help of a pneumatic single-acting cylinder crank mechanism. Hadi *et al.* [7] developed an automatic crusher using a programmable logic controller with an inductive and capacitive sensor to detect whether the object is metal or non-metal.

Despite the growing interest in crusher design and development, the invented crusher design concepts present the respective invention without considering sustainability concerns regarding the three pillars; environment, economic and social impact throughout the product life cycle. This study shows the potential selection of crusher design concepts as the most sustainable product using data collected and verified via the Weighted Decision Matrix (WDM) approach concerning the sustainable product consideration.

METHODOLOGY

Weighted Decision Matrix

A weighted decision matrix is one of the powerful quantitative design tools widely used in evaluating a set of competing concepts based on the weighting factors of design criteria and giving a score to the concept against a set of design criteria that need to be taken into account [8]. The weighted score used to determine the degree of importance of each criterion was obtained through heuristic benchmarking and system designers' opinions [9]. Therefore, the concept with the highest cumulative assessment score is the most preferred concept of the design criteria.

Sustainable Product Consideration

A sustainable product is much discussed and has become an important topic today due to increasing environmental degradation and violation of human rights [10]. Sustainable development is defined as the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. The use of all dimensions area of sustainability which is good for the environment, can improve the quality of social life and are

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profitable to the company will be considered an ideal design or product.

This study determined the criteria by identifying previous researchers' most frequent sustainability criteria. The criteria consist of the product life cycle, which involves the pre-manufacturing (PM) stage, manufacturing (M) stage, usage (U) stage, and post-used (PU) stage. All the sustainability pillar is considered to evaluate the most sustainable product throughout its life cycle, as presented in Table-1.

Table-1. The determined sustainability criteria.

Stages	Environmental Criteria	Economic Criteria	Social Criteria
PM	Raw material Product manufacturing Number of components	Raw materials cost Storage cost Marketing cost	Storage capacity Market demand Product weight
M	Manufacturing scrap Energy consumption Finished good storage space	Transportation cost Product price Labor cost	Manufacturing cost Manufacturing time
U	Noise produced Product waste	Maintenance/repair cost Energy cost	User safety Ergonomic Product efficiency
PU	Material disassembly Material recyclability Product lifespan	Disposal cost Recycling cost Disassembly cost	Product disassembly Product lifespan

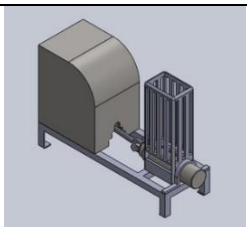
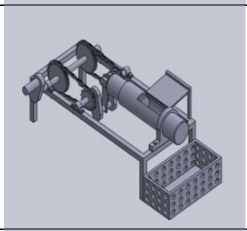
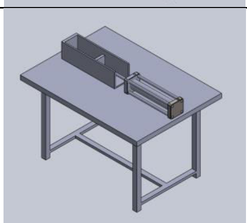
CASE STUDY

This study has selected three can crusher design concepts from previous researchers: motor-operated crusher, mechanical crusher, and pneumatic crusher, as shown in Table-2.

WEIGHTED DECISION MATRIX ANALYSIS

This study used the Weighted Decision Matrix to evaluate product sustainability from the selected can crusher design concepts. The weights were allocated from the most important to the least important criteria. The product sustainability criteria consisted of the three pillars; environmental, economic, and social impact throughout its lifecycle from the pre-manufacturing, manufacturing, use, and post-used stages. The evaluation was done using a three-level scale with decreasing grade scores from excellent to the bad performance of the products.

Table-2. Selected crusher design concepts.

	1) Motor-operated crusher The motor-operated crusher operates using a motor to move the piston to crush cans. Several aluminium cans can be inserted into the can collector to produce the crushed can higher in a minute. The primary material used for this type of can crusher is cast iron, and there was a set of gear covered using the frame cover to prevent any unwanted accident.
	2) Mechanical crusher The mechanical crusher needs a human workforce to operate the system. It uses two sets of gear to move the piston for crushing the can. A platform is used to guide each can moving into the cylinder casing. The can collector is also provided at the end of the machine to collect the crushed can. The primary material used for this type of can crusher was steel.
	3) Pneumatic crusher The pneumatic crusher design operated using a pneumatic system. Only one tin can be inserted at one time. This design uses steel as the primary material. The design has a higher platform compared to the other design concepts. A workforce is needed to insert and collect the crushed can.

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ARPN Journal of Engineering and Applied Sciences

a) Environmental Analysis

The environmental criteria for the pre-manufacturing stage involved the raw material selection, product manufacturing process, and several parts or components. The primary material used for motor-operated crushers was cast iron, while the mechanical crusher and pneumatic crusher material was steel. According to The World Counts Website, steel production is highly polluting. Steel production requires massive inputs of coke (a form of coal) which will be highly environmentally damaging. In contrast, cast iron promotes environmental stability compared to steel. It does not rust because it oxidizes very slowly. This process gives off carbon-based iron ashes that are good for the environment, promoting green growth in plants and increasing planktonic life in the oceans to counter the global warming problem. Next, the product manufacturing process may also affect the environment, such as noise, water, or air pollution. The proposed crusher design concepts involve machining processes such as grinding, drilling, and cutting. The machining process produces several by-products or waste like metal chips, metal powder, oil-polluted water, oil nebula, and excessive energy use. These wastes have significant health, environmental, productivity, and manufacturing impacts. The number of components also will affect the manufacturing process. The higher the number of parts, the more significant the environmental effects as the manufacturing process is needed. The mechanical crusher has the highest number of components, consisting of 13 separated parts, compared to the motor-operated crusher and pneumatic crusher, consisting of 12 and 4 components.

The environmental criteria that need to be considered in the manufacturing stage are the manufacturing scrap, energy consumption, and storage space. Manufacturing scrap is divided into two categories which include recyclable and non-recyclable waste. Cast iron produced scrap in terms of powder when it was drilled because it was very hard. In comparison, steel produces chips if it is ground. Both scraps need to be disposed of properly to prevent any effect on the environment and human safety. The energy consumption during the manufacturing process will also cause an environmental impact. The differences in the general properties of materials, such as strength, hardness, and impact, would significantly affect the power consumption of the machine used to complete the product. The environmental impact can be reduced if the design is proposed to use fewer materials [11]. Even though cast iron has good machinability compared to steel, the few parts that need to be manufactured will reduce the energy used. The finished good storage space is also considered during the manufacturing stage. The product's sizing will affect the number of transportations needed to be sent to the customers, affecting the environment in terms of fuel burning. The larger the product sizing, the more transports or trips will be used to send the product to the customers. The mechanical crusher has a larger design and more components that affect the product's weight than the motor-operated crusher and the pneumatic crusher.

Next, the energy consumption during the usage stage has also been evaluated. The energy consumption was related to the energy source used by each proposed design concept. The motor-operated crusher used a motor to operate the crusher. While the pneumatic crusher used compressed air, and mechanical crusher only required the workforce's energy to crush the can or bottle. The noise was defined as unwanted sound which considered unpleasant, loud, or disruptive to hearing. The World Health Organization (WHO) defines noise above 65 decibels (dB) as noise pollution. The health and safety executive websites listed a few common noises, including the noisy machine. During the operation, motor and pneumatic systems sometimes make a noise that may disturb others. For this study, the noise produced by the motor and pneumatic system was not measured but considered because the mechanical crusher produces less noise compared to them. The last criteria for the usage stage were the product waste. Product waste refers to the lubricant that has been used to operate the product. The waste from the lubricant needs to be disposed of properly to avoid any possible pollution. To move the chain and gear smoothly, the motor-operated crusher and mechanical crusher used lubricant to make sure the product may function well. Thus, this problem will increase the possibility of environmental pollution if not properly managed.

The product disassembly method was considered during the post-used stage. Disassembly is the systematic removal process of the assembly's suitable components to ensure that the components are not damaged due to the operation. The disassembly process involved two methods which are destructive and non-destructive. The destructive disassembly process is commonly involved in shredding processes. In contrast, the non-destructive disassembly process is the process that enables the complete recycling of products and possible reuse of pieces and subassemblies [7]. Both methods will reduce waste disposal to the landfill, affecting the environment and society. In this study, both the disassembly method was considered. Next, the recyclability of the materials defines as the materials that can be recycled to produce a new product. The Steel Recycling Institute website stated that steel and iron (ferrous metals) were categorized as the most recyclable material globally, more than all other materials combined. The unique metallurgical properties of steel allow it to be continuously recycled with no performance degradation. The materials used for all the proposed design concepts were categorized as recyclable materials, reducing the impact on the environment. Lastly, the product life span is also considered as the environmental criteria. The longer the product lifespan, the lower the disposal of materials process that will be released to the environment. Thus, the lifespan for each design concept was estimated to be up to 5 years, and safely used without harming the environment.

As shown in Table-3, the pneumatic crusher was determined as the design with the lowest impact on the environment with an overall score of 2.74 compared to the mechanical crusher and mechanical crusher, which have a score of 2.57 and 2.05, respectively. The design, type, and the number of materials used influence most of the stated criteria, leading to the environmental impact.

b) Economic Analysis

For the pre-manufacturing stage, the economic criteria that have been evaluated were the raw material cost. The steel and cast-iron prices were compared based on Dandong Foundry (china) websites that show cast iron's price was lower than the steel. From the comparison, the motor-operated crusher has higher scores because cast iron was cheaper than the steel used for the other two crusher design concepts. Next, the storage cost needs to be considered during this stage. The factors that will affect the storage cost include the product sizing, the location of the storage warehouse, and the condition of the storage space, such as temperature and humidity. The bigger the product size needs, the larger the storage space, increasing cost. Besides, the product price that needs climate-controlled storage will be 25% to 50% higher than the regular storage units.

Table-3. Weighted decision matrix analysis for environmental criteria.

Environmental criteria		WF	Motor-operated Can Crusher		Mechanical Crusher		Pneumatic Can Crusher	
			Score	Rating	Score	Rating	Score	Rating
PM	Raw materials	0.12	3	0.36	2	0.24	2	0.24
	Manufacturing process	0.09	2	0.18	1	0.09	3	0.27
	Number of components	0.09	2	0.18	1	0.09	3	0.27
M	Manufacturing scrap	0.12	3	0.36	2	0.24	2	0.24
	Energy consumption	0.10	2	0.20	1	0.10	3	0.30
	Finished good storage space	0.05	2	0.10	1	0.05	3	0.15
U	Noise produced	0.05	2	0.10	3	0.15	2	0.10
	Product waste	0.05	2	0.10	2	0.10	3	0.15
PU	Materials disassembly	0.08	3	0.24	3	0.24	3	0.24
	Materials recyclability	0.10	3	0.3	3	0.3	3	0.3
	Product lifespan	0.15	3	0.45	3	0.45	3	0.45
Total		1.0	2.57		2.05		2.74	
Rank			**2**		**3**		**1**	

The only factor that has been considered in this study is product sizing. Motor-operated crusher was rated with a high score, followed by the mechanical crusher and pneumatic crusher, as this design is more extensive and more elevated than others. The marketing cost also needs to be evaluated in this stage. The proper marketing plan may lead to a higher profit for the company. Based on the survey of over 300 enterprises and marketing directors, almost half of the marketing budget will go to advertising. For this study, the marketing cost was assumed to be the same for all products.

The economic criteria for the manufacturing stages include the transportation cost. For the transportation cost, the sizing and weight of the product were measured. It is because the number of transportations used, or the number of trips needed to send the product to the customers will be increasing. Thus, the amount of fuel needed will also be increased. The distance from the manufacturing place to the users was fixed to be 200 kilometers for all the products. The only considered factors that affect the transportation cost in this study are the sizing and weight of the product. Thus, the motor-operated crusher was rated the highest score, followed by the mechanical and pneumatic crushers. Next, labor is crucial to producing a product. The labor was assumed to be only one person, but the time needed to finish a product before sent to the customers fully was calculated. The longer the time required to manufacture each product, the higher the company's cost to the worker. The pneumatic crusher has less assembly time than the motor-operated crusher and mechanical crusher. The last economic criteria during the manufacturing stage were the product price. The final product price can be determined in this stage as all the affected cost that company needs to afford was calculated. The correct product pricing was vital because it would impact almost every aspect of the business. The profit margin was assumed to be fixed, and the total variable cost was considered based on the type and amount of materials used and the transportation cost for this study. The motor-operated crusher was assumed to be more expensive than the mechanical crusher and pneumatic crusher.

Economic criteria in the usage stage usually refer to the customers' finances. In this stage, the maintenance or repair cost is considered. The maintenance or repair cost was estimated according to the damage or broken part type. The mechanical crusher was assumed to have less tendency to wear or damage parts than others. The motor-operated crusher and pneumatic crusher use a motor and pneumatic system that will need periodical maintenance to ensure the machine can function well. Next, the usage stage involves energy cost. A motor is an electrical tool that requires electricity to operate, while a pneumatic system needs compressed air to operate it. The International Energy Agency stated that Electric Motors and Drive System (EMDS) is the most prominent single electricity use, accounting for more than 40% of global electricity consumption. It also states that 32% of EMDS is attributed to compressors. The report from International Energy Agency noted that tremendous energy efficiency was found untapped in EMDS. Around 25% of EMDS electricity use could effectively save costs and reduce the total global electricity demand by about 10%. However, the mechanical crusher does not use an electric source to function, and the energy cost is not considered. Thus, make this design concept is rated with a higher score.

The economic criteria for this final stage involved the disposal cost of the product, the recycling price, and the disassembly cost. The disposal cost includes transportation cost and landfill cost. The weight and volume also affect the disposal cost. The mechanical crusher was assumed to have the highest disposal cost because of its weight and volume, affecting the transportation fee to send the part to the disposal center. Besides, the recycling price is also crucial during the post-used stage. The material that can be recycled needs to be sent to the recycling center. But the recycling price is constantly changing according to the market. IScrap Apps is an online platform that shows the updated price for various scraps. This website shows the price of cast iron is $103.00 per ton while the steel price is $112.00 per ton, which indicates that steel has a higher recycling price than cast iron. Lastly, the economic sustainability criteria are the disassembly cost. The products will be evaluated at every stage, whether the disassembly process should be continued or the part should be recycled or disposed of. The permanent joint was one of the reasons that the part could not be recovered for reuse. Thus, this study considered the joint used to evaluate the disassembly cost related to the time and labor cost. The mechanical crusher was regarded as the design with high disassembly cost compared to the motor-operated crusher and pneumatic crusher because it has many parts. Besides, the joining used was welding which was a permanent joint.

As shown in Table-4, the most economical product was a pneumatic crusher, followed by a motor-operated crusher and a mechanical crusher. The mechanical crusher has the lowest economic criteria, which only scored with 1.77 compared to motor-operated crusher and pneumatic crusher, which the total score was 2.32 and 2.41, respectively.

Table-4. Weighted decision matrix analysis for economic criteria.

Economic criteria		WF	Motor-operated Crusher		Mechanical Crusher		Pneumatic Crusher	
			Score	Rating	Score	Rating	Score	Rating
PM	Raw materials cost	0.15	3	0.45	1	0.15	2	0.30
	Storage cost	0.05	3	0.15	2	0.10	1	0.05
	Marketing cost	0.10	3	0.30	3	0.30	3	0.30
M	Transportation cost	0.12	3	0.36	2	0.24	1	0.12
	Product price	0.10	1	0.10	2	0.20	3	0.30
	Labour cost	0.05	2	0.10	1	0.05	3	0.15
U	Maintenance/ repair cost	0.13	2	0.26	1	0.13	3	0.39
	Energy cost	0.10	2	0.20	3	0.30	2	0.10
PU	Disposal cost	0.10	2	0.20	1	0.10	3	0.30
	Recycling price	0.05	2	0.10	3	0.15	3	0.15
	Disassembly cost	0.05	2	0.10	1	0.05	3	0.15
Total		1.0	2.32		1.77		2.41	
Rank			**2**		**3**		**1**	

c) Social Analysis

For the pre-manufacturing stage, the social criteria that have been analyzed were the storage space, market demand, and product weight. The optimum design is the design that compromises the size, shape, and topology of the part and utilization of minimum possible material while ensuring the overall performance of the part. For this study, the product's sizing might affect users' movement. The size of the mechanical crusher was bigger than the pneumatic crusher and motor-operated crusher, which will take more space to store the product. Next is the market demand. A previous study stated that owning a crusher will benefit anyone who cares about the environment and wants to recycle aluminium cans instead

ARPN Journal of Engineering and Applied Sciences

of throwing them away. Based on testing conducted by the previous study, crushers may reduce the amount of space up to 45-75%. As all the product selected was from the same categories, the market demand will be the same. The product weight will affect the product portability. Usually, customers want a lightweight, portable product that can be moved easily. For this study, the motor-operated crusher has the heaviest weight than the mechanical crusher and pneumatic crusher, affecting the product portability.

During the manufacturing stage, the social criteria include manufacturing risk and time. The manufacturing risk involved the manufacturing process, such as welding, grinding, and cutting process. For example, the incorrect welding process may affect the worker's safety. The worker might expose to the electric shock risk, UV and IR radiation, and fumes and gasses. For this study, the pneumatic crusher is determined to have low manufacturing risk. This design has the least manufacturing process, resulting in the least possible safety risk to the workers. Next was the manufacturing time. The manufacturing time affects social sustainability because the longer the manufacturing time, the longer the time for the customers to receive the product. The number of components for each design effect the manufacturing and assembly time. Thus, the mechanical crusher has many components compared to the motor-operated crusher and pneumatic crusher, with fewer components to be assembled.

For the use stage, the social criteria involve are user safety, ergonomic design, and product efficiency. User safety was one of the crucial criteria to ensure the product does not harm the users. For the motor-operated crusher, the frame cover will protect the rotation of gear and chain to prevent any unwanted accident. However, both chain and gear pairs were not covered for the mechanical crusher. This design needs the users to be more careful to operate the machine to prevent unwanted accidents. For the pneumatic crusher, there is no platform to collect the uncrushed and crushed cans, and this situation may harm the user to insert and take out the cans while the pneumatic piston crushes the other cans. In terms of user safety, the motor-operated crusher was assumed to be safer, followed by the pneumatic crusher and the mechanical crusher.

Ergonomic is the study of how people interact with machines. A failure to deal with the social requirement may result in poor design [12]. The designer should adopt the existing ISO standards on ergonomics to improve human well-being and overall system performance [13]. This study considers the users' posture while operating the machine. The motor-operated crusher is the most ergonomic design because the users can insert a few cans in time. The can crusher will operate using a motor that will reduce the user's movements. Even though the crusher's height is low, the users may put the machine on the table according to their height to ensure comfort. Product efficiency was the first thing that customers wanted besides the price. Product efficiency will make human life more manageable. For this study, the product efficiency was measured based on the number of outputs produced and the complete crushed cans in one minute. For the motor-operated crusher, the number of cans crushed entirely per minute was 15 cans. While for the mechanical crusher, the number of completely crushed cans was estimated at only four cans per minute. And for the pneumatic crusher, the estimated number of completely crushed cans was eight cans per minute. Thus, the motor-operated crusher has high efficiency, followed by the pneumatic crusher and mechanical crusher.

During the post-used stage, the product disassembly process has been evaluated. The product disassembly process was necessary whenever the product could not be used anymore and was ready to be recycled or disposed of. The method of joining during the manufacturing process will affect this criterion because the permanent joint use makes the disassemble process harder and needs time. In this study, the pneumatic crusher was assumed to have a more straightforward disassembly process because the components used were fewer and used screws as joining. Next, the users usually consider the product that can last longer. Thus, the product life span was measured in this analysis as the social criteria because the longer the product lifespan, the lesser users will spend to buy the new product that will be not considered a necessity. In this study, all the product lifespan was specific to be last five years. Lastly, the disposal mechanism was also regarded as the social criterion. This criterion refers to the user's knowledge about the proper way to dispose of the things. Improper waste disposal will lead to environmental pollution that affects human life. In this study, the user's disposal mechanism knowledge was assumed to be the same for all crusher design concepts.

Based on Table-5, the pneumatic crusher shows the highest score for social sustainability, followed by the motor-operated crusher and mechanical crusher. Thus, the pneumatic crusher was the most sustainable design in the social aspect.

Table-5. Weighted decision matrix analysis for social criteria.

Social criteria		WF	Motor-operated Crusher		Mechanical Crusher		Pneumatic Can Crusher	
			Score	Rating	Score	Rating	Score	Rating
PM	Storage capacity	0.05	3	0.15	1	0.05	2	0.10
	Market demand	0.08	3	0.24	3	0.24	3	0.24
	Product weight	0.10	1	0.3	2	0.1	3	0.5
M	Manufacturing risk	0.10	2	0.3	1	0.1	3	0.5
	Manufacturing time	0.05	2	0.1	1	0.05	3	0.15
U	User safety	0.15	3	0.45	1	0.15	2	0.75
	Ergonomic	0.12	3	0.36	1	0.12	2	0.24
	Product efficiency	0.12	3	0.6	1	0.36	2	0.6
PU	Product disassembly	0.08	2	0.24	1	0.08	3	0.4
	Product lifespan	0.10	3	0.3	3	0.5	3	0.5
	Disposal mechanism knowledge	0.05	3	0.15	3	0.15	3	0.25
Total		1.0	3.19		1.9		4.23	
Rank			**2**		**3**		**1**	

CONCLUSIONS

The WDM approach has been conducted to select a sustainable product among the invented can crusher design concepts. The sustainable criteria have considered the three pillars; environment, economic and social impact throughout the product life cycle from pre-manufacturing, manufacturing, and use to post-use. The pneumatic crusher has been identified as the most sustainable design concept through the determined sustainability criteria, which obtains the highest score compared to the other crushers. Thus, this selection method serves as helpful information for product designers to select suitable design concepts based on multiple criteria and verifies the suggested sustainable crusher product.

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