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An entropy-based metric for product remanufacturability

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Abstract

Manufacturing contributes heavily to environmental life cycle measures such as energy, material use, and water consumption through depletion and pollution. To lessen the environmental impacts, a number of initiatives have been developed. One of such initiatives is the used product take back, a process through which manufacturers collect used products and remanufacture them to like-new condition. However, remanufacturing of the used products at a modest cost is becoming a daunting task for many manufacturers due to the increasing complexity in many products. To mitigate this remanufacturing challenge, this paper develops a metric to quantify the remanufacturability incorporated into the new product at the design stage. The metric is based on entropy, a phenomenon well known in engineering.

Keywords: Remanufacturing, Entropy, Metric

Background

Remanufacturing is the process of restoring durable used product to like-new condition (in terms of product functions) with only a modest investment. The process involves the complete disassembly of a product, during which each component is thoroughly cleaned, examined for damage, and reprocessed to its original equipment manufacturer specifications [1-3]. A remanufactured product often comes with a warranty, another major criterion that differentiates remanufacturing from other end-of-life strategies [4] (Figure 1). It is worthy to always emphasize the differences between remanufacturing and other product recovery processes due to the lingering confusion about the characteristics of different product recovery processes.

Remanufacturing differs from recycling in that value added for original manufacturing including labor, energy, and equipment expenditure is conserved. The added value is lost during recycling, which reduces the product to its material constituents and requires additional labor, energy, and machinery [3,5,6]. On the other hand, remanufacturing preserves the product's (or the part's) identity and performs the required operations in order to bring the product to a desired level of quality like that of a new product.

Remanufacturing also differs from repairing, a process limited to making a product operational as opposed to thoroughly restoring it to like-new condition [4,5]. If the remanufacture of the product is not extensive, i.e., few parts are replaced, either of the terms reconditioning or refurbishing are more suitable. Reconditioning typically refers to the restoration of parts to a functional and/or satisfactory condition by surfacing and painting. Remanufacturing typically involves greater work content than other product recovery processes, and as a result, its products tend to have superior quality and performance [2,3,6,7].

Prominent among remanufacturing problems is the poor remanufacturing potential of many products as designs have typically focused on functionality and cost at the expense of environmental issues. Moreover, designers may lack remanufacturing knowledge because there is a paucity of remanufacturing knowledge, design, and research. Design-for-recycling has received more attention among design and manufacturing engineers than design-for-remanufacture (DfRem) [8,9], even though remanufacturing may provide greater environmental and financial benefits than recycling.

As environmental awareness is gaining more ground, manufacturers have begun to emphasize remanufacturing

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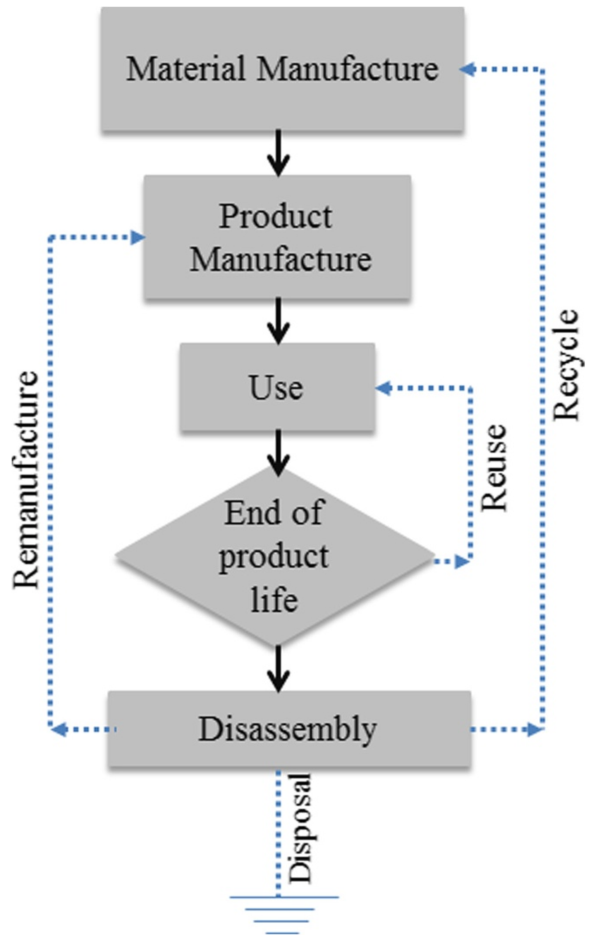

Figure 1 End-of-life strategies.

of post-consumed products. Many manufacturers, such as Xerox, HP, and Caterpillar, now have programs to collect their products after first life cycle and remanufacture them for sale. Moreover, environmental legislations are becoming strict in many countries, as reflected in legislations such as Waste Electronics and Electrical Equipment and End of Life Vehicle directives [10,11]. Remanufacturing can help original equipment manufacturers meet their commitment to environmental issues as well as legislations in a profitable manner [12]. Also, Lund indicated in his studies the total energy required for remanufacturing compared to energy used in initially producing a product, the ratios of which are in the order of 1:4 and 1:5, though these ratios are being disputed by Gutowski et al. [1,3,4]. Still, these gains, coupled with evidence from the auto industry [4,13,14], indicate remanufacturing to be a great idea for both economical and sustainable advantages. However, the increasing complexity of many products nowadays [8,15], as customers are demanding multifunctional and complex products, is hindering the venture of making remanufacturing a relatively easy task with modest investment (Figure 2). This new trend of increasing complexity in products necessitates the need for more research in remanufacturing.

The opportunity to implement remanufacturing at the onset of product design culminates into one particular research area in the field of remanufacturing, which is called 'design-for-remanufacture' [3,16]. This is the area that requires a lot of work and research to achieve efficiency in remanufacturing without diminishing the functional deliveries of a product. Research has indicated that whether a product is suitable for remanufacture or not greatly depends upon decisions made during the design stage. The importance of considering remanufacturing issues in product designs has frequently been stated in many literatures [17,18], and it is well concluded that the largest gain in enhancing remanufacturability could be made in the product design [4,19]. Zwolinski et al. [4,20] argued that remanufacturing must be considered as early as possible in the design process, ideally as the 'concept generation phases'. However, many of the tools offered so far are too complex and technical to be used at a very early stage of the design process. Given the issues and in order to assist the product designers in developing products which can be remanufactured efficiently at the end of its life cycle, there is a need to have a less fuzzy quantitative methodology through which the designers can systematically assess the degree of remanufacturability incorporated into the new product at the design stage.

Therefore, the aim of this paper is to develop a metric through which the product development team at the onset of design can quantify the degree of remanufacturability incorporated into a new product before actual manufacturing of the product takes place. The metric, however, must rely on uncomplicated methodology to assess the design. The methodology in turn must rely on theoretical basis that could be easily understood by

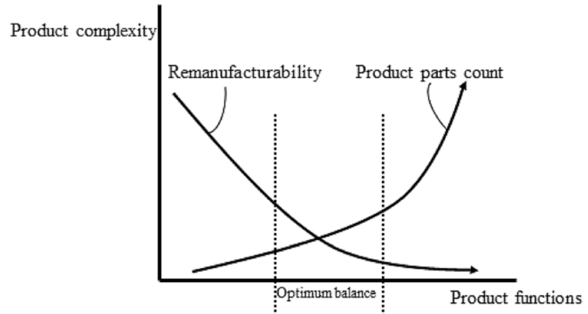

Figure 2 Effect of increasing product complexity on remanufacturing.

designers and engineers who are involved in the product development. The metric will allow the designers to translate properties of a design into quantitative scores in terms of product remanufacturability and thus provide a means of identifying weaknesses in the design and comparing alternatives.

The metric proposed in this paper is based on the property of thermodynamics. Thermodynamics has been used for many years as a foundation of methodologies for assessments of systems or resources. The underlying hypothesis in this study is that thermodynamics offers a comprehensive basis for the development of such metric as entropy for assessment.

Literature review

A number of studies has been done to measure product remanufacturability or to determine end-of-life strategy for a product. Prominent among such studies are the works of Rose and Ishi [7] Lee [21], Sundin and Bras [5], Sundin et al. [6], Brasand Hammond [22], Ijomah et al. [3], and Hatcher et al. [4].

Sundin and Bras [5] studied which product properties are important to facilitate remanufacturing by looking at properties that are suitable for the different remanufacturing steps (inspection, cleaning, disassembly, storage, reprocess, reassembly, and testing); a matrix called RemPro was created to rank and correlate the properties to appropriate strategies. Rose and Ishi [7] developed an end-of-life design advisor (ELDA) based on product characteristics to determine the end-of-life strategies; reuse, service, remanufacture, or recycle. The ELDA makes the designers aware of the impacts of their decision on the end-of-strategy and provides designers with a guide to appropriate end-of-life strategy. The ELDA works at the early stage of product design, which might require substantial knowledge from the designer in determining the appropriate end-of-life strategy [1]. Therefore, finding the balance between designer knowledge and effective end-of-life strategy might be subjective and even problematic.

Lee [21], in her paper, provided an ontology-based design for processing product information to provide decision supports in determining product end-of-life performance. Boothroyd and Dewhurst developed a metric for product assembly; their method involved simple part counts involved in the assembly of the product, which provide close measure for the assemblability of a product [17,18,22].

Bras and Hammond [22] developed a metric for assessing product remanufacturability based on Boothroyd and Dewhurst design-for-assembly as a foundation for remanufacturability assessment metrics based on product design features. Their method also involved aggregation of defined remanufacturing criteria such as disassembly, reassembly, cleaning, testing, and inspection. These criteria were assigned with different weight to measure product remanufacturability.

Review of most of these studies indicates that the tools and metrics provided are only suitable for use later in the product development when most of the major decisions have already been made. A detailed review provided by Hatcher et al. [4] indicates that many of these studies remain largely within the academic realm due to issues such as the complexity of the design aids and metrics and the lack of life cycle thinking in their designs. These issues prompt the need to have a metric that will be less cumbersome and whose methodology will be more familiar with the designers.

Some studies have been done on the use of entropy as a measure to assess systems of either product or service and provide feedback on their complexity for the purpose of making improvements. Frizelle and Woodcook [23] defined an entropy measure to quantify complexity in the supply chain based on Shannon's information entropy. Their entropy measure was qualitatively used to classify complexity as structural and operational (dynamic). Structural complexity deals with variety (schedule), and operational complexity deals with uncertainty (deviation from the schedule).

A static measure of complexity based on entropy measure was used for part mix in job shop scheduling [23,24]. Karp and Ronen [25] developed an approach which includes a formula for the determination of a lot location based on entropy measurement [23]. Fujimoto et al. [8] introduce a complexity measure based on product structure using different stages of process planning. ElMaraghya et al. [26] applied entropy function to quantify the complexity of manufacturing systems and their configurations with examples in machining processes. Guenov [12] uses the fundamentals of architectural design and entropy to introduce a system design metric for a comparison of alternative base cost, value, and performance and technical risk or complexity.

Entropy as a statistical mechanics of thermodynamics

From the perspective of statistical mechanics, entropy is viewed as the probability that certain events may occur within the framework of all possible events. By observing the behavior of large numbers of particles, statistical mechanics has succeeded in providing equations for the calculation of entropy as well as justification for equating entropy with a degree of disorder.

Shannon [27-29] looked at information as a function of a priori probability of a given state or outcome among the universe of physically possible states. He considered entropy as equivalent to uncertainty.

Thus, information theory parallels the second law of thermodynamics in expressing that the uncertainty in the world always tends to increase [27,28]. In Boltzmann's definition, entropy is a measure of the number of possible microscopic states (or microstates) of a system in thermodynamic equilibrium consistent with its macroscopic thermodynamic properties (or macrostate).

Shannon's measure of entropy

Consider a situation where there are n possible outcomes (the functional requirements), each with a probability of occurrence of p_i (design parameters). Let $p = (p_1, p_2 \ldots, p_n)$ be the probability distribution, such that $p_i \geq 0$ for all i and $\Sigma_i pi = 1$ for all i and for i between 1 and n.

The measure of entropy for this distribution is given by

$$S = \sum_i p_i \ \ln \ p_i$$

for i between 1 and n and whose function decreases from infinity to 0 for p_i ranging from 0 to 1. This measure is derived by using the axiomatic method of Euclid to quantify the concept of the uncertainty of a probability distribution.

Shannon used the following properties:

- S depends on all probabilities $(p_1, p_2 \ldots, p_n)$.
- S $(p_1, p_2 \ldots, p_n)$ is a continuous function of $p_1, p_2 \ldots, p_n$.
- S $(p_1, p_2 \ldots, p_n)$ is permutationally symmetric. It does not change if S $(p_1, p_2 \ldots, p_n)$ are reordered among themselves. This property is desirable since the labeling of outcomes should not affect the value of entropy.
- S $(1/n, 1/n \ldots, 1/n)$ should be a monotonic increasing function of n. As the number of outcomes increases, then, entropy increases.
- The maximum value of $S = (p_1, p_2 \ldots, p_n)$ occurs when all the outcomes have an equal probability of occurring. This maximum value is indicated as equal to ln n from the statistical description [28-31].

Statistical description of entropy

Examining the behaviors of the statistical definition of entropy as regards randomness, a uniform probability distribution reflects the largest randomness; a system with n allowed states will have the greatest entropy when each state is equally likely. In these probabilities where n = total number of microstates, the entropy is thus $S = n \ln n$.

Therefore, the summation can be summarized as S is maximum when ln n is maximum, which permits many states, hence much randomness; equally, S is minimum when ln n is minimum. For instance, $n = 1$, the randomness will be zero, and S will be zero. For the additive property of entropy with respect to probabilities, if there is a quantum state when A is in its state x and B in its state y, it would be $p_{\mathrm{Ax}} * p_{\mathrm{By}}$ since the two probabilities are independent. The number of probabilities for the combined system is thus defined as $n = n_{\mathrm{A}} * n_{\mathrm{B}}$. The entropy of the combined $S = \ln (n_{\mathrm{A}} * n_{\mathrm{B}})$ is $S = S_{\mathrm{A}} + S_{\mathrm{B}}$.

Entropy and remanufacture structure matrix

Entropy is defined as the measurement of system disorder. In this study, the function called entropy is used to evaluate the remanufacturing sequences, which are systemically generated by design alternatives of a product, and to select the design with the lowest entropy value. A high degree of entropy indicates a significant disorder and a high degree of symmetrical effect, while low levels of entropy represent an orderly state and a high degree of asymmetrical effect [16,30]. Therefore, in designing for remanufacturing, it is important to understand the entropy level and to control or adjust the design when the product design shows result towards a disadvantaged state of remanufacturability.

Axiomatic design is used to create a design structure matrix that assesses how the product, after its life cycle, passes all the different remanufacturing operation [16,32]. The relationship between the design structures can be determined and used to assess the extent of ease the entire remanufacturing operations would take place. The idea here is to study each stage required in remanufacturing, determine the functional requirement (FRs) of the product at a particular stage of remanufacturing, and transform the requirements into design parameters (DPs). The design parameters are affected by the remanufacturing operation variables (RVs) which might cause the transformation process to incur some degree of uncertainty. This uncertainty in this paper is interpreted as the unlikelihood that functional requirement will be achieved after the remanufacturing. Meanwhile, the goal of DfRem is to achieve FRs, and thus, any uncertainty in accomplishing the goal is considered to incur complexity. To solve or reduce the complexity, what is required is information. Therefore, information is an effective measure of uncertainty since it is what is required to resolve any uncertainty. In that sense, complexity should be proportional to the information. Axiomatic design theory has the quantity called information content, which is quite similar to that of Shannon's. Since axiomatic design complexity is explicitly defined in terms of uncertainty, it is natural to relate complexity to information indicated in the design structure [29,30,32].

To evaluate the adequacy of the product design to meet remanufacturing goal, the information content, via FRs and DPs, of a product can be calculated by Shannon's entropy. The high entropy value indicates a high degree of uncertainty, which provides deviation from the expected state in the process of remanufacturing the product.

The advantages of the metric developed in this paper lies in the familiarity of the product development team with the axiomatic designs whose approach focused on the low-level structure of the product to be remanufactured [32]. Axiomatic design (AD) would help in providing information on technical solution and expected performances about the product after its remanufacturing.

AD approach is akin to designers finding information about what the customer would require from the product after its first life cycle and transform the knowledge into design parameters that would be embedded into the product. Design parameters are collections of physical/non-physical entities that cooperatively deliver overall functional requirements of a product. Both functional knowledge and design parameters could be quantified to assess how easy the remanufacture of the product could be carried out. Hence, the metric on this approach provides a systematic assessment for deriving and optimizing designs for remanufacture and helps avoid traditional design-build-use-remanufacture cycles for remanufacture solution search.

For instance, the cleaning stage of remanufacturing is the process of removing anything that is not intended to be present in the part; it involves removing any substance like oil, sand, and other foreign materials. Let us assume that a customer wants a pipe (used pipe) attached to a pump machine (Figure 3) to serve as conduit for drawing water. The used pipe needs to be cleaned as part of remanufacturing the pump machine, and both soil and grease debris could be cleaned by a solution of cleaning agents and/or mechanical brushing.

$$C = conduit$$

$$\begin{Bmatrix} remove\ soil \\ remove\ grease \end{Bmatrix} = \begin{pmatrix} \mathrm{a11} & \mathrm{a12} \\ 0, & \mathrm{a22} \end{pmatrix} \begin{Bmatrix} mechanical\ brush \\ chemical\ solution \end{Bmatrix}$$

The mechanical brush will only remove the soil, and the solvent will both dissolve the grease and rinse away the soil. Thus, it is more appropriate to use the chemical solution for the cleaning operation of the pipe remanufacture [16].

Figure 3 A pump machine.

Hence, in the design for such pipe or conduit, the materials should not be made of anything susceptible to chemical solution. New design will enhance the efficiency of remanufacturing operations.

At each stage of remanufacturing operation, a design hierarchy is created. The relations (the dependencies) between the FRs and the DPs can be represented in an equation of the form:

FR = [A] DP

Also, the design parameters are affected by the RVs.

DP = [B] RV

By substituting, the two matrix equations can be combined into a single relation, linking requirement with remanufacturing operation.

FR = [A] [B] R

FR = [C] RV

where [C] = [A] [B]. The multiplication orders reflect the chronological order of the design and all remanufacturing operations. In theory, if the resulting matrix [C] is diagonal, then the design is uncoupled, and all design parameters and remanufacturing operation variables satisfy the functional requirements, as well as Axiom 1. The same iteration process would be done for all other process [7,12,16,30].

However, in reality, obtaining this formation might not be easy; either [A] or [B] has to be adjusted to meet the customer's needs. Minimizing the information content of design parameters would increase the chance of satisfying a function and meeting the customer's needs in the used product.

Illustrations

A new product is being developed; assuming that after the first life cycle, the manufacturer would want to remanufacture the product for reuse. The product part (pipe) will have to go through a series of processes: cleaning, reprocessing, and reassembly.

Let us assume that the functional requirements of the product part (pipe) after the cleaning process are: (1) strength, (2) aesthetic appearance, (3) attachment to the machine, (4) ability to draw liquid, and (5) ability to provide direction [30]. The functional requirements are mapped into design parameters as follows:

$$\overset{FR}{\left\{\begin{array}{l} strength \\ aesthetic\ \ appearance \\ attachment\ \ to\ \ the\ \ machine \\ ability\ to\ draw\ \ liquid \\ ability\ to\ provide\ \ directions \end{array}\right\}} = \overset{A}{\begin{pmatrix} \times & & & & \\ & \times & & & \\ & & \times & & \\ & & & \times & \\ & & & & \times \end{pmatrix}} \overset{DP}{\left\{\begin{array}{l} structure \\ color \\ joining\ \ process \\ hole \\ label \end{array}\right\}}$$

Table 1 The derived design matrices and coupling for cleaning process matrices

	DP1	DP2	DP3	DP4	DP5
FR1	×				
FR2		×			
FR3			×		
FR4				×	
FR5					×

Table 2 The design matrices and coupling for reprocessing process

	DP1	DP2	DP3	DP4	DP5
FR1	×				×
FR2		×			
FR3			×		
FR4		×		×	
FR5				×	×

From the structure above, Table 1 is the derived design matrices and coupling for the cleaning process matrices, {FR} = [A]{DP}. Table 2 represents the design matrices and coupling for the reprocessing process. Table 3 represents the design matrices and coupling for reassembly process.

Remanufacture and entropy-based analysis

Definition 1: (Function entropy): For a function requirement 1(FR_1), its entropy is defined as

$S\ (FR) = -\Sigma_i^n FRi \ln FRi$

where FR*i* is the number of all functional requirements *i* assigned to the design parameters, and *n* is the number of design parameters corresponding to functional requirement FR*i*. *S* (FR) is meant for the determination of all customer requirements in the product after the remanufacturing of the product has taken place.

To normalize the value of functional requirement, the logarithm of the number of design parameters is taken.

S (cleaning/FR) = 1ln1 + 1ln1 + 1ln1 + 1ln1 + 1ln1 = 0

S (cleaning process/FR) = Log_5 (0) = 0

Table 3 The design matrices and coupling for reassembly process

	DP1	DP2	DP3	DP4	DP5
FR1	×				
FR2		×			
FR3		×	×		
FR4		×		×	
FR5		×			×

S (reprocessing/FR) = 1ln1 + 2ln2 + 1ln1 + 2ln2 + 2ln2 = 4.16
S (reprocessing/FR) = Log_5 (4.16) = 0.89
S (reassembly/FR) = 1ln1 + 4ln4 + 1ln1 + 1ln1 + 1ln1 = 5.5
S (reprocessing process/FR) = Log_5 (5.5) = 1.06

Definition 2: (Design parameter entropy): For a design parameter (D), its entropy is defined as the average entropy of all design parameters for functional requirement. Since not all the customer requirements might be met in the remanufactured products, it is necessary to determine the entropy of design parameters that would fulfill customer requirements.

S (DP) = $(\Sigma_i^k \text{DP}i)/k$
S (cleaning/DP) = (1 ln1)/1 = 0
Log_5 (0) = 0
S (reprocessing/DP) = (2ln2 + 2ln2 + 2ln2) = (4.16) / 3 = 1.38
Log_5 (1.3) = 0.16
Similarly, S (reassembly/DP) = 2.77
Log_5 (2.77) = 0.62

Definition 3: The literature on remanufacturing indicates that the processes are sequential for almost all remanufacturing operation [30]. For a given product, from its design matrices of remanufacture, we can define the entropy metric as the sum of the values of its entropy value of functional requirements and design parameters from all the processes proposed for the product's remanufacturing.

S (remanufacturing) = S (cleaning, reprocessing, reassembly)
S (remanufacturing/FR) = 0 + 0.89 + 1.06 = 1.95
S (remanufacturing/DP) = 0 + 0.16 + 0.62 = .78

$$\Sigma\ S\ (\text{processes in remanufacturing}) = 1.95 + 0.78$$

Entropy metric of remanufacturability = Log $\sum$ (entropy of all required stages, via FRs and DPs, in the remanufacturing) = 1.95 + 0.78 = 2.73.

To normalize between (0, 1), take $\log_{10}$ of the value.

Entropy metric value for the illustrated product's remanufacturability = $\log_{10}(2.73) = 0.44$.

Discussion and conclusion

The design matrix has been identified as tools to express the dependence and information flow between various stages in designing a product for remanufacture. Moreover, the main point offered in this paper is that the existing tool of thermodynamics such as entropy could be engaged to develop a metric for the analysis of a product's remanufacturability via its design matrices. Considering the illustrations provided in the paper, it is shown that by finding functional requirements from the product after its life cycle, its corresponding design parameters, and establishing design matrices for potential processes for the product remanufacturing, one can determine the degree of remanufacturability existing in the product at the product development stages.

The main advantage of using this metric is that its theoretical basis can easily be understood by the product designers and engineers. Subsequently, this metric may be associated with monetary value owing to the fact that remanufacturing must be done with minimum investment, especially with contentious arguments of some authors that economic consideration must be at the forefront of DfRem. Quantifying remanufacturability on the product labeling may serve as an incentive for the customers to buy the product, just like energy consumption is nowadays labeled on many products.

The functionality of the metric is contingent on developing information about the status of product end-of-life and functional deliverables after product remanufacturing. Therefore, it might not be sufficient to conclude that the metric developed is far better than other metrics, but the metric reinforces life cycle thinking and early use in the design stage of the product development, both critical components missing in many other metrics.

However, a design having a very high entropic value for its product remanufacturability might not necessarily mean it would not be remanufacturable but require more information to understand what is happening in the design. Therefore, developing methods for acquiring information needed to conclude designs will require more research.

Competing interests

The authors declare that they have no competing interest.

Authors' contributions

MOR and HCZ made contributions to all parts of the manuscript. Both authors read and approved the final manuscript.

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