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Aihua Huang
University of Kentucky, aiwa0115@gmail.com

Fazleena Badurdeen
University of Kentucky, badurdeen@uky.edu

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Sustainable Manufacturing Performance Evaluation: Integrating Product and Process Metrics for Systems Level Assessment

Aihua Huang[a,b]*, Fazleena Badurdeen[a,b]

[a]*Department of Mechanical Engineering, University of Kentucky, Lexington, KY, 40503, USA*
[b]*Institute for Sustainable Manufacturing, University of Kentucky, Lexington, KY, 40503, USA*

Abstract

This paper builds on the previously developed product sustainability index (*ProdSI*) and process sustainability index (*ProcSI*), and presents a framework for sustainable manufacturing performance evaluation at the systems level. The framework is then used to propose a comprehensive set of metrics for the enterprise level following a five-stage metrics hierarchy (individual metrics, sub-clusters, clusters, sub-index and index). The 6R concept (reduce, reuse, recycle, recover, redesign and remanufacture), total life-cycle emphasis, and triple bottom line (TBL) are considered for selecting relevant metrics. Finally, the metrics are integrated to develop an index for enterprise level sustainability assessment and demonstrated using a numerical example.

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Keywords: Sustainable manufacturing; enterprise sustainablity index; performance evaluation; systems level; 6R; total life-cycle.

1. Introduction

Manufacturing enterprises today face an increasingly complex environment due to scarcity of natural resources, stricter regulations and increasing customer demand for sustainable products. In order to meet these demands for sustainable products, manufacturing companies have adopted numerous strategies including sustainable manufacturing. The concept of sustainable manufacturing has emerged over the past 40 years [1]. The commonly

* Corresponding author. Tel.: +1-859-323-3210; fax: +1-859-257-1071.
E-mail address: aihua.huang@uky.edu

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referred definition for sustainable manufacturing is that proposed by the U.S. Department of Commerce, which defined as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [2]. In addition to this original definition, National Council for Advanced Manufacturing (NCFAM) emphasizes the need for considering manufacturing of “sustainable” products and the sustainable manufacturing of all products [3]. Adapting these two definitions, Jawahir et al. (2014) [4] stressed that “Sustainable manufacturing at product, process and system levels must: demonstrate reduced negative environmental impacts, offer improved energy and resource efficiency, generate minimum quantity of waste, provide operational personnel health while maintaining and/or improving the product and process quality with the overall life-cycle cost benefits.”. Sustainable manufacturing aims to provide sustainable benefits to all the stakeholders. Thus, economic, environmental, societal impacts must be fully considered. When evaluating these impacts in sustainable manufacturing, the total life-cycle, including the four life-cycle stages (pre-manufacturing, manufacturing, use and post-use) must also be considered. Further, the 6R concept (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture) needs to be incorporated for a multiple life-cycle concept to achieve a closed-loop material flow [5]. In order to evaluate the extent to which each of these criteria are achieved. Sustainable manufacturing performance evaluation must be done at different levels within the manufacturing organization, such as product level, process level, and systems level. The systems level can range from line, plant, enterprise to entire supply chain. Comprehensive methods have been presented in literature to evaluate sustainable manufacturing performance at the product and process levels. However, holistic approaches to evaluate systems level sustainable manufacturing performance are lacking. This paper presents a comprehensive framework for sustainable manufacturing systems level assessment and demonstrates its application to a case study at the enterprise level.

The paper is organized as follows. Section 2 provides a literature review on sustainability performance evaluation at product and process, line, cell, and finally enterprise levels. Section 3 describes the framework for identifying system (line, plant, enterprise and supply chain) level sustainability metrics by integrating product and process level metrics. A case study is introduced and a comparison is made for enterprise sustainability performance evaluation in two calendars years in Section 4. Conclusions and future work are covered in Section 5.

2. Literature review

In recent years, different frameworks and indicator systems have been proposed to evaluate sustainable manufacturing at the product, process, and system levels. This section presents some of the more prominent methods.

2.1. Sustainability performance evaluation at product and process levels

Fiksel et al. [6] proposed the product sustainability indicators. The product sustainability evaluation considered the economic, environmental and societal aspects of resource consumption and value creation throughout its life-cycle. The proposed indicators also provided a foundation to measure the comprehensive product sustainability. These proposed indicators do not consider the product’s end-of-life management, which play an importance role for product sustainability performance evaluation from total life-cycle perspective. De Silva et al. [7] developed a sustainability scoring method, which was used to evaluate electronics products’ sustainability performance. This method considered six sustainability elements (environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact) and their sub-elements. A product sustainability assessment method, known as *ProdSI*, is proposed by Shuaib et al. [8]. This product sustainability metrics system is developed by building on some earlier work. This method proposed a set of product sustainability metrics by covering TBL, total life-cycle and 6R concept. Correspondingly, Lu [9] proposed a set of process sustainability metrics which considered manufacturing cost, environmental impact, waste management, energy consumption, operational safety and personnel health. These two method applied similar calculation procedure for evaluating product/process sustainability performance. The metrics proposed for product and process can be integrated to identify the sustainability metrics at the enterprise level later.

2.2. Sustainability performance evaluation at line and cell levels

One of the attempts at sustainability performance evaluation at line level is presented by Faulkner et al. [10], where a comprehensive methodology, known as sustainable value stream mapping (Sus-VSM), is proposed to assess manufacturing sustainability performance at production line level. As a by-product, the suitable sustainability metrics and methods to visualize them are identified. This approach is also demonstrated through application to an industry case study and has later been applied in different manufacturing system configurations by Brown et al. [11]. In this work, however, metrics development does not integrate total life-cycle focus or 6R. To be a comprehensive metrics development at systems level must consider TBL, Total Life-Cycle, and 6R simultaneously from a sustainable manufacturing point of view. Zhang et al. [12] developed an approach to assess broader sustainability impacts by conducting economic assessment, environmental assessment, and social impact assessment at the work cell level. Then, these assessment results at each aspect of TBL are integrated into a sustainable manufacturing assessment framework with modified weighting methods. In order to demonstrate the detailed assessment steps, this approach is applied to an example for producing steel knives at a machining work cell level. The assessment results for three production scenarios are compared to investigate the largest production cost contributor, which is proved to be cutting tool cost. All the sustainability assessments for the case study are evaluated using a set of selected metrics. The limitations of this approach are the lack of societal metrics; further they only considered cost in the economic aspect.

2.3. Sustainability performance evaluation at the enterprise level

The commonly referred method/tool for industrial companies is Global Reporting Initiative (GRI), which proposed 91 measures in G4 reporting guidelines [13]. However, GRI only provide guidelines for sustainability evaluation without detailed measurement steps. Another widely used method in industry is called Corporate Responsibility Magazine (CRM) [14], which evaluate enterprise sustainability performance from 7 categories known as climate change, employee relations, environmental, financial, governance, human rights and philanthropy and community support. The CRM collected and analyzed the data from company web sites, sustainability reports, company 10-Ks and other public resource. Then the relevant performance is ranked from 1-1000 with 1 being the best rank. The relative weights for the 7 categories is decided by the methodology committee. Further, the final rank for the enterprises can be calculated by aggregating the ranks to get the final rank for the enterprise. Keeble et al. [15] presented two case studies for developing corporate sustainability indicators. The first case study established nine indicators to help measure corporate sustainability performance through implementing a five-step approach. In the second case study, 69 sustainability indicators were developed which was applicable to the project-level. Krajnc and Glavic [16] developed a composite sustainable development index for corporations. A seven-step process for developing the composite index was employed. The analytic hierarchy process (AHP) was used to determine the weights of the indicators included in the index. The presented composite index consisted of 6 economic, 22 environmental and 10 social indicators. They also applied the index in a case study to compare two multinational oil companies on the selected indicators, including 4 economic, 6 environmental and 4 social indicators. A set of core indicators of sustainable production was proposed by Veleva and Ellenbecker [17]. The Lowell Center for Sustainable Production (LCSP) indicator framework composes of five levels. These five levels are: company compliance/conformance indicators; company material use and performance indicators; company effects indicators; supply chain and product life-cycle indicators; and sustainable system indicators. The proposed 22 core indicators including energy and material use, natural environment, economic performance, community development and social justice, workers and products were accompanied by detailed guidance on their application. All these methods for enterprise sustainability performance evaluations partially covered TBL, total life-cycle stages and 6R concept. Therefore there is a necessity to develop a methodology to evaluate enterprise sustainable manufacturing performance from a comprehensive perspective.

3. Integrating process and product metrics for enterprise level sustainable manufacturing metrics

Sustainable manufacturing has been promoted by a significant amount of research that focused on developing more sustainable products and processes. Therefore, when identifying enterprise level sustainable manufacturing metrics, integrating product and process sustainability metrics is essential. At product level, this means moving the practice of going from cradle-to-grave to cradle-to-cradle [5] as opposed to most previous research which focuses merely on pre-manufacturing, manufacturing and use stages of a product life-cycle. Total life-cycle approach which incorporates upstream suppliers and downstream customers, require the implementation of 6R concept. When it comes to process level, sustainable manufacturing ensures more efficient resource utilization, emission reduction as well as health and safety improvement. The integration of product and process sustainability for system sustainability, has been overlooked by researchers. To achieve sustainability in manufacturing, design and improvements must be coordinated across products, processes and the system. A comprehensive framework was proposed for developing sustainable manufacturing metrics at the systems level which integrated process and product sustainability metrics [18] as shown as sustainable manufacturing performance measurement house in Fig. 1. The foundation of this framework is sustainable manufacturing. TBL, total life-cycle and 6R are the concrete pillars to support this house. Then in the middle is the performance measurement framework, that will provide a consistent and acceptable approach to systematically collect, analyze, utilize and report the sustainability performance. In the pillar of product metrics, the metrics developed in the previous product sustainability index (*ProdSI*) are taken into consideration for systems level metrics development. In the pillar, process metrics developed in a previous study of process sustainability index (*ProcSI*) are incorporated for systems level metrics development. In the middle of the house are the stakeholders, who should be considered for sustainability metrics development. Then systems metrics forms the roof of the house, which can be formulated at four levels ranging from line level, plant level, enterprise level, to supply chain level. Given the framework presented in Fig. 1 below, the focus of this paper will be on developing enterprise level sustainability metrics (not line, plant or supply chain levels).

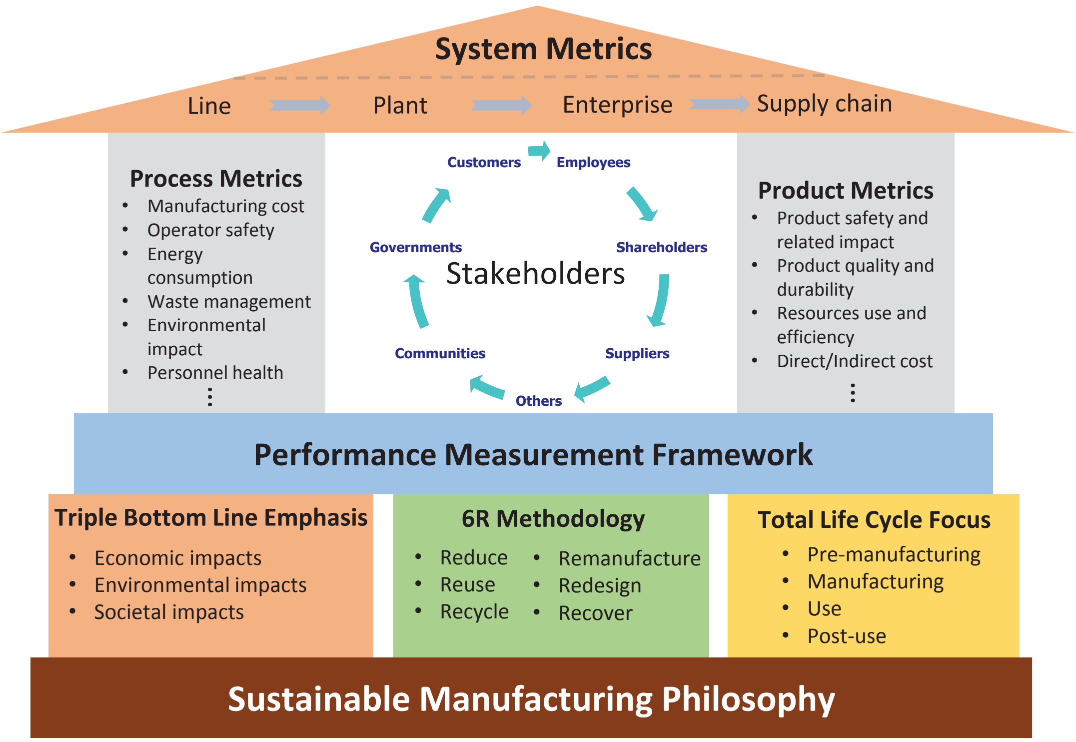


Fig. 1. Sustainable manufacturing performance measurement house [18]

4. Enterprise sustainability index (*EnSI*) methodology for enterprise sustainable manufacturing performance evaluation

In order to better present the enterprise sustainability behavior, numerous metrics were evaluated and selected to cover TBL, total life-cycle stages and 6R perspectives. We propose a five-level hierarchical structure for enterprise sustainable manufacturing metrics in the sequence of individual metrics, sub-clusters, clusters, sub-index, and the index. To make the enterprise sustainability metrics comprehensive, the established metrics system will consist of 9 clusters each of which represents an area of enterprise sustainability. To better reflect the context of assessment, they are further categorized into sub-clusters and metrics are identified for each sub-cluster. The metrics are sequentially aggregated at sub-cluster and cluster levels to develop sub-indices for economic, environmental and societal aspects. The sub-indices are then aggregated to compute the Enterprise Sustainability Index (*EnSI*). Fig. 2 shows the coverage of the sustainability clusters for the product, process and enterprise levels.

As can be observed from Fig. 2, some clusters from the *ProdSI* and *ProcSI* are included in the *EnSI*, directly or with some minor modifications. This reflects the ideology presented in Fig.1 where some aspects of products performance and process performance must be integrated to evaluate system level performance (in this case at enterprise level). Fig. 3 presents the entire set of metrics for enterprise sustainability evaluation including the relevant indices, sub-indices, clusters, and sub-clusters. The metrics were identified following the thorough review of literature and previous work. Pre-manufacturing, manufacturing, use and post-use stages were considered when selecting metrics for the proposed *EnSI*.

Clusters	Economy						Environment								Society								
	Initial investment	Direct/Indirect costs and overhead	Benefits and losses	Net profit	Capital charge	Manufacturing cost	Material use and efficiency	Energy use and efficiency	Other resources use and efficiency	Waste and emission	Product EOL	Energy consumption	Waste management	Environmental impact	Product safety and health impact	Product societal impact regulations and certification	Product quality and durability	Functional performance	Product EOL management	Health and safety	Stakeholder engagement	Operational safety	Personnel health
ProdSI	√	√	√				√	√	√	√	√				√	√	√	√	√				
ProcSI						√						√	√	√								√	√
EnSI				√	√		√	√	√	√	√									√	√		

Fig. 2. Comparison of clusters for sustainability performance evaluation for *ProdSI*, *ProcSI* and *EnSI*.

Because the variety of metrics will have different units, the measured data are to be normalized according to a 0-10 scale, the score of 10 representing the best case is assigned only when a theoretically perfect case is achieved. Correspondingly, a score of zero is assigned only when the worst possible conditions are met for an enterprise to make it totally unsustainable. The procedure of normalization can be completed by using two methods: objective and subjective. The objective normalization method can be decided in two ways: (1) regulation and/or standard-guided scenario; (2) purely best and worst case scenario [8]. The subjective normalization method can be taken when a quantitative measurement is difficult to apply. The score of 0-10 can be assigned by subjective surveys of opinions from customers, employees, academic researchers, industrial expert, and government/non-government organizations. The procedure of weighting can be completed by three commonly used weighting methods: equal weighting, subjective, weighting and weighting from analytical approached such as analytical hierarchy process (AHP). The calculation of final score *EnSI* is mostly the same as the method proposed for *ProdSI* and *ProcSI*. The difference for calculating *EnSI* is with how the sub-index score of economy is calculated. The methods to evaluate enterprise economic performance is well established. Therefore, the method developed by Lambert [19] called Economic value added (EVA) is used to compute enterprise economic sustainability (*Ec*). The score aggregation for calculating *EnSI* is expressed in equations (1), (2) and (3), where the normalized data are aggregated into the higher level based on the weighting factors assigned.

$$EnSI = w_{Ec}Ec + w_{En}En + w_{So}So = w_{Ec}Ec + w_{En}\sum_{i=3}^{7} w_i^c C_i + w_{So}\sum_{i=8}^{9} w_i^c C_i \tag{1}$$

$$C_m = \sum SC_j w_j^{sc} \ \forall j \tag{2}$$

$$SC_n = \sum M_k w_k^m \ \forall j \tag{3}$$

Where:

w_{Ec} , w_{En} , w_{So} - Weighting factor for economy, environment, society sub-indices, respectively
Ec, En, So - Sub-index score for economic, environmental and societal impact, respectively
w_i^C, w_j^{SC}, w_k^m- weighting factor for i^{th} cluster, j^{th} sub-cluster, k^{th} metric, respectively
C_m - Score for m^{th} cluster. C_1 and C_2 are the clusters in the economy sub-index, C_3 to C_7 are the clusters in the environment sub-index and C_8 to C_9 are the clusters in the society sub-index.
SC_n , M_k - Score for the nth sub-cluster, the k^{th} metric, respectively

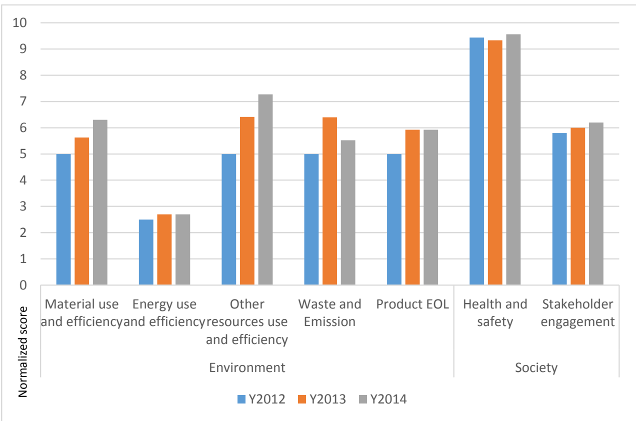
Sub-Index	Cluster	Sub-Cluster	Standard Metrics
Economy	Net Profit	Profit from Operations	Sales revenue
			R&D expenditure
			Material cost
			Energy cost
			Labor cost
			Water cost
			Transportation cost
			Warehouse cost
			Other Expenses
		Taxes	Taxes
	Capital charge	Current Assets	Inventory
			Other current assets
		Fixed Assets	Facilities
			Equipment
			Other fixed assets
		Cost of capital	Cost of capital
Environment	Material use and efficiency	Material efficiency	Material intensity
		Product material content	Percentage of hazardous material use
			Percentage of recycled material use
	Energy use and efficiency	Energy from renewable resource	Percentage of renewable energy usage
		Energy efficiency	Energy intensity
	Other resources use and efficiency	Water efficiency	Water intensity
		Recycled water use	Percentage of water recycled/reused
	Waste and Emission	Waste	Percentage of non-hazardous waste recycled/reused
			Percentage of hazardous waste recycled/reused
			Total waste generation intensity
		Emission	GHG release intensity
			Hazardous gaseous emission
	Product EOL	Product EOL	Percentage of products landfilled
			Percentage of product EOL recovered

Sub-Index	Cluster	Sub-Cluster	Standard Metrics
Society	Health and Safety	Employees	Percentage of employees receiving safety training
			Employees exposed to high-risk work environment
			Work-related injuries and incidents rate
		Customer	Customer injury rate
		Other stakeholder related	Health/safety risk to community
	Stakeholder Engagement	Supplier diversity and development	Local sourcing
			Supplier support & development
			Percentage of sustainability-oriented suppliers
		Employee diversity and well-being	Employee training
			Employee diversity
			Employee turnover
		Customer satisfaction	Repeat customers
			Product satisfaction rate
			Number of customer complaints
		Product end-of-life practice	Job creation from product EOL processing
			Reduction of product disposed directly to landfill
			Benefits to society by virgin resource saving
		Other stakeholders development	Community outreach/engagement activities
			Local community hiring percentage

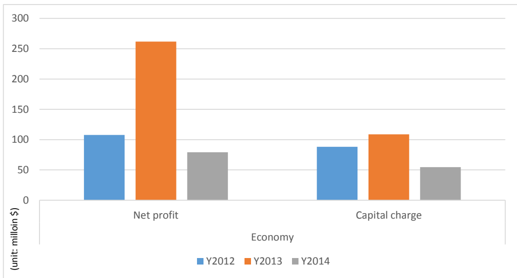
Fig. 3. Enterprise sustainability metrics

5. Case study: sustainable manufacturing performance evaluation for a consumer electronic company

A case study is presented to demonstrate the *EnSI* methodology discussed in the previous section. In this case study, all the data are collected from a local consumer electronic company in situations where data was not available, reasonable estimates were assumed. To compute the index, equal weights are assigned to the metrics, sub-clusters, clusters and sub-indices. A visual comparison of enterprise sustainable manufacturing performance for years 2012 (Y2012), 2013(Y2013) and 2014 (Y2014) are shown in a histogram in Fig. 4. Fig. 5 shows the normalized score of sub-indices and overall *EnSI* for Y2012, Y2013 and Y2014. For the calculations, performance at Y2012 is considered as the baseline and given a score at 5.00. The performance in Y2013 and Y2014 is then calculated and normalized correspondingly. Results clearly show that the sustainable manufacturing performance for Y2013 is the best compared to that in Y2012 and Y2014. The ideal enterprise performance would be when the enterprise economic performance is highest while the environmental and societal negative impact is lowest. However, it is reasonable to expect that improvement of environmental and societal positive impact in the short term can only be achieved through sacrificing some economic profitability. From the visual representation of Fig. 4 (b), it is not difficult to find that the economic score of Y2013 is much better than that in Y2012 and Y2014 due to a significant increase in operating income in Y2013. Meanwhile, the societal performance score of Y2014 is a little bit higher than that in Y2012 and Y2013 resulting from the societal benefits due to better environmental sustainability strategy implementation. Therefore, the comparison of enterprise sustainability performance in three years helps assess the trade-offs that may have to be made when balancing economic profitability and the environmental and societal impacts simultaneously.



(a)



(b)

Fig. 4. (a) Environmental and societal performance comparison at cluster level (normalized values)
(b) Economic performance comparison (absolute values)

		Y2012	Y2013	Y2014
Sub-index	Economy	5	10	6.32
	Environment	4.5	5.41	5.54
	Society	7.64	7.67	7.88
Index	*EnSI*	5.71	7.69	6.58

Fig. 5. Comparison of sub-indices and *EnSI* for Y2012, Y2013 and Y2014

6. Conclusions and future work

This paper presents a metrics-based methodology for an Enterprise Sustainability Index (*EnSI*) to evaluate sustainable manufacturing performance at the enterprise level. Existing metrics for enterprise sustainable manufacturing performance evaluation are analyzed and suitable metrics identified by integrating the previously developed product sustainability metrics and process sustainability metrics. The structure of *EnSI* is demonstrated and the calculation of the final score for *EnSI* is stated as well. A case study is presented to demonstrate how the proposed methodology is applied to evaluate the enterprise sustainable manufacturing performance. From the comparison of results in the case study, it is not difficult to find that the final *EnSI* score in Y2013 is higher than that in Y2012 and Y2014 due to the significant increase in operating income compared to that in Y2012 and Y2014. Although the economic profitability performance in Y2014 is lower than that in Y2013, the sustainability performance at the environmental and societal aspects have been improved. Further, the total enterprise sustainability performance has improved though at the expense of economic sustainability performance. This helps reiterate that the trade-offs have to be considered when evaluating enterprise sustainability performance from economic, environmental and societal aspects.

Future research work will identify other systems levels sustainable manufacturing metrics---including line, plant and supply chain levels---and propose sustainability performance evaluation methods at those levels. Another challenge is to evaluate and compare the enterprise sustainable manufacturing performance at the enterprise level using alternate ways such as from a sustainable value perspective.

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