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Sustainability index development for manufacturing industry

Hasan H. Latif [a,*], Bhaskaran Gopalakrishnan [b], Ashish Nimbarte [b], Kenneth Currie [b]

[a] Department of Industrial & Systems Engineering, North Carolina State University, Raleigh, NC 27606, USA
[b] Department of Industrial and Management Systems Engineering, Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, WV 26506, USA

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ABSTRACT

Manufacturing industries are adopting new techniques and philosophies to address the acute shortage of non-renewable energy. Many of these manufacturing industries are focusing on achieving sustainability in every possible stage of their production, from raw material to the recycling of waste. Thus, the significance of using renewable energy, properly handling waste, and progressively conserving the environment is increasing day by day. In this research, the definition of sustainability is quite specific: being productive while making little to no impact on non-replenishable resources. The objective of the research is to determine the sustainability index of manufacturing plants. Since the topic has a broad scope, this research is limited to small and medium scale industries, which have common sets of operation and defined process plans. Besides, the focus is on non-hazardous waste and the indicators of the index are selected with respect to energy efficiency, workers' health and safety and waste reduction potential. An interactive model has been developed to determine the sustainability index based on user responses. Based on the sustainable index, the model is able to provide suggestions to improve sustainability as well as carbon footprint reduction. The research has used datasets from various projects of the Industrial Assessment Center (IAC) at West Virginia University to build the knowledge database. The interactive model is validated by case studies from the IAC. The outcome of this research is a model that can assist industry to identify their shortcomings in achieving sustainability, determine the carbon footprint reduction potential, and compare the sustainability index as a benchmark measure.

Introduction

Sustainability in manufacturing has recently received an increasing amount of attention. It is considered as an effective solution to advance the continuous growth and expansion of the manufacturing industry [1]. Recently National Council for Advanced Manufacturing (NACFAM) has shaped a policy initiative towards sustainable manufacturing [2]. The covered sectors of manufacturing lie within North American Industry Classification System (NAICS) 311-339 definition [3]. The manufacturing industry sectors have significant anomalies. Minimal effort has been given on sorting the anomalies; however, sustainable manufacturing is considered a key step in moving forward. To provide a useful tool for comparing sustainability across processes and companies, a comparative and quantitative scoring system or index is essential. The literature lacks clear efforts for creating a sustainable manufacturing index. The goal of creating such an index is to enhance the decision-making capability for modifications to manufacturing processes. Current efforts have failed to provide a rigorous index for examining the sustainability of manufacturing processes. To provide a useful tool for comparing sustainability across processes and companies, a comparative and quantitative scoring system is critical.

The aim of this research is to develop an interactive model to develop the sustainability index for small and medium scale manufacturing industry. According to Industrial Assessment Center (IAC) program of Department of Energy (DOE), the manufacturing industries with gross annual sales below 100 USD million and employees fewer than 500 at plant site are considered as small to mid-sized category [4]. A low score in sustainability index will indicate the area that needs improvement. Simultaneously, the carbon foot print will be determined to enhance the energy and waste management efficiency potential. This research addresses the problems of overcoming the research gap in sustainability determination by integrating the various indicators. The contribution of this research is threefold: 1) introducing an index based scoring system 2) evaluating the benefits of having sustainable policy 3) identifying the potential scope of opportunities within

* Corresponding author.
E-mail addresses: hhlatif@ncsu.edu (H.H. Latif), bgopalak@mail.wvu.edu (B. Gopalakrishnan), Ashish.Nimbarte@mail.wvu.edu (A. Nimbarte), krcurrie@mail.wvu.edu (K. Currie).

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existing manufacturing industry. The flow of information of this paper has been presented in the following manner: Section 1 of this paper has discussed the need of sustainable manufacturing indices and Section 2 has covered the literature review in this area. Section 3 has explained the methodology of determining the sustainability index (SI). Section 4 has modeled the determination of the sustainability index and Section 5 has conducted analysis. Section 6 of this paper has provided the conclusion.

Literature review

Until now, agricultural systems, ecological systems, and financial institutions have introduced sustainability indices despite having many different approaches applied in various ways without any standardization. Most of the research has been focused on few factors with a holistic approach, although pragmatic, quantitative analysis is much needed in this area. First, this paper has investigated the different sectors where sustainability index has been exercised. Dow Jones Sustainability Indices (DJSI) in collaboration with RobecoSAM provided a financial sustainability index for investors [5]. Although the authors are working with a varying definition of sustainability, the method for determining sustainability provides a baseline for calculating diversified indices. Lee and Huang use fifty-one sustainability indicators to determine a sustainability index for Taipei, a city of Taiwan [6]. The authors have divided the indicators into four different categories such as economic, social, environmental, and institutional dimensions. Zhou et al. discuss how to work with composite indicators while condensing multidimensional indices into one index score [7]. Composite indicators depend on aggregation methods of sub-indices, normalization methods, and a specific weighting scheme. The conceptual requirements for a City Sustainability Index (CSI) were discussed by Mori and Christodoulou [8]. They place importance on creating a CSI and compared the sustainability performances of various cities to observe the global impact of cities on the environment and human life compared to their economic contribution. Chavez and Alipaz created a dynamic and aggregated watershed sustainability index indicator [9]. They integrated hydrologic, environmental, life and policy issues to develop their model. A sustainability index should have a proper definition with specific objectives. For example, according to Emerson et al., Environmental Performance Index (EPI) focuses on the impacts of countries on the environment, which includes twenty-five indices with two objectives: (i) reducing environmental stresses to human health and (ii) protecting ecosystems and natural resources [10]. Singh et al. combined all the initiatives and framework for sustainable indicators. The selection of indicators is very important [11]. Mayer mentioned the impacts of selecting a wrong set of indicators in his review article [12]. He put significant importance on indicator selection and accumulated the current discrepancies in sustainability indices. Sands and Podmore worked on design and development of an Environmental Sustainability Index (ESI) and described a case study used to validate the performance of the index [13]. The EPIC model (Erosion Productivity Impact Calculator) was used and fifteen sustainability sub-indices were chosen to determine the index. Ngai et al. exposed the intangible benefits of environmental management practices and their potential to drive organizational competitiveness [14].

A collective review on sustainable manufacturing efforts by previous researchers are depicted as below. Nagalingam et al. measured the performance of product returns with recovery for sustainable manufacturing [15]. They developed a framework for performance measurement with the help of six sigma methodology. A survey of sustainability indices for countries was developed by Bohringer and Jochem [1]. The article examined the power of indices on policy making. Smith and Ball described the steps required to achieve sustainable manufacturing though modeling material, energy and waste flows [16]. Despeisse et al. showed that some companies such as Brandix, Ford, Sony, and Rolls-Royce are already reaping the benefits of focusing on sustainable manufacturing [17]. According to Ball et al., zero carbon manufacturing (ZCM) can be considered as a constituent element of sustainable manufacturing. ZCM improves the environmental performance of systems by understanding and examining MEW process mapping [18]. Some of the latest techniques on sustainable manufacturing has been implemented by Fuzzy based assessment models. Singh et al. has done a study on fuzzy interference system models for the evaluation of manufacturing sustainability of small and medium enterprises [19]. At first a list of sustainability indicators for manufacturing small and medium sized enterprises (SMEs) is identified and weak areas are detected to enhance the performance of overall sustainability. This approach will assist the decision maker to select an appropriate strategy to reduce the environmental impact.

There are many key performance indicators required to define the sustainability index of a manufacturing plant. Some researchers specify that a lean approach can be one of these indicators, even though the notion is not fully supported by all the peers in researching sustainability index in manufacturing plants. Marhani et al. discussed how lean approaches can help the cause of achieving sustainability [20]. Abolhassani et al. analyzed how lean approaches can impact a continuous improvement process in a manufacturing industry [21]. Yang et al. showed that lean practice will not improve environment performance all the time [22]. This is even though reducing waste and reusing resources across the spectrum of a manufacturing system is mandatory within the context of lean manufacturing. Gunasekaran and Spalanzani investigated the sustainability of manufacturing and services [23]. The researchers classified and performed a critical review to develop a framework for sustainability business development, and suggested future research directions with tools, techniques and some performance measures and metrics for sustainable business development. The classification scheme for the literature in manufacturing sustainability are i) sources of sustainable challenges and problems, ii) advances in sustainable business development in manufacturing and services, iii) sustainability in product/process design and development, iv) sustainability in supply operations, v) sustainability in production operations, vi) sustainability in distribution chain operations, and vii) sustainability through remanufacturing, recycling and reverse logistics.

Despeisse et al. discussed sustainable manufacturing approaches and cross functional factory modeling. They focused on the gap in knowledge on how to acquire expected conceptual aims at the operational level [24]. method to provide connection between the generic sustainability concepts and more specific examples of operational practices for resource efficiency in factories were presented in the paper. Finally, a resource flow analysis was tested and presented via a prototype tool. The overall analysis focuses on the events within the ecosystem of a factory (gate to gate). It accounted for location and time as well as manufacturing processes in a manner that was not supported by the independent disciplines of either process simulation or building energy analysis tools. Sustainable Energy Ireland published a draft of an energy management system which complies with ISO 14001 and is based on the plan of to-do-check-act cycle [25]. Sustainable energy Ireland (SEI) is referring to it as EN 16001 and it helps organizations set up a comprehensive energy management system and continually improve their utilization performance, leading to lower carbon footprint and lower energy costs. ISO 50001 works in the same direction by establishing the benchmarking energy management framework for industrial plants, commercial facilities and organizations.

Kimura discussed evolution and the future of sustainable manufacturing [26]. The author advocated a comprehensive framework for resource circulation to improve resource efficiency. System planning and product design technology, manufacturing technology, resource circulation technology are the important research and development items for sustainable manufacturing. In the future, product quality management and innovation, efficiency in manufacturing processes, improvement of resource circulation and new product/service for social innovation need to be addressed to attain progress on sustainable manufacturing. Mizuno et al. approached designing sustainable manufacturing scenarios using a 3S simulator [27]. The 3S simulator means sustainable society scenario which is an integrated design support environment for sustainable society framework. The designing of a scenario involves with formulating a problem, constructing a logic tree, determining scenario structure and describing sub-scenario dimensions. Joung et al. addressed the need for an improved version of indicator sets [28]. The author showed how the indicators can play role to assess a company's manufacturing process from five different dimensions of sustainability: environmental stewardship, economic growth, social happiness, technological advancement, and performance management. Yuan et al. stated sustainable manufacturing from a pollution prevention standpoint by taking into consideration three key components of manufacturing: technology, energy, and material [29]. They also performed a case study on a nano-manufacturing technology utilizing atomic layer deposition.

In regard to the discussion of literature, most of the previous research have focused on very few factors with a holistic approach, although a quantitative analysis is needed in this area. Minimal amount of work has been found on the methodology for a systematic approach to sustainability with every aspect of manufacturing industries. A systematic methodology is required to improve energy efficiency, productivity, and a work environment to achieve sustainable manufacturing goals. For that reason, a sustainability index is an important goal. This paper has provided an estimation of sustainability index by incorporating key factors.

Methodology

A sustainability index should be designed in such a way that it becomes applicable to all industry. The index should be chosen carefully so that it truly reflects the sustainability of a manufacturing organization, irrespective of any borders. The success and accuracy of a sustainability index depends on how appropriately the given data sets resemble the actual occurrences. To achieve the appropriate resemblance, the index should be properly within the context of the developed algorithm. The algorithm should also provide relative sensitivity to the changes in the index's parametric attributes. The most important aspect of the research is to integrate energy, waste and workers' safety into one sustainability index.

Aiming to assess sustainability in manufacturing industries, this research is focused on integrating some recognized indicators into an index value. Since sustainability is a dynamic and holistic process, it is assumed that a sustainability index is a function of energy efficiency (E), waste management (W), and workers' safety and health environment (H). This research will try to develop an algorithm that will consider each of these indicators and provide an index numerical value to compare among small to medium scale manufacturing industries. Considering the influence of indicators on sustainability, specifically in the environment of small to medium scale manufacturing industries and depending on the availability of related data, three indicators have been selected as the input parameters to model the sustainability index structure. The selected parameters with rationale for their selection are given below.

1. *Energy Efficiency (E)*: Energy efficiency is the first and foremost indicator of sustainability prediction. The National Association of Manufacturers (NAM) stated that the manufacturing sector consumes around one third (32%) of all energy in United States [30]. A company or organization's sustainability largely depends on how efficiently it is using energy. In many cases, the energy efficient mode is a lucrative upfront approach that pays for itself over time, while providing the extra benefits of minimizing energy cost and maximizing energy productivity. Afgan, N.H. et Al. discussed how energy system assessment is an important indicator of sustainability [31]. Indeed, the growing adoption of energy saving techniques is a recent trend in manufacturing industries. From the Industrial Assessment Center (IAC) database, the sub-indices or questions have been prepared. There is software named 'Energex' that has been used widely to estimate the efficiency of energy. Energex was created by Gopalakrishnan et al. for the NRCCE at WVU [32]. By adapting the Energex software and using the IAC database, twenty-nine factors have been selected from eight sub-groups that affect the efficient usage of energy. The eight sub factors are lighting, heating, ventilation, and air conditioning (HVAC), steam, process heat, pumps and fans, motors, air compressors, and cooling towers or chillers.
2. *Waste Management (W):* Mayer discussed the strengths and weaknesses of a sustainability index [12]. One of the important guidelines for achieving better sustainability is following the triple bottom line of sustainability [33]. Waste management falls into the environmental aspects of sustainability. Reducing waste is one of the most effective ways to achieve sustainable manufacturing processes. Manufacturing industries are confronted with several challenges, such as energy and water efficiency, environmental emissions, carbon footprint, and lost workdays due to workers' injury and illness. All these factors collectively add waste to the production of goods, significantly impacting "the bottom line of sustainability" and future growth of these industrial facilities. Mangalampalli created the software called 'Wastex' which deals with waste minimization [34]. This research has used Wastex features and factors to estimate waste minimization performance. Only solid waste has been considered for this research. In total, fifteen factors are used to calculate a sustainable manufacturing index. There are nine types of waste which contributes to nine factors, as stated in the appendix. The waste management approach forms rest of the six factors. These waste management approaches are focused on general strategy of handling waste for manufacturing plants.
3. *Workers' health and Safety (S):* If workstations are not designed ergonomically, they increase the risk of acute as well as chronic injuries. Most of the non-ergonomically designed workstations or tasks have at least one human factors issue. According to Chengalur et al., simple design suggestions based on the ergonomics interventions are known to eliminate or reduce possible risks for workplace accident or injuries [35]. Further, Monden revealed that improved workstations and tasks have a positive effect on workers' health and overall attitude [36]. Based on these findings, it is apparent that sustainability depends on workers' health and safety. Since the cost of injuries and accidents due to human factors issues varies significantly, sustainable manufacturing must have consideration for workers' health and safety. National Institute for Occupational Safety and Health (NIOSH) uses a standard questionnaire to assess a workplace environment [37]. This research has used the relevant parts of that questionnaire and adapted it into thirty-

Table 1
Details of indicators in sustainability index.

Indicators	Details	Source	Structure
Energy Efficiency (E)	Measuring the energy efficiency approach	Energex IAC Database	29 Factors 8 Sub-groups
Waste Management (W)	Finding out the waste management attitude	Wastex	15 Factors
Workers Health & Safety (H)	Workers health and safety environment	NIOSH	33 factors 4 Sub-groups

three factors with four sub-groups to determine the sustainability impact of a manufacturing industry. The four subgroups are physical exposure, psychosocial and psychophysical exposure, environmental exposure, and general policy. Working methods differ among industries. There should be a method to address different focuses and needs for different industries so that subgroups can get adequate importance.

In Table 1, all the indicators, explanations, sources of sub-indices and structures of indices are presented. A questionnaire containing all the indicators, subgroups, and factors is prepared for user input. The questionnaire is designed in such a way that positive answers represent good sustainable approaches and negative answers represent poor sustainable approaches. For example, in the energy efficiency index section, there is a subgroup on Compressed Air. The questionnaire has 5 factors, or 5 questions in this section. Users will respond to the 5 questions with "Yes", "No" or "Not Applicable." The questionnaire is provided in the appendix as a data collection form. This questionnaire is an important component of this research because it shows a glimpse of all the details of different sectors that are being analyzed for sustainability.

After collecting the responses from the users, it is critical to integrate the responses in a proper way. "Yes" responses are recorded as positive responses and "No" responses are recorded as negative responses. "Not Applicable" responses are eliminated from further calculation. Performance indicator is simply the ratio of the positive responses to the total number of responses.

$$\text{Performance Indicator}, Q_i = \frac{\text{Number of Positive Responses}}{\text{Number of Positve Responses} + \text{Number of Negative Responses}}\% \quad (1)$$

The performance indicator reflects the sustainable approach of that subgroup. Better sustainable approaches can provide higher positive responses. They lead to the plant obtaining a higher performance indicator. Because of the diverse nature of the individual sustainability indicators, the physical measurement of individual metrics cannot be directly aggregated. All the indicators need to be converted into a normalized scale. In this research methodology, all the individual indicators are normalized to a scale from 0 to 100%, where 0 is the worst sustainability performance and 100% is the best sustainability performance.

From the literature review, it has been found that there are several ways to approach this challenge, but these approaches have to consider all aspects, such as counting relative boundary limit, and comparison across indices. Without prior information, the weight can be placed by matching percentile methodology in indices. Foa showed the appropriateness of using matching percentile methodology when some data are imputed [38]. In the questionnaire, there are "Not Applicable" responses. In that case, matching percentile methodology eliminates those responses. For instance, if a subgroup gets all "not applicable" responses, it will not take part in further analysis. If a subgroup gets all negative responses, it will provide a performance indicator of 0%.

Determining the relative importance or impact levels on overall sustainability index is another challenge. Another widely used technique in this research is using pairwise comparison. The NASA Task Load Index (TLX), prepared by the Human Performance Research Group, California used this pairwise technique effectively and exhibited how this technique is very useful in calculating index [39]. Pairwise comparison is a method where each candidate is matched with each of the other candidates. Based on the user selection, each candidate gets prioritized. In this research, the pairwise comparison technique has been applied to figure out relative weight among different categories. At the subgroup level of workers' health and safety, it has been applied, and relative weight among different subgroups is determined.

The weighting of the indicators is set from the calculation of the selections from the pairwise technique. The rationale behind choosing this method is to apply relative importance with respect to the individual organization's setup. Every manufacturing plant is unique. At the same time, the manufacturing industries have some common basic traits that can be considered. A sustainability index should focus on those areas. Even though there are common traits, their levels of importance vary among industry. Some of those levels are intentionally ignored, whereas some of those levels of common traits are out of scope for the research on sustainability. For example, one industry may generate more waste than another industry producing different products. Hence, there is a high chance that one industry will focus more on waste management, whereas the other will focus more on a lean approach. Both industries should have a common approach towards energy efficiency and workers' health and safety. Based on their focus and need, the weight on each indicator will be changed according to the response, thereby providing the adaptive weighting approach towards the sustainability index.

Modeling sustainability index

The methods used to calculate each indicator's index are discussed in the following section.

Energy efficiency index

In the energy efficiency sector, consumption-based relative weighting has been placed to acclimatize different systems of manufacturing plants. Energy consumption profiles vary among industries; therefore, energy usage needs that adaptation capability to provide a meaningful sustainable index. The input and output parameters of energy efficiency index are given in Table 2 as below.

The model elicits the consumption percentage from each user and uses the weighted average to develop a 100% ratio. Later on, performance Q_i is multiplied by the relative weighting average to capture the overall impact of each group. In this research, all three sections of energy efficiency, waste management and workers' health and safety have used this performance indicator at various levels. Fig. 1 shows the calculation method of performance indicator for subgroup "Compressed Air."

For the energy efficiency section, there are twenty-nine factors in eight subgroups. The user is required to provide an approximate energy consumption percentage with respect to each of those eight sub-groups. Using the ePEP software designed and provided by the Department of Energy (DOE), the user can estimate energy

Table 2
Input and output parameters for energy efficiency index.

Input parameters	Output parameters
Energy distribution profile (Total annual energy consumption for electricity in kWh/yr & fuel in MMBtu/yr, and consumption percentage distribution of subgroups by ePEP analysis)	Consumption percentage
Response of the questionnaire	Performance indicator
Number of implemented projects in last 5 years	Carbon footprint reduction potential

consumption percentage based on energy bills and usage of the equipment [40].

The model requires consumption percentage with respect to electricity and fuel (natural gas/coals/saw dust). Moreover, the model needs the total annual consumption usage for electricity (kWh/yr) and fuel (natural gas/coal/sawdust/others) (MMBtu/hr). Total annual consumption is required to calculate carbon footprint reduction potential. Consumption percentages are given for each subgroup with respect to electricity and fuel. The equation to determine the usage for each subgroup is as follows.

$$\text{Usage of subgroup i,}M_i = \frac{x_{ie}\frac{a_e}{293} + x_{ig}a_g}{\frac{a_e}{293} + a_g}\% \tag{2}$$

here i = 1, 2, ..., 8 whereas i_1 = Lighting, i_2 = HVAC, ..., i_8 = Chillers/Cooling Towers; X_{ie} = Electricity consumption percentage of i subgroup; X_{ig} = Fuel (natural gas/coals/sawdust/others) consumption percentage of i subgroup; a_e = Total annual electricity consumption, kWh/yr; a_g = Total annual fuel (natural gas/coal/sawdust/others) consumption, MMBtu/yr; 293 is the constant which comes from 1 MMBtu = 293 kWh.

From Eq. (2), the total consumption of a particular subgroup can be calculated. These calculations will eventually serve as relative weightage (M_i).

The energy efficiency index is the multiplication of relative weightage (M_i) and performance (Q_i) from Eq. (1).

$$\text{Energy efficiency index} = \sum(M_i \times Q + i) \times 100; \quad i = 1, 2, \ldots 8 \tag{3}$$

here M_i = Relative weightage of group i; Q_i = Performance of group i.

The carbon footprint reduction potential for the energy efficiency section is described below.

Carbon Footprint Reduction Potential

$$= \left[\sum_{i=1}^{8}\{(1 - Q_i) \times x_{ie}\} \times a_e \times 2.19 \times P\right] + \left[\sum_{i=1}^{8}\{(1 - Q_i) \times x_{ig}\} \times a_g \times 139 \times P\right] \text{lbs} \tag{4}$$

here Q_i = Performance of group i; X_{ie} = Consumption percentage of electricity of i group; a_e = Total annual electricity consumption, kWh/yr; 2.19 is used as constant since 1 kWh = 2.19 lbs CO2; P = Constant, based on number of implemented project, k where

$$P = \{0.15 \text{ when } k < 5 \quad 0.10 \text{ when } 5 \leqslant k \leqslant 10 \quad 0.05 \text{ when } k > 10\}$$

X_{ig} = Consumption percentage of fuel (natural gas/coals/saw dust) of i group; a_g = Total annual fuel (natural gas/coals/saw dust) consumption, MMBtu/yr.

139 is used as a constant since 1 MMBtu = 139 lbs CO_2. From the above Eq. (4), carbon footprint reduction potential can also be achieved by being more sustainable in using energy. In the Eq. (4), the values of P signify the extent of the carbon footprint reduction potential. It is widely known in the energy efficiency field that implemented energy efficiency measures tend to save 5% to 20% of the energy in most situations [4]. The carbon footprint reduction potential is related to the energy savings potential. The value for P, estimated to vary between 5% and 15%, is integrated with the overall electricity and natural gas consumption and the implemented nature of the projects contained therein, as can be observed from Eq. (4). Moreover, there are energy efficiency projects which save significant energy as opposed to others that may not save as much energy. The plant managers tend to implement projects that have significant energy savings potential with low payback on investment. More the projects implemented, less will be the carbon footprint reduction potential. The value of P has been designed to ensure the validity and estimated accuracy of the carbon reduction potential.

Waste management index

For the waste management segment, there are fifteen factors without any subgroup. Industries generate various kinds of waste, making it time consuming for users to respond to groups of nonrelated waste questions on the questionnaire. To make it effective and compact, all fifteen factors are arranged without any association with subgroups. Table 3 shows the input and output parameters for waste management index.

The user is required to provide an approximate tonnage of waste generation per year and a recycling percentage. Table 4 depicts nine types of generated waste. In Energy Analysis of 108 Industrial Processes, Harry analyzed the carbon footprint of different raw materials and other resources [41]. Based on this data and the Wastex software [34], it has been concluded that manufacturing industries are generating nine types of waste. The model does not provide any relative weighting among the waste; rather, it focuses on the plant's approach to deal with the waste. Users pro-

1.7 Compressed Air

- Do you have air leaks survey routine for your pressure line?
  Yes / No/ Not Applicable
- Do you use vortex nozzle for cleaning?
  Yes / No/ **Not Applicable**
- Do you use sequencer for compressors, if you have multiple main compressors?
  Yes / No/ **Not Applicable**
- Do you recover the heat from the compressor?
  Yes / No/ Not Applicable
- Are the compressors running at the lowest possible set pressure?
  Yes / **No**/ Not Applicable

The user provides 2 positive responses, 1 negative response and 2 not applicable responses, so the performance indicator Q_i is 2/ (2+1) = 2/3 = 67%

Fig. 1. Sample calculation for performance indicator, Q_i.

Table 3
Input and output parameters for waste management index.

Input parameters	Output parameters
Response of the questionnaire Waste generation amount in tons/yr with recycle percentage	Performance indicator Carbon footprint reduction potential

Table 4
Carbon footprint value, Y_j with respect to waste type.

Type of Waste	Carbon Footprint (lbs/ton)
Plastic	2300
Glass	2004
Metal Cleaning Solvent	113
Waste Water	700
Chemicals	3400
Paint	400
Waste Sludge	19,510
Wood Waste	570
Scrap Metal	9200

vide recycling percentages from which the aggregated recycling percentage can be determined from the following Eq. (5).

$$\text{Aggregated Recycling Percentage, G} = \frac{\sum_{i=1}^{9} R_i t_i}{\sum_{i=1}^{9} t_i}\%; \quad i = 1, 2, \ldots, 9 \tag{5}$$

here i_1 = Plastic, i_2 = Glass, ..., i_9 = Scrap Metal; R_j = Recycle percentage of waste group i; t_j = Total waste amount of group i, tons/yr.

The performance indicator Q_i is an important element to the waste management index. It is similar to the energy efficiency performance factor mentioned in Eq. (1). Here, a "Not Applicable" response means this kind of wastage is not being generated by the particular manufacturing plant, so it is ruled out from any further analysis. To improve the waste management index, the manufacturing industry has to focus on its waste handling technique. If a plant has a high recycling percentage with better waste management approaches, a higher waste management index can be achieved. So, waste management index can be calculated as below per Eq. (6).

$$\text{Waste Management Index} = (\text{G} \times \text{Q}_\text{i}) \times 100 \tag{6}$$

For the carbon footprint reduction, a company should have the capability to recycle all of their generated waste. While this is very challenging, companies must try to achieve that target, as it can significantly reduce the carbon potential. In fact, better waste management approaches reduce more carbon footprint than can be obtained through energy efficiency. The carbon footprint reduction potential for the waste management section is described below by Eq. (7). This opportunity demonstrates how much carbon emissions is saved by embracing better waste management approaches.

$$\text{Carbon Footprint Reduction Potential} = \sum_{j=1}^{9} \{(1 - R_j) \times t_j \times Y_j\} \text{lbs} \tag{7}$$

here $j = 1, 2, \ldots, 9$; R_j = Recycle percentage of waste; t_j = Total waste amount, tons/yr; Y_j = Constant which varies with each type of waste, lbs/ton.The values of Y_j with respect to different wastes are given in the following Table 4.

Workers' health and safety index

Worker duties and responsibilities change based on the practice of the industry. An automated manufacturing industry, for example, is quite different from a physical labor dominated industry. Moreover, there are many industries in which the cognitive part is the dominant section for workers. After analyzing several industry records from NIOSH and the E3 projects of West Virginia University, it has been found that four major areas are contributing profoundly towards workers' health and safety in a working place. These four major areas are physical exposure, psychosocial and psychophysical exposure, environmental exposure and general policy. Thirty-three factors as well as questions in total have been designed for the workers' health and safety index within four subgroups. Table 5 shows the input and output parameters for workers' health and safety.

The pairwise comparison technique discussed earlier has been used here to determine the relative weight of each subgroup. Two options are presented each time. The user has to choose one of two available options. At this time, two further options with different combinations will be presented to user. Similarly, the user will choose an option again, and based on the selection, the relative weighting will be determined. In spite of using the same technique for top level relative weighting calculation, this method can vary among situations possessing varying outcomes. In total, six selections can get recorded and each candidate can get any number of selections ranging from 0 to 3; thus, the selections become difficult to keep track of and analyze based on the developed scenario. Another normalization technique has been applied based on the recorded responses, showing the impending relative weight as a percentage from the ratio of recorded selections to the total number of selections. Eq. (8) shows the normalization technique on the selection.

Relative weightage for the subgroups of workers' health and safety index,

$$\text{U}_i = \frac{\text{Number of Selections for Subgroup i}}{\text{Total Number of Selections}} \tag{8}$$

here i = 1,2,3,4 and total number of selections = 6, i_1 = Physical posture, i_2 = Psychosocial and psychophysical exposure, i_3 = Environmental exposure, i_4 = General policy.

Again, performance indicator Q_i is vital in a waste management index. It is the same as the energy efficiency performance factor as mentioned in Eq. (1). The workers' health and safety index is the multiplication of relative weightage (U_i) and performance (Q_i).

$$\text{Workers' Health \& Safety Index} = \text{U}_\text{i} \times \text{Q}_\text{i} \tag{9}$$

here i = 1, 2, 3, 4; U_i = Relative weightage of group i; Q_i = Performance of group i.

For workers' health and safety, carbon footprint is not directly connected to the index, but it affects productivity; hence, more sustainable working conditions can reduce carbon footprint. However, this research is not focusing on this factor due to this factor's low impact on the carbon footprint reduction potential.

Overall sustainability index

Overall Sustainability Index (SI) for manufacturing industries will be obtained by the following equation:

$$SI = \frac{\sum_{i=1}^{3} Z_i a_i}{\sum_{i=1}^{3} Z_i}; \quad i = 1, 2, 3 \tag{10}$$

where SI (0–100) is the sustainability manufacturing index; a_i = Individual index on each indicator = Any values from 0 to 100;

Table 5
Input and output parameters for workers' health & safety index.

Input parameters	Output parameters
Pairwise comparison among 4 subgroups	Relative weightage
Response of the questionnaire	Performance indicator

Z_i = Weightage on each factor.a_1 (0–100) is the energy efficiency indicator; a_2 (0–100) is the waste management indicator; and a_3 (0–100) is the workers' health and safety indicator. Weight on each factor is calculated using the pairwise comparison technique. The user has to choose one of two available candidates, and based on their selection, relative weighting will be determined. There are only two situations that may occur: each candidate gets the same amount of selection, or each candidate gets a different amount of selection ranging from 0 to 2. The following Table 6 shows the two possible situations and relative weighting according to the scenario.

The relative weight for situation 2 is quite simple and clear. For situation 1, candidate three with zero responses should not be totally ruled out because its impact on sustainability index cannot be completely negated. Thus, candidate one is obtaining more importance while candidates two and three also have significant importance on the sustainable index situations. The relative weight distribution is justified by case studies in later stages.

The sustainability manufacturing index is simply the weighted average of three indicators (E, W, S). As per Eq. (10), the indicators have been assigned with the relative weighting, Z_i. In the event of a situation in which indicator weights might vary from plant to plant, weights should be selected by consensus among several stakeholders of the organization. Using the adaptive weight helps to avoid the skewing of results, and allows for effective differentiation between stakeholders. Furthermore, the linear and weighted average structure of Eq. (10) is simple and transparent, allowing for error compensation in the indicators and parameters.

From the recorded responses of the questions and pairwise comparison, the score for individual indicators is calculated from a database. It can also point out the sector where the organization is lacking in terms of sustainability. Thus, a sustainability index can help give the user information on the organization's sustainability performance and pathway for subsequent improvement.

Analysis of the model

The model requires further analysis and validation for overall effectiveness. Different scenarios can provide a better understanding of the model's behavior. Case studies using the IAC and E3 databases were used to assess and analyze the sustainability index of the manufacturing industry.

Analysis of case study one

From the IAC database, one company which shows the possibility of good sustainable manufacturing practice is used to test the sustainability index. The main product of the company is automotive sensors and spark plugs. On the day of IAC assessment, plant managers participated in the survey and were given the chance to examine all the possibilities of the model. The input details from respective company personnel are described below. At first the user had to select one option from each row from Table 7. User's selections are displayed in bold letter.

Based on the response, the manufacturing company prioritizes workers' health and safety, energy efficiency, and waste management. According to Table 6, the relative weighting are 30%, 20%, and 50% for energy index, waste index and worker index respectively. For energy index calculation, total annual energy consumption profile is required for case study 1. The total annual consumption of electricity is 10,529,750 kWh/yr and other fuel (natural gas/coals/saw dust) consumption is 12,116 MMBtu/yr. Based on ePEP and recorded responses, the sustainability index is given below. Table 8 shows the energy consumption details and Table 9 shows the waste generation profile of the case study 1.

At this stage, the company personnel required to answer the questions. The interactive model records the responses and formulates the equations accordingly. Table 10 displays summary of the recorded responses. Applying Eq. (1) to each of subgroups, performance indicator (Qi) is calculated. For example, the first entry in the Table 10 "Lighting" has 3 positive responses and 1 negative response. Thus performance indicator of lighting is 75%.

By using Eq. (2), consumption of the subgroup can be determined. For example, the first entry in Table 8 "Lighting" has 10% of total electricity consumption and 0% fuel (natural gas/coals/saw dust) consumption. Thus consumption percentage with respect to total energy becomes 7.48%. Now applying Eq. (3) to all of the subgroups of energy, the energy index can be found. Performance indicator and consumption percentage of each subgroup are displayed in Table 11. Thus energy efficiency index = 58.76.

In the last five years, the management has implemented more than ten projects designed to improve these areas. From Eq. (4), the value of 'P' is found as 0.05. Using Eq. (4), the possible carbon footprint savings is calculated. which is 28,825 lbs CO_2. Similarly, by applying the Eq. (4) to the each of subgroups, total carbon footprint reduction potential is shown in Table 11.

Now, the steps of calculating the waste index are shown in the following section. Applying Eq. (1) to the waste management section, performance indicator (Q_i) is calculated. In total, the waste management has 7 positive responses and 2 negative responses with 6 "Not Applicable" responses. Thus, performance indicator of waste management is 78%. Now applying Eq. (5) to Table 9, aggregated recycling percentage is calculated. Aggregated recycling percentage = 94.97%. By using Eq. (6), waste management index is found, which is 73.86. Using Eq. (7), the carbon footprint savings in terms of emissions reduction is calculated. The amount is not significant because of the plant's affinity for recycling the accumulated waste. The value of Y_j is found from Table 4. The carbon footprint savings for waste management is 180,481,060 lbs CO_2.

For the workers' health and safety part, the user form plant 1 had to select one option from each row again from Table 12. User selections are displayed in bold letter.

Based on the responses, the manufacturing company prioritizes environmental exposure with 3 selections, psychosocial and psychophysical exposure with 2 selections, physical posture with 1 selection and general policy with no selection. Applying Eq. (1) to the worker section, performance indicator (Q_i) is calculated. Table 13 shows the recorded responses and performance indicators. By using Eq. (8) on the selection number, relative weighting can be found in Table 14. For instance, relative weighting of psychosocial and psychophysical exposure with 2 selections is 0.33.

Now applying Eq. (9), the worker' health and safety index can be found. Performance indicator and relative weight of each subgroup are displayed in Table 14. Thus workers health and safety index is 72.61. After calculating all the indicators indices, it is quite simple to calculate overall sustainability index. By using Eq. (10), overall sustainability is calculated, which is 68.71.

Sustainability index can help to assess a plant's status with sustainability. It is a relatively easy and quick way of assessing various plants across industries. Collected information can help further to analyze and sort the problems, bottlenecks, etc. For example,

Table 6
Relative weightage with possible different scenarios.

Candidates (Energy efficiency, waste management, workers health & safety)	Situation 1		Situation 2	
	recorded response	relative weightage, Z_i	recorded response	relative weightage, Z_i
Candidate one	2	50%	1	33.33%
Candidate two	1	30%	1	33.33%
Candidate three	0	20%	1	33.33%

Table 7
User's selection to prioritize indicators.

Select the option that is more important at manufacturing plant	
Energy usage	Waste management
Waste management	Workers health & safety
Workers health & safety	Energy usage

Table 8
Energy consumption details for case study 1.

Electricity		Fuel (Natural gas/Coal/Sawdust)	
Total annual usage (kWh/yr)	10,529,750	Total annual usage (MMBtu/yr)	12,116
Consumption percentage		Consumption percentage	
Sector	Percentage	Sector	Percentage
Lighting	10%	Lighting	0%
HVAC	0%	HVAC	30%
Steam	0%	Steam	20%
Process heat	0%	Process heat	50%
Pumps & fans	25%	Pumps & fans	0%
Motors	30%	Motors	0%
Compressed air	15%	Compressed air	0%
Chillers/cooling towers	20%	Chillers/cooling towers	0%
Total	100%	Total	100%

Table 9
Waste generation profile for case study 1.

Waste sector	Total waste amount (tons/yr)	Recycling percentage (%)
Electronic Waste	0	–
Glass Waste	0	–
Metal Cleaning Solvent	1200	90
Wood Waste	0	–
Waste Water	0	–
Paint Waste	0	–
Chemicals	0	–
Waste Sludge	0	–
Scrap Metal	185,000	95

Table 11
Calculated parameters for each subgroups of energy.

Sub groups	Performance indicator, Qi	Consumption percentage	Carbon Footprint reduction (lbs CO2)
Lighting	75%	7.48%	28,825
HVAC	50%	7.56%	12,631
Steam	0%	5.04%	16,841
Process Heat	0%	12.61%	42,103
Pumps & Fans	100%	18.70%	0
Motors	50%	22.44%	172,951
Compressed Air	40%	11.22%	103,771
Chillers/Cooling Towers	100%	14.96%	0
Total			377,122

Table 12
User's selection to prioritize subgroups of workers' health and safety.

Select the option from each row that better suits your workplace	
Physical posture	Psychosocial and psychophysical exposure
Environmental exposure	General policy
Physical posture	Environmental exposure
Physical posture	General Policy
Environmental exposure	Psychosocial and psychophysical exposure
General policy	Psychosocial and psychophysical exposure

Table 11 displays the energy index, as well as breaking down the major energy consumption areas into Motors (22.44%), Pumps & Fans (18.70%) and Chillers/Cooling Towers (14.96%) with their respective recorded responses. Motors subgroup has 2 "Yes" and 2 "No" responses, Chillers/Cooling Towers subgroup has 1 "Yes" response and Pumps & Fans subgroup has 1 "Yes" response with 1 "Not Applicable" response. This results in an energy efficiency index score of 58.76. Table 9 shows waste generation profile which helps to calculate aggregated recycling percentage (94.97%) and recorded responses with waste management index. For waste management, the index score is 73.86, due to the fact that the company is doing quite well with 7 "Yes" and 2 "No" responses. In addition to that, recorded responses, selection numbers, relative weight, and performance indicator for workers' health & safety are mentioned in Tables 12–14. Table 14 shows that psychosocial and psychophysical exposure received 2 selections, environmental exposure received 3 selections and physical posture subgroup received 1 selection. In accordance with the plant's claim to value workers' health & safety, the workers' health and safety index score is 72.61, and the resultant sustainability index of 68.71.

It is very important to focus on the right sector. For example, by changing the focus on energy, the sustainability index can instantly

Table 10
Summary of recorded responses from energy sector.

Sub groups	Number of questions	Positive response	Negative response	Not-Applicable response	Performance indicator, Q_i
Lighting	4	3	1	0	75%
HVAC	4	2	2	0	50%
Steam	7	0	1	6	0%
Process Heat	2	0	2	0	0%
Pumps & Fans	2	1	0	1	100%
Motors	4	2	2	0	50%
Compressed Air	5	2	3	0	40%
Chillers/Cooling Towers	1	1	0	0	100%

Table 13
Summary of recorded responses from workers' health and safety.

Sub groups	Number of question	Positive response	Negative response	Not-applicable response	Performance indicator, Q_i
Physical posture	8	3	2	3	60%
General policy	8	2	6	0	25%
Psychosocial and psychophysical exposure	9	6	3	0	67%
Environmental exposure	8	4	1	3	80%

Table 14
Different parameters for workers' health and safety.

Sub groups	Selection number	Relative weightage, U_i	Performance indicator, Q_i
Physical posture	1	0.17	60%
General policy	0	0	25%
Psychosocial and psychophysical exposure	2	0.33	67%
Environmental exposure	3	0.50	80%

be altered. If the priorities are arranged in a way where waste management is foremost with energy efficiency and workers' health and safety following, then the sustainability index changes to 69.14.

Fig. 2 demonstrates a relative comparison of sustainability index between waste and worker safety with respect to energy efficiency. Sustainability index shows inclination towards the indicator with higher index. For example, whenever energy gets low priority, sustainability index reflects higher number. If priority of energy remains same, prioritizing waste can reflect higher sustainability index.

By observing Fig. 3, it is evident that the sustainability index can be improved by focusing on the highest individual factor's index. For example, the sustainability index can be improved by focusing more on waste and worker. This observation also helps to prioritize the suggestions.

Analysis of case study two

From the IAC database, another company is used to test the sustainability index. The company's main product is rolled aluminum foil. On the day of IAC assessment, the maintenance manager participated in the survey and was given the chance to explore all the possibilities of the model. The manufacturing company prioritizes waste management, then energy efficiency and finally workers' health and safety. In the last 5 years, the management has implemented less than 5 projects in these areas. The total annual consumption of electricity is 5,017,410 kWh/yr and fuel (natural gas/coals/saw dust) consumption is 32,623 MMBtu/yr. Based on ePEP and recorded responses, the sustainability index is given below.

Energy efficiency index is 42.74. Waste management index is 21.51. Workers' health and safety index is 50.56. The overall sustainability index is 33.69. The sustainability index is low because of their low score on waste management, in spite of the company's claim that they focus on this area. Surprisingly, the plant performed relatively better on workers' health and safety, with an index score of 50.56. Since the plant manufactures hot rolled aluminum foil, the workers take mandatory safety precautions. It is difficult to move the hot rolled product from one place to another, which is why the plant is equipped with equipment such as pallet trucks, movable cranes, and accessible safety instructions. If the plant shifts its focus to improving workers' health and safety, then energy efficiency and finally waste management, then the sustainability index score becomes 42.41.

As per the analysis from case study 1, the sustainability index can be improved by shifting the focus on the workers' health and safety. The user just has to select workers' health and safety in the questionnaire as the primary focus area; however, this does not improve the actual environment. Fig. 4 displays the part of implementation suggestions from the model that can be implemented for a better sustainability index score

Figs. 4 and 5 reiterate the finding of case study 1, which is focusing on the high indicator's index can deliver better sustainability index. These figures also represent how the sustainability index changes when the focus changes from energy efficiency, to waste management or workers' health and safety. Therefore, focusing on workers appears to be the right path for the company. Since the plant claims to focus on waste management, this indicates that major efforts are still needed. This observation helps to prioritize the implementation suggestions and improving sustainability.

By understanding how focusing on different areas can affect the sustainability index, a strategic plan can be developed. With the aforementioned significance of the sustainability index, real change can be achieved by attempting to improve the company's performance. The company, as well as society, can benefit by implementing the suggestions

At this point of the discussion, it is important to analyze which implementations require immediate attention. Assuming that, company two decides to implement 5 projects from each of the sectors.

Situation 1

Assuming the plant implements 5 projects from energy sector. The 5 implementations are given as below.

1. Installing economizer on the process heat.
2. Using VFD on large pumps and fans which have variable load.
3. Using occupancy sensors in warehouse.
4. Establishing motor management system.
5. Creating vibration program.

After running the model again, the sustainability index stands as 42.07 and energy efficiency index is 70.67 from 42.74. So the energy index has increased 65% with 5 implementations.

Situation 2

Assuming the plant implements 5 projects from waste management. The 5 implementations are given as below.

1. Placing labels on all of the harmful substances and storing them properly.
2. Establishing a trash pickup program.
3. Making the trash program as a companywide initiative.
4. Establishing a single stream waste collection program.
5. Following a proper guideline and methods to dispose electronic waste.

After running the model again, the sustainability index stands as 51.61 and waste management index is 57.35 from 21.51. So the waste management index has increased 167% with only 5

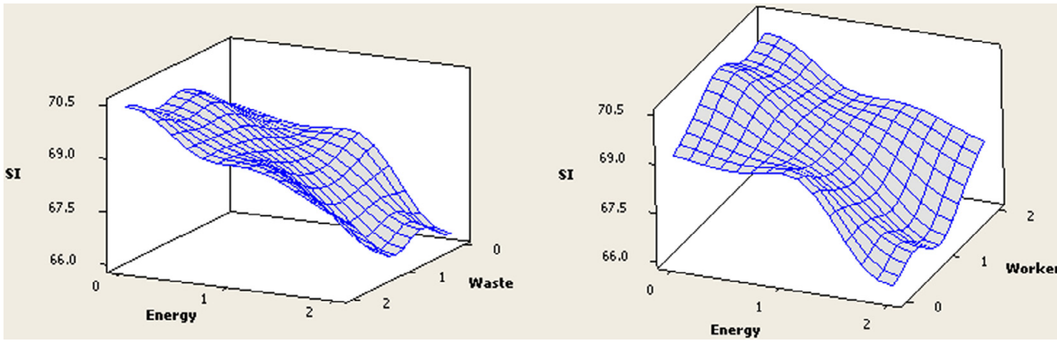

Fig. 2. Surface Plot of sustainability index vs worker, energy and sustainability index vs waste, energy.

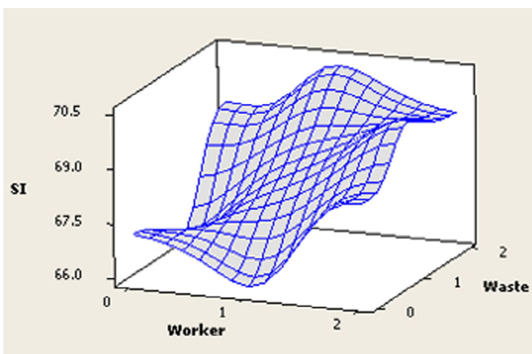

Fig. 3. Surface plot of sustainability index vs worker, waste.

implementations. Since the number of factors are very limited and the plant has a decent aggregated recycling percentage, implementations on this segment has better impact than other two sections.

Situation 3

Assuming the plant implements 5 projects from workers' health & safety. The 5 implementations are given as below.

1. Creating a good work-life balance.
2. Re designing the work so that moderate force is enough to perform the task.
3. Stopping repetitive motions such as lifting, pushing, and bending.
4. Using proper protection for noisy environment.
5. Facilitating strong trade unions.

After running the model again, the sustainability index stands as 38.74 and workers' health and safety index is 75.83 from 50.56. So the workers' health & safety index has increased 50% with only 5 implementations.

From this analysis, it is observed that focusing on the prioritized segment can have a better impact on the sustainability index. Overall sustainability index gets affected by the plant's focus. Implementations on waste management will provide better sustainability index. As an example of the impact of these suggestions, industry personnel can focus on the waste-related suggestions so that the immediate impact will be greatest.

Carbon footprint reduction potential is inversely related to sustainability index. If sustainability index increases, the carbon footprint reduction amount decreases. When a plant is achieving good sustainability index, few implementation suggestions are available. Thus, opportunities for reducing carbon footprint will be reduced and hence the carbon footprint reduction potential will be lower. Similarly, when sustainability index decreases, the carbon footprint savings potential will be higher. For example, case study 1 shows the overall sustainability index as 58.76 with 377,122 lbs CO_2 carbon footprint savings potential for energy efficiency. After implementing 5 suggestions from energy section, the overall sustainability index becomes 74.09 with 100,400 lbs CO_2 carbon footprint savings potential for energy efficiency.

The benefits of determining the sustainability index is multifaceted. The analysis in the aforementioned section is an example of how the information can be used for increasing the sustainability initiatives. By shifting the focus or making small changes, a company can achieve sustainability easily. Industries can benefit financially by making these changes to improve sustainability, thus acquiring support from upper management for implementation resources.

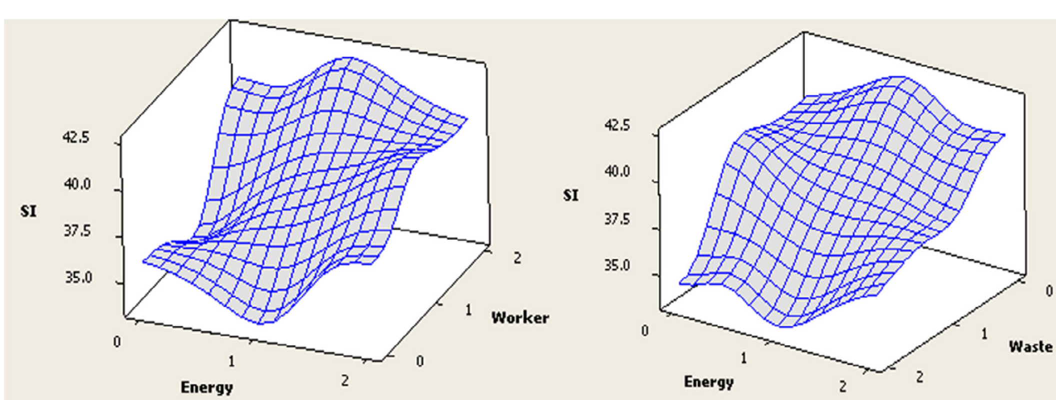

Fig. 4. Surface plot of sustainability index vs worker, energy and sustainability index vs waste, energy.

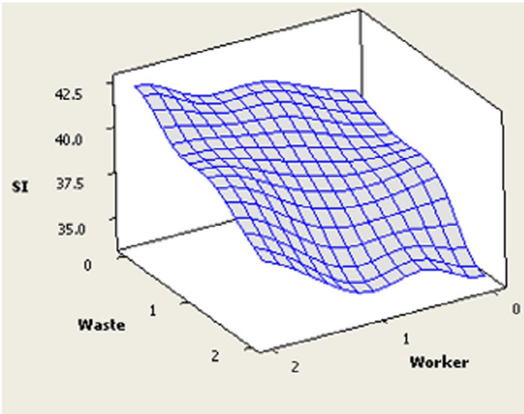

Fig. 5. Surface plot of sustainability index vs worker, waste.

Conclusion

In this research, the manufacturing industries' situations have been studied and factors influencing sustainable manufacturing have been analyzed. In order to achieve sustainable manufacturing in a competent way, it is important to have a meaningful sustainability index through which manufacturing industries can compare among themselves and measure internal improvement. The large manufacturing industry has not been included in this sustainability index model because of following reasons: 1) large industry has complex business structures. It is difficult to integrate them into a generic model. 2) the available sources of data are collected from IAC database, which is focused on small to medium scale industries. For this reason, a model has been designed by selecting significant factors and integrating them in various ways for small to medium scale industries.

The developed model has been justified using various techniques and reflects realistic approaches in the manufacturing plants. Pairwise comparison, weighted average, normalization techniques, and relative adaptive weighting methods form the backbone of the model. The model takes inputs from users and adapts the weightings according to the input. Based on the inputs, it provides a sustainability index score for the three factors individually, as well as the overall score. The model also shows the carbon footprint score and suggestions that may help the particular company improve sustainability. The analysis shows that giving the lowest performing factor the highest priority leads to the fastest improvement in sustainability.

Obtained results and graphs are meaningful and reflect the realistic situation. Two case studies were run through the model. The individual factor indices and overall sustainability index show the sensitivity towards changes and ultimately provide guidance towards improvement. Though the model works well, it can still be improved. This research has performed the first and most critical step, but many interesting research questions remain unanswered. The author's recommendations for further improvement are as follows:

1) Weight the questions and factors inside each subgroup based on the overall impact. For example, using dimmer control in lighting saves less than installing T8 bulbs in the facility. The current model does not differentiate the weight of these factors. In future, the questions can be weighted and impact differently in the energy efficiency index.
2) Categorize implementation suggestions with respect to cost and impact factors. The author envisions this as the database taking input from the user and calculating the potential savings as well as the payback. Because situations can vary among industries, care will need to be taken to ensure the general model is representative.
3) Add more questions as well as factors to make the model more robust. However, it is necessary to limit the number of questions so that the survey does not take too much time to complete.
4) Incorporate the ability to consider large-scale manufacturing industries. This requires adding the capability to deal with variations of fuel, workstations, energy equipment, and types of waste.
5) After collecting and maintaining a database, a standard approach can be prepared. This standard approach will help to identify the quantitative range of the sustainability index.
6) Selection of priority is crucial in current algorithm. A method needs to be developed to restrain biased selection. For instance, indices, itself can provide a basic understanding on priority. Number of employees, energy consumption amount, waste generation amount can also influence the selection.

Appendix

Data collection form

Select the option between each row that is more important in your manufacturing plant	
Energy usage	Waste management
Waste management	Workers health & safety
Workers health & safety	Energy usage

Energy efficiency questionnaire

How many projects you have implemented to improve your energy efficiency in last 5 years?

Less than 5 projects	5–10 projects	More than 10 projects

Electricity		Fuel (Natural Gas/Coal/Saw Dust)	
Total Annual Usage (kWh/yr)		Total Annual Usage (MMBtu/yr)	
Consumption Percentage[1]		Consumption Percentage	
Sector	Percentage	Sector	Percentage
Lighting		Lighting	
HVAC		HVAC	
Steam		Steam	
Process heat		Process Heat	
Pumps & fans		Pumps & Fans	
Motors		Motors	
Compressed air		Compressed Air	
Chillers/cooling towers		Chillers/cooling towers	
Total		Total	

[1]Additional help on defining usage percentage can be generated from ePEP software which is available at https://ecenter.ee.doe.gov/EM/tools/Pages/ePEP.aspx.

Lighting

- Does your plant have more than 80% of T5 or T8 fluorescent or LED light?
- Yes/No/Not Applicable.
- Do you use occupancy sensors in your plant/warehouse?
- Yes/No/Not Applicable.
- Do you use skylights in your plant?
- Yes/No/Not Applicable.
- Do you use dimmer controls in your plant?
- Yes/No/Not Applicable.

HVAC

- Do you use economizers on the HVAC units?
- Yes/No/Not Applicable.
- Do you have setback temperature controls during nights and weekends?
- Yes/No/Not Applicable.
- Do you maintain the least possible temperature difference between inside and outside of the plant and office areas?
- Yes/No/Not Applicable.
- Have you checked the dock door seals in last 5 years?
- Yes/No/Not Applicable.

Steam

- Do you have an air to fuel boiler tuning program?
- Yes/No/Not Applicable.
- Does air to fuel ratio of your burner stay within 3.0% to 5.0%?
- Yes/No/Not Applicable.
- Is the burner used in process heating equipment or boilers in your factory less than 20 years old?
- Yes/No/Not Applicable.
- Do you have a steam trap maintenance system?
- Yes/No/Not Applicable.
- Are you recovering waste heat from boiler stack to produce hot water or heat the plant?
- Yes/No/Not Applicable.
- Do you use adequate insulation for the boiler surface, pipeline and steam line?
- Yes/No/Not Applicable.
- Do you use economizers on the boilers?
- Yes/No/Not Applicable.

Process heat

- Do you use pre-heat combustion air on the process heating equipment?
- Yes/No/Not Applicable.
- Do you increase the temperature of feed charge materials by using stack heat available in the furnace?
- Yes/No/Not Applicable.

Pumps & fans

- If you have a variable working load in pumps and fans, do you use Variable Frequency Drives (VFD) on pumps and fans and other process motors as applicable?
- Yes/No/Not Applicable.
- Do you have vibration checking program for electrical motors associated with pumps and fans?
- Yes/No/Not Applicable.

Motors

- Do you use a significant amount of cogged belts?
- Yes/No/Not Applicable.
- Do you have vibration checking program for motors?
- Yes/No/Not Applicable.
- Do you have a motor management system in term of rewinding and replacing?
- Yes/No/Not Applicable.
- Do you have capacitor banks at the motors to increase power factor?
- Yes/No/Not Applicable.

Compressed air

1) Do you have air leak checking program?
2) Yes/No/Not Applicable.
3) Do you use vortex nozzles for cleaning and other types of air related applications?
4) Yes/No/Not Applicable.
5) Do you use sequencer for controlling multiple compressors?
6) Yes/No/Not Applicable.
7) Do you recover the heat from the compressor exhaust?
8) Yes/No/Not Applicable.
9) Are the compressors discharging air at the lowest possible set pressure?
10) Yes/No/Not Applicable.

Chillers/Cooling towers

- Can you set a higher set point for cooling tower/chiller, if it does not impact production?
- Yes/No/Not Applicable.

Waste management questionnaire

Waste sector	Total waste amount (tons/yr)	Recycling percentage
Electronic Waste		
Glass Waste		
Metal Cleaning Solvent		
Wood Waste		
Waste Water		
Paint Waste		
Waste Sludge		
Total		

- Do you have a trash pickup program?
- Yes/No/Not Applicable.
- Is it a company-wide initiative?
- Yes/No/Not Applicable.
- Do you have single stream wastage collection program?
- Yes/No/Not Applicable.
- If you have glass materials in waste, do you separate it?
- Yes/No/Not Applicable.
- If you have metal cleaning solvents in waste, do you have proper disposable method for them?
- Yes/No/Not Applicable.
- If you have waste water, do you recycle it?

- Yes/No/Not Applicable.
- Do you pay for the waste water sewage?
- Yes/No/Not Applicable.
- Do you use chemicals to prevent scale formation in cooling towers?
- Yes/No/Not Applicable.
- If you have any scrap metal waste, do you recycle or sell it?
- Yes/No/Not Applicable.
- If you generate paint waste, do you dispose the filter in an environmentally friendly manner?
- Yes/No/Not Applicable.
- If you generate waste sludge, do you recycle it?
- Yes/No/Not Applicable.
- If you generate wood waste, do you send it to a power plant or other end users?
- Yes/No/Not Applicable
- Is all of your harmful substances labelled and stored properly?
- Yes/No/Not Applicable.
- Do you have proper guideline and methods for electronic waste disposal?
- Yes/No/Not Applicable.
- Does your workplace perform any of these: reuse envelopes, print both side of the papers, reusable coffee mugs, use rechargeable batteries and battery chargers?
- Yes/No/Not Applicable.

Workers health & safety Questionnaire[1]

Select the option from each row that better suits your workplace	
Physical posture	Psychosocial and psychophysical exposure
Environmental exposure	General policy
Physical Posture	Environmental exposure
Physical posture	General Policy
Environmental exposure	Psychosocial and psychophysical exposure
General policy	Psychosocial and psychophysical exposure

Physical exposure

1) Do the employees hardly ever complain about work-related pain or discomfort (neck, back, upper extremity, etc.) due to physical exertion?
2) Yes/No/Not Applicable.
3) Are the workstations/work-activities designed to prevent use of sustained awkward postures?3
4) Yes/No/Not Applicable.
5) Are the workstations/work-activities designed to prevent use of forceful arm exertions?
6) Yes/No/Not Applicable.
7) Are the workstations/work-activities designed to prevent use of repetitive or high frequency exertions?
8) Yes/No/Not Applicable.
9) Are the employees prevented from using same equipment/-workstation continuously for >=4 h per day?
10) Yes/No/Not Applicable.
11) Do you have policy that prevents workers from lifting, pushing, pulling heavy loads?
12) Yes/No/Not Applicable.
13) Do you provide annual or bi-annual safety or ergonomics training?
14) Yes/No/Not Applicable.
15) Do you have policy that ensures job rotation?
16) Yes/No/Not Applicable.

Psychosocial and psychophysical exposure

- Do the employees frequently complain about work-related stress due to the social work environment (social support, relationship with supervisor, colleague, etc.?)
- Yes/No/Not Applicable.
- Do you have policy that encourages/trains the employees on maintaining healthy work-life balance?
- Yes/No/Not Applicable.
- Do you provide annual or bi-annual stress management training?
- Yes/No/Not Applicable.
- Is it easy for the employees to take time off during work to take care of personal or family matters?
- Yes/No/Not Applicable.
- Do you have trade union that represent/protect workers interest?
- Yes/No/Not Applicable.
- Do you have policy that encourages employee participation in day-to-day decision making?
- Yes/No/Not Applicable.
- Do you have policy/mechanism (suggestion box, complain box, employee counselling, etc.) that promotes healthy work environment?
- Yes/No/Not Applicable.
- Do you promote regular outings/games/fun activities/team building exercises among employees?
- Yes/No/Not Applicable.

Environmental exposure

- Do the employees frequently complain about work-related discomfort or stress due to physical work environment (noise, illumination, climate, etc.)?
- Yes/No/Not Applicable.
- Do you routinely conduct survey to monitor employees' noise exposure?
- Yes/No/Not Applicable.
- Do you routinely conduct survey to monitor employees' vibration exposure?
- Yes/No/Not Applicable.
- Do you routinely conduct survey to ensure that the workstations/work-activities do not have excessive illumination/glare issues?
- Yes/No/Not Applicable.
- Do you provide sufficient sizes/options for all the necessary personal protective equipment (PPE)?
- Yes/No/Not Applicable.
- Do you have policies to prevent slipping/tripping hazards?
- Yes/No/Not Applicable.
- Do you have after work housekeeping policies to ensure that the workstations are maintained neat and clean?
- Yes/No/Not Applicable.
- Are the mechanical ventilation systems in good condition and regularly maintained so that employees do not get exposed to dust, fumes, and gases?
- Yes/No/Not Applicable.

[1] http://www.cdc.gov/niosh/topics/stress/pdfs/qwl2010.pdf

- Do you have policy that prevents outdoor work under severe weather condition without proper protection?
- Yes/No/Not Applicable.

General policy

- Do you maintain emergency response plan?
- Yes/No/Not Applicable.
- Do you have a procedure for recording work-related incidents and near misses?
- Yes/No/Not Applicable.
- Do you have policy that enforces routine review of all the reported incidents and near misses?
- Yes/No/Not Applicable.
- Do you routinely provide training on health and safety regulations relevant to your plant?
- Yes/No/Not Applicable.
- Do you have policy that enforces regular maintenance check-up?
- Yes/No/Not Applicable.
- Do you have policy that enforces adequate machine guarding?
- Yes/No/Not Applicable.
- Do you have competent persons trained to ensure the safe evacuation of all persons from buildings in the event of serious and unexpected events (fire, cyclone, tornado, etc.)?
- Yes/No/Not Applicable.
- Do you have policy in place to treat workers in an event of emergency/accident?
- Yes/No/Not Applicable.

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