Journal of Cleaner Production 229 (2019) 528–541

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A questionnaire-based methodology to assist non-experts in selecting sustainable engineering analysis methods and software tools

Kamyar Raoufi*, Addison K. Wisthoff, Bryony L. DuPont, Karl R. Haapala

School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR, 97331, USA

A R T I C L E I N F O

Article history:
Received 21 July 2018
Received in revised form
21 March 2019
Accepted 2 May 2019
Available online 5 May 2019

Keywords:
Sustainable engineering analysis (SEA)
Life cycle assessment (LCA)
Sustainable product design
Sustainable manufacturing
Decision making

A B S T R A C T

Currently, there are limited techniques for non-experts to learn about the strengths and weaknesses of different methods and software tools developed by industry and academia for assessing each aspect of product sustainability performance. Moreover, the variety of available methods and software tools makes it challenging for non-experts to identify the most appropriate analysis option. This research aims to assist non-experts in selecting the most appropriate set of analysis methods and software tools prior to conducting sustainable engineering analysis (SEA) based on life cycle data accessible to them. A questionnaire-based ranking methodology is developed for non-experts, which reduces their time investment in examining the myriad SEA methods and tools and avoids non-value added effort. The questionnaire uses an interaction matrix within a general mathematical modeling approach to map a given set of methods and tools to user responses. Relevance weights are integrated within the matrix to rank available environmental, economic, and social assessment methods and tools for user consideration. To demonstrate the application of the methodology, a pilot project was conducted to improve the design of a hexacopter. Results were compared using lower- and higher-fidelity software tools to demonstrate the effectiveness of the relevance weights assigned to each tool. Assigned weights were determined to enable differentiation between low and high fidelity methods and tools, but as new methods and tools enter into use, these weights must be updated. The process of selecting SEA methods and software gives insight into the utility of the interaction matrix implemented within the tool developed in this research. Moreover, non-experts can compare various design alternatives using the selected analysis methods and software tools to arrive at a solution with improved sustainability performance.

1. Introduction

If organizations are to pursue sustainable manufacturing, they will need to assess the sustainability performance of their activities (Gunasekaran and Spalanzani, 2012). This can be achieved by evaluating the results obtained from sustainable engineering analysis (SEA) (Hutchins et al., 2009), which encompass environmental, economic, and social impacts (Elkington, 1997). Due to the relevance of each of the three aspects of SEA to improving the design and manufacturing of consumer products (Ramani et al., 2010), which are generally sold to a myriad of customers in large volumes, these are the focal point for applying this research. A single product affects workers across the supply chain, end consumers, and waste management personnel that interact with the product at its end of life (EOL) (Kremer et al., 2016). Social analyses can be conducted at any point in the product's life cycle, with impacts being determined using data acquired from the manufacturer or from publicly available information (Jørgensen et al., 2007). Similar to its social impact, the economic impact of a product originates from high volume production. Consumer products often have low margins, which can affect a product's production viability or lead to lower worker wages or use of less skilled labor in developing nations (Fisher, 1997). Some of these effects can be quantified using economic impact analysis. Finally, the production, use, and disposal of large quantities of consumer products can have a significant impact on the natural environment (Duflou et al., 2012).

The environmental impacts of the way products are made, used, and disposed can be quantified using life cycle assessment (LCA) (Umeda et al., 2012). As LCA has evolved, relevant methods and software tools have emerged and developed, as well. Sections 2.1 and 2.2 discuss several methods and software tools for

* Corresponding author.
E-mail address: raoufik@oregonstate.edu (K. Raoufi).

https://doi.org/10.1016/j.jclepro.2019.05.016

conducting SEA that are commercially available in the market or have been developed by researchers for different users. Ciroth (2012) distinguished two user types: professional modelers who generate new models and model users who use available software tools. In addition to these user types, a new type is defined herein as *non-experts in sustainable engineering*, who are *decision makers (e.g., engineering students and engineering practitioners) that do not possess specialized knowledge of the different analysis methods and software tools developed to assess each aspect of sustainability during product design*. These non-experts are unfamiliar with the available SEA methods and software tools and need guidance to identify the most appropriate ones based on the available information and the goal and scope of their study.

The increasing number of methods and tools available in the market requires users to invest their time in evaluating the vast array before they can apply them for a specific purpose. To address this need, Seto et al. (2016) developed a questionnaire enabling practitioners to evaluate and select the most appropriate software tool prior to conducting an LCA study. They defined adequate flexibility, required sophistication and complexity of the analysis, and usefulness of outputs as three key criteria for evaluating the quality of the analysis. They applied the questionnaire to evaluate five LCA tools, i.e., the Athena Impact Estimator for Highways, the Building for Environmental and Economic Sustainability (BEES) tool, Ganzheitliche Bilanz (GaBi), Quantis Suite 2.0, and SimaPro, for assessing the environmental impacts of seven concrete products in Canada. While the authors were able to evaluate the quality of life cycle inventory (LCI) data in each tool based upon their criteria, the focus was only on the environmental aspect of sustainability.

Prior research in the sustainable engineering domain has not addressed the needs of non-experts for selecting the most appropriate SEA software tools and methods to analyze product design alternatives by considering all three aspects of sustainability (Khan et al., 2017; Sharma et al., 2017). This process may be confusing for non-experts, since an increasing number of SEA methods and tools are available (Raoufi et al., 2019b). Thus, the objective of this research is to enable non-experts to identify a set of appropriate methods and software tools prior to conducting SEA through the use of a decision support tool. A decision support methodology, in the form of a brief questionnaire, is developed in this research. This approach will help non-experts avoid the effort of examining the myriad methods and tools and aid them in more rapidly identifying the best options for performing SEA. The rest of this article is organized under four sections. Recently developed methods and software tools for conducting SEA are presented in Section 2. The methodology, questionnaire, and supporting interaction matrix developed under this research are described in Section 3. The application of the methodology is demonstrated in Section 4 using a hexacopter design case study. Discussion of the results is presented in Section 5. Finally, conclusions and directions for future work are discussed in Section 6.

2. Literature background

Sustainable development requires product designers and engineers to be cognizant of potential environmental and social impacts of their decisions, as well as costs of production, from the earliest phases of design. Since the rise of mass production, manufacturers have endeavored to manage resources (e.g., materials, energy, and labor) efficiently with the goal to reduce costs. Sustainable manufacturing expands this traditional philosophy to also include social and environmental aspects in continuous improvement activities, policies, and practices. Sustainable manufacturing has been defined as *the creation of goods or services using a system of processes that simultaneously addresses economic, environmental, and social aspects in an attempt to improve the positive or reduce the negative impacts of production by means of responsible and conscious actions* (Garretson et al., 2016). Various methods and software tools have been developed for impact analysis for each of the three aspects of sustainability. Recent methods developed for conducting SEA are presented in Section 2.1. In Section 2.2, the recent SEA software tools are presented. In Section 2.3, the limitations of prior work are summarized.

2.1. SEA methods

SEA methods have been developed for economic and social impact assessment. The main goal of economic impact assessment is to evaluate the economic viability of a product for a company or for a consumer. Lu et al. (2011) defined product economic metrics (e.g., operating cost and profit) as well as process economic metrics (e.g., labor and maintenance cost) to evaluate the sustainability performance of a product or a manufacturing process. From an economic perspective, a commercial product cannot survive in the marketplace if it is not financially viable for the consumer and/or the company that produces the product. Some commonly used economic analysis methods include life cycle cost analysis (LCCA), cost-benefit analysis (CBA), and break-even analysis (BEA). Compared to economic and environmental life cycle assessment methods and software tools, social life cycle assessment needs further development (Raoufi et al., 2019a). Social LCA focuses on the broad-reaching positive and negative impact production of a product can have on people, including impacts on wages, working hours, workload, injuries, and local employment (Chen et al., 2015). Social impact assessment methods have emerged that follow LCA methodology, e.g., a Social LCA framework developed by the United Nations Environment Program (Ciroth, 2012) and an impact assessment handbook developed by the Roundtable for Product Social Metrics (Goedkoop et al., 2018).

In addition to methods to assess economic and social aspects individually, several researchers (e.g., (Dreyer et al., 2006; Jørgensen et al., 2007; Parris and Kates, 2003; Wilhelm et al., 2015)) have developed methods applicable for combined economic and social impact assessment. In the research presented herein, methods for more comprehensive SEA were of interest. Thus, all three pillars of sustainability were considered to query articles from international conference and journal articles using the Web of Science™ database (Clarivate Analytics, 2018). Relevant publications between January 1, 1987 and May 31, 2018 were gathered using two sets of keywords as follows:

Keyword Set 1: (Life Cycle) AND (Design OR Decision Making) AND Manufactur* AND (Framework OR Method OR Methodology OR Model) AND Econom* AND Soci* AND Environment*;

Keyword Set 2: (Life Cycle) AND (Design OR Develop*) AND Process AND (Software OR Tool) AND Econom* AND Soci* AND Environment*

Each keyword set was used to search the Web of Science™ database, restricting the search to the Topic field, which includes the document title, abstract, and author keywords. The first set of keywords was used to find publications involving SEA methods, while the second set targeted SEA software tools. Both databases were then refined based on two categories provided by the Web of Science™, i.e., *engineering environmental* and *engineering manufacturing*, to focus on engineering-related research. The first keyword set returned 62 documents. These were refined using the Web of Science™ categories mentioned above. The 42 remaining documents were investigated to confirm if they developed frameworks, methodologies, or models to quantify economic, social, and environmental aspects of sustainability. Of these documents, thirteen were found to be highly relevant. Abstracts for the thirteen documents contained terms associated with all three pillars of sustainability; they were included in the results of the final search. While some past work quantified all the three pillars of sustainability, some research focused on only one or two aspect(s) of sustainability. The detailed results are presented in the supplementary material, Table A.

2.2. SEA software tools

Ness et al. (2007) developed a framework to classify SEA tools as indicators and indices, product-related assessment, and integrated assessment tools based on temporal characteristics, coverage areas, and integration of nature-society systems. SEA software has been mainly developed for conducting assessment of environmental impacts using life cycle assessment (LCA). The market for software packages to support LCA has grown over the past twenty years from approaches for performing calculations based on spreadsheet models or general mathematical modeling software, to full-featured software systems such as GaBi, SimaPro, and Umberto (Ciroth, 2012). Recently, researchers have developed LCA software tools with specialized capabilities that focus on specific issues. Some require costly commercial licenses, while others are freely disseminated (e.g., GREET and openLCA). However, creating and maintaining inventory databases to support free software can be costly, limiting their utility for small businesses and educators.

To identify SEA software tools capable of considering all three aspects of sustainability, the second set of keywords (Section 2.1) was used to search the Web of Science™ database. The process of refining the returned documents related to SEA software tools was similar to the process used for SEA methods. For the second set of keywords, 119 documents were initially returned, which were reduced to 52 using the Web of Science™ categories. After evaluation of each of these documents, it was found that thirteen articles reported the development of software tools to conduct SEA analysis, while the remaining articles reported no software tool development. Instead, they utilized the LCA framework for conducting sustainability assessment. Some of the relevant articles mentioned SEA analysis in their abstracts, while the software tool developed concentrated on only one or two aspect(s) of sustainability. The developed software tools to quantify all the three pillars of sustainability. The results of the literature review are presented in the supplementary material, Table B.

In addition to the *engineering environment* and *engineering manufacturing* categories, which were first selected to refine the results of the systematic search, the *engineering chemical* category was utilized to target the software tools developed for evaluation of other production processes. In total, 15 articles were found and, among them, nine documents were considered highly relevant. They developed software tools to quantify sustainability aspect(s) for chemical production processes. In Table C, presented in the supplementary material, the detailed results of the systematic literature review are described.

2.3. Limitations of prior work

To identify the main barriers that restrict their effective use in industrial companies, Rossi et al. (2016) reviewed eco-design methods and software tools over the past twenty years. They found that due to the large number of software tools developed for conducting LCA, selecting the most appropriate tool is difficult. Other studies also found it challenging to identify the most suitable means to conduct sustainability assessment for a given situation (Zijp et al., 2017) or to assess the environmental performance of a company (Zhang et al., 2013). Lindahl and Ekermann (2013) developed a structure to provide guidance to analysts by categorizing a variety of eco-design methods and tools. They presented criteria such as *time*, *difficulty*, *expected results*, and *considered life cycle stage* for selecting, developing, or modifying eco-design methods and tools. The methods and tools they identified referred to *any specific procedure with a specified desired outcome that could be performed in a product development process in order to* support *the work towards an environmental goal*. Their research focused on eco-design methods and tools, and did not consider economic and social assessment methods, which would be necessary for more comprehensive sustainability assessment.

This gap was also captured in the research reported by Buchert et al. (2017), who conducted a systematic literature review to identify eco-design methods and tools and, ultimately, developed an IT-based assistance system entitled *Design Decision Support Assistant (DDSA)* to select eco-design methods and tools in the product development process. To address the need of experts such as scientists and consultants in selecting sustainability methods, Zijp et al. (2015) developed a sustainability assessment identification key by considering five domains, i.e., system boundaries/inventory, impact assessment/theme selection, aggregation/interpretation, method design, and organizational restrictions. Each domain has specific criteria derived from literature for selecting appropriate methods, however, as noted for the prior studies, the approach focuses on the environmental aspect of sustainability. Moreover, it is mainly developed for experts, which makes it not suitable for non-expert users.

To address the needs of non-experts in selecting sustainability methods, Vargas Hernandez et al. (2012) integrated design for environment principles into the design process to develop an expert system framework, called GREENESYS (GREEen ENgineering Expert SYStem). This framework enables non-expert engineers and designers to select the appropriate environmental assessment method and tool by answering few simple questions. Although some researchers have focused on addressing the need to support non-experts in selecting appropriate analysis methods and tools, the developed methodologies remain deficient in assisting non-experts in selecting the most relevant methods and software tools considering all three aspects of sustainability. The methodology developed in the research herein to address these two issues is presented in the following section.

3. Methodology

A questionnaire-based methodology for assisting SEA method and software tool selection is developed herein that incorporates the various features these methods and tools have to offer. A typical SEA study for a product would begin with defining the goal and scope of the analysis, followed by answering the questionnaire to determine the most appropriate methods and tools to be used for the evaluation of the product. Upon determining the relevant methods and/or tools for evaluating each aspect of sustainability, they would then be used to perform the individual analyses. The major steps of the methodology from the user perspective are illustrated in Fig. 1. The steps and proof-of-concept selection tool are described in more detail below.

The first step of the methodology is to define the goal and scope of the study, as noted above. The study goal and scope provide the framework for the assessment and help identify the types of assessment inputs that will be required, the types of outputs expected and how they will be reported, and how the assessment will be conducted. The second step of the methodology is to complete the questionnaire, which is intended to query the non-expert analyst about the design and manufacturing information they have available for the product under study. The questions are designed based on the requirements, inputs, outputs, and features of the SEA

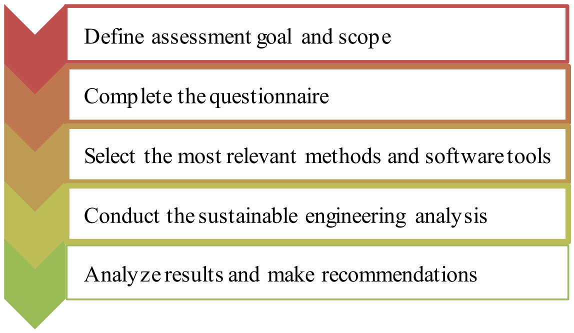

Fig. 1. Questionnaire-based methodology to assist sustainable engineering analysis studies.

tools and to allow distinctions to be made between the different approaches. The questions developed in the questionnaire and the intents of each question are presented in Table 1. The purpose of the questionnaire is to ask simple but targeted questions to guide the users in selecting the most appropriate methods and software tools.

A sample inventory of currently available SEA methods and software tools is integrated into the questionnaire to provide a proof-of-concept for demonstrating the developed methodology. In creating this inventory, a key goal was to identify an assortment of resources that could facilitate varying levels of detail, quality of detail, and ease of access for a user to obtain (cost consideration). The term *fidelity*, accompanied with the modifiers *low* and *high*, are used to describe the level and quality of detail given. Low fidelity SEA methods provide generalized results, with limited amounts of data, while higher fidelity methods generally produce numerical data linked to multiple categories. Both low- and high-fidelity methods have the potential to provide a user with relevant information; depending on a user's specific situation, certain methods can be better utilized. Thus, low- and high-fidelity methods and tools are included in the questionnaire to enable recommendations to the user about SEA resources that can appropriately accommodate the data sets available. The list of economic and environmental methods and software tools utilized in the questionnaire can be found in Table 2. The questionnaire results also display a list of social impact assessment approaches, which are not ranked since none have been established as *de facto* analysis methods, as discussed below.

With a sample inventory of SEA resources collected, methods and tools were mapped to questions in the questionnaire using an interaction matrix. The sample inventory of currently available SEA methods and software tools integrated into the questionnaire is intended to demonstrate the methodology for providing non-experts with similar tools for selecting the most relevant SEA resources. The sample inventory was collected to provide the questionnaire the ability to accommodate limited to large data sets as well as licensed and open source software tools for product and/or process analysis. *Relevance weights*, the values assigned to each SEA method and tool, are used to account for differences between low- and high-fidelity methods and software tools. High-fidelity methods are assigned a relevance weight of two, while low fidelity methods have a weight of one and non-relevant methods have a weight of zero. These relevance weights are determined using the authors' existing knowledge of each of the selected SEA methods and tools. The weights were assigned to each response utilizing a trial and error process to fine-tune the weight associated with each response. This process was repeated until the results reflected the advice that a person familiar with SEA methods would likely suggest to a non-expert. Since the relevance weights were assigned for only the methods and tools used in the sample inventory, weights would need to be adjusted as additional methods and tools are populated into the selection tool interaction matrix.

The questionnaire developed has seven questions associated with the three pillars of sustainability. The first question helps determine what results need to be displayed to the user. For example, if the user only selects the environmental aspect, then the results screen will only show the applicable environmental assessment methods and software tools. The second question queries whether the user has access to licensed software. Since the software tools often require costly licenses, this question weights freely available tools higher than commercial software tools if the user does not have access to licensed software. The third question is intended to help judge the appropriateness of higher fidelity analysis methods and tools. Higher fidelity methods provide more informative analysis when detailed product and manufacturing data is provided. Relevance weights are assigned to improve the filtering of higher fidelity SEA methods and software tools under circumstances when the user has limited knowledge of process-related data, which would reduce their effectiveness. If the user has detailed knowledge about the intended product life cycle, the higher fidelity methods that require more data would be favored.

The fourth question is related to economic assessment. The responses for this question were chosen to reflect four types of consumer products from an economic point of view (Claessens, 2017). A *convenient product* is a product that a customer would purchase with little to no forethought. These products are generally chosen based on impulse or brand recognition, such as when a consumer always buys the same brand of soft drink. They are also generally inexpensive. A *shopping product* is defined as a standard consumer product in which the customer generally compares prices before making a purchase, such as when purchasing clothing or small household appliances. The third response is a *specialty product*. Consumers select these products in a manner similar to those of the shopping product type, but specialty products could be

Table 1
Questions and their associated goals.

No.	Question	Question intent
1	In what aspect(s) of sustainability are you most interested?	Determine SEA aspect(s) of interest
2	Do you have access to software at your company/institution?	Weight free methods and software tools higher than commercial tools if licenses are not available to the analyst
3	How much process information (inputs/outputs) is available for the different manufacturing processes?	Weight high fidelity methods and software tools higher when more detailed **process** information is available
4	What type of consumer product are you analyzing?	Determine level of economic responsibility
5	Is the product an existing or a new product?	Weight high fidelity methods and software tools higher when more detailed **product** information is available
6	Does the use phase of the product require more than just electricity as an input?	Determine the complexity of the product's use phase
7	Are there CAD model(s) available for this product?	Determine availability of solid models to aid analysis using CAD-based software tools

Table 2
Interaction matrix.

	N		Methods/Software Tools									
	x	y	GaBi	SimaPro	openLCA	CES EduPack Eco Audit Tool	SolidWorks Sustainability	Eco-Indicator 99	Economic Input-Output LCA	Life Cycle Cost Analysis	Cost-Benefit Analysis	Break-Even Point
Questions	2	a	2	2	2	1	1	1				
		b										
	3	a				1	1	1				
		b	2	2	2	1	1	1				
		c	2	2	2							
	4	a							1			1
		b								1	1	1
		c								1	1	1
		d									1	
	5	a	2	2	2			1				
		b	2	2	2	1	1	1				
	6	a					1					
		b	2	2	2	1		1				
	7	a	1	1	1	1	2	1				
		b	1	1	1	1		1				

considered luxury items that are less-frequently purchased, such as a car or high-end electronics. The final type is an *unsought product*. These are products that the customer would rather not purchase, but are required due to their circumstances. An example would be a replacement for a broken window.

The fifth question helps determine whether a lower fidelity analysis method or tool is required. There are several higher fidelity tools, e.g., GaBi, SimaPro, and openLCA, that provide detailed information and can be used in the design of new products. It is assumed that if the user selects an existing product, sufficient information will be available in the design phase to use higher fidelity tools. The sixth question determines the complexity of the product use phase. Through investigation of the listed SEA methods and software tools, it was found that some available methods and tools are not suited to evaluate the impact of consumables during the product use phase, other than electricity. Thus, it is necessary to distinguish those methods that can evaluate use phase complexities. The seventh and final question is related to whether there are CAD models of the product available to the user. The purpose of this question to distinguish the appropriateness of CAD-dependent software tools, such as SolidWorks Sustainability, which perform calculations using the solid model of the intended product.

Based on the responses given by the user, the relevance weights for one or more of the available SEA methods and software tools are recorded by the questionnaire's selection algorithm, using the interaction matrix (Table 2). The weights related to each method are then summed, as shown in Eq. (1). Indices x and y are related to Questions 2 to 7 and the options for the answers of each question, respectively. Index k represents each of the environmental impact and economic analysis methods and software tools, as reported in the table.

$$M_k = \left[\sum_x \sum_y (N_x)_y\right]_k \tag{1}$$

The values in the matrix indicate the relevance weights associated with each option for each question. As an example, the algorithm will assign higher weights to GaBi (Thinkstep, 2013), SimaPro (PRé Consultants, 2013), and openLCA (GreenDelta GmbH, 2013) compared to CES EduPack Eco Audit Tool (Granta Design Ltd., 2017), SolidWorks Sustainability (Dassault Systems, 2013), and Eco-Indicator 99 (Goedkoop and Spriensma, 2001), if the user selects Option b for Question 3. The potential methods and software tools are ranked in descending order, with the highest sum indicating the most relevant method. It is important to note that the user's response to Question 1 is not considered in weighting, since it is used solely for toggling the visibility of the different SEA aspects in the results presented to the user.

In the third step of the methodology (Fig. 1), once the total relevance weights for each method and software tool are calculated based on the interaction matrix, the methods and software tools presented to the user for each of the SEA aspects are ordered from most to least relevant. Multiple methods and software tools are provided to allow the user to select the most accessible and appropriate methods and/or software tools for their study. Next to each environmental software tool suggestion, a check box is provided, such that the user can check off any software tools to which they do not have access. Upon checking a box, that software tool will then disappear from the GUI display window. In the fourth step, once the appropriate method and/or software tool is selected, the analyst can then conduct the SEA. Based on the goal and scope defined in the first step, the user would gather the necessary information for carrying out the assessment using the selected methods and/or tools.

Social impact analysis approaches are not included in Table 2 since more investigation is needed into relevant method and software tool development. However, to support the user in assessing the social aspect, some alternative frameworks, databases, and metrics are investigated in this research, and presented in the questionnaire results. In the demonstration presented herein, two metrics are adopted for quantifying social impacts as reported by Alsaffar et al. (2016): nonfatal occupational injuries and illnesses (NOII) and days away from work (DAW). These two metrics are commonly understood and tracked by companies (Eastwood and Haapala, 2015). Moreover, the values of NOII and DAW help to investigate the safety level in the work environment.

To quantify these two social metrics, data available from the company or the U.S. Bureau of Labor Statistics (BLS) (2015) can be utilized. To calculate nonfatal occupational injuries and illnesses for manufacturing ($NOII_{mfg}$), process cycle time (T_{mfg}) is multiplied by the production volume (PV) and the rate of nonfatal occupational injuries and illnesses ($RNOII_{mfg}$) reported by the BLS for various industries (U.S. Bureau of Labor Statistics, 2015). This value, as represented in Eq. (2), is divided by 200,000 h, which is assumed as the annual working hours for 100 equivalent full-time workers. To calculate DAW (Eq. (3)), the percentage of injuries and illnesses that result in days away from work must first be determined. The percentage is provided by dividing the rate of days away from work

(RDAW) by the rate of nonfatal occupational injuries and illnesses (RNOII) for the relevant industry segment from BLS data. This ratio is then multiplied by $NOII_{mfg}$ to provide the total number of cases resulting in days away from work. Finally, this quantity is multiplied by the median days away from work (MDAW), from BLS data, to provide the total number of days away from work for each manufacturing activity.

$$NOII_{mfg} = RNOII_{mfg} \cdot \left(\frac{T_{mfg}.PV}{200000} \right) \tag{2}$$

$$DAW_{mfg} = \left(\frac{RDAW_{mfg}}{RNOII_{mfg}} \right) .NOII_{mfg}.MDAW_{mfg} \tag{3}$$

In addition to manufacturing, NOII and DAW values (Eqs. (4) and (5)) must be determined for transportation activities. While process cycle time was used in the calculation of $NOII_{mfg}$, to determine $NOII_{trans}$, transportation time is divided by the number of packaged products that could be transported by the transportation mode to allocate the total number of injuries and illnesses impacts on a per-product basis. DAW_{trans} is calculated in the same manner as DAW_{mfg}.

$$NOII_{trans} = RNOII_{trans} \cdot \left(\frac{\left(\frac{T_{trans}}{N_{trans}} \right) .PV}{200000} \right) \tag{4}$$

$$DAW_{trans} = \left(\frac{RDAW_{trans}}{RNOII_{trans}} \right) .NOII_{trans}.MDAW_{trans} \tag{5}$$

The final step of the methodology is to analyze the assessment results. Based upon the goal and scope of the study, the decision maker will need to identify the most impactful phases in the product life cycle and make recommendations such as changing raw material, making the product with other manufacturing processes, and developing a new breakdown of EOL treatment scenarios to improve sustainability performance. In addition to the product, the user will need to investigate and to compare the performance for each of the selected analysis methods and software tools to identify the best alternative. This analysis will provide a better understanding about the relative performance of higher and lower fidelity methods and software tools.

4. Case study

Although the target users of the selection tool are non-experts, the pilot project was conducted by two graduate students in sustainable engineering who were involved in the research. Thus, the authors were able to test and improve the usability of the proof-of-concept tool. To demonstrate the application of the methodology and proof-of-concept, a pilot SEA project was conducted to evaluate the sustainability performance of a hexacopter. Over the past few years, multicopters and drones have received increasing attention and market growth (Raoufi et al., 2017b). They have become ubiquitous in the toy market, with products sold in a large variety of configurations and sizes. Similar to other toys, multicopters can break or wear out quickly, representing a sustainability concern. The components of the hexacopter investigated in the study are injection-molded polymer components, i.e., upper shell, lower shell, propellers, propeller shields, and battery cover, as presented in Fig. 2.

These components are assumed to be made of acrylonitrile butadiene styrene (ABS). In the representative supply chain network configuration, it is assumed that raw material (crude oil) extraction, material processing (conversion to ABS pellets), and manufacturing processes (injection molding and assembly) occur in Kansas City, Missouri. This location was found based on the geographical midpoint, *the average coordinate for a set of points on a spherical earth* (GeoMidpoint, 2018), for the top 30 U.S. cities selected by population (U.S. Census Bureau, 2018), assumed to be the target markets for the hexacopter. This research has two assumptions: One manufacturing plant will be able to cover retailer demands and all the retailers have the same demand.

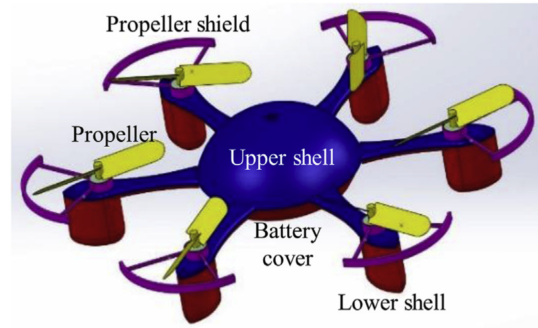

Fig. 2. CAD model of the case study hexacopter.

Since electronic components will be purchased from outside suppliers, the impact of their manufacture is expected to be independent of other design modifications and not considered in this study. Upon completion of manufacturing, the final product will be transported to retailers using an over-the-road truck. The distance between the manufacturing location and the retailers in each target market was determined utilizing the distance calculator in Google Maps (Google, 2017). Then, the average of these 30 values was considered as the distance between the manufacturing location and the retailers. The use phase considers electricity use for charging the battery of the hexacopter. It was assumed that the battery will be charged once a week for one year. The last phase in the product life cycle is EOL, which considers three scenarios: recycling, incineration, and landfill disposal.

4.1. Step 1: define assessment goal and scope

The goal of the study is to improve the sustainability performance of a hexacopter by considering environmental, economic, and social impacts. The scope of the study is a cradle-to-grave analysis (Fig. 3). A single hexacopter was assumed as the functional unit, *quantified performance of a product system for use as a reference unit* (International Organization for Standardization [ISO], 2006), which includes a traditional use and disposal scenario. Based on the goal and scope, supply chain information including raw material, supplier, transportation modes and routes, manufacturing process, use phase, and breakdown of EOL scenarios is required to analyze the product from a cradle-to-grave life cycle perspective.

4.2. Step 2: complete the questionnaire

For Question 1, economic, social, and environmental aspects were selected, since the objective for this analysis is to evaluate more comprehensive sustainability performance. Questions 2–7 were then completed with respect to the available product design and manufacturing information as presented in Fig. 4.

4.3. Step 3: select the most relevant methods and/or software tools

Upon completion of the questionnaire, methods and software

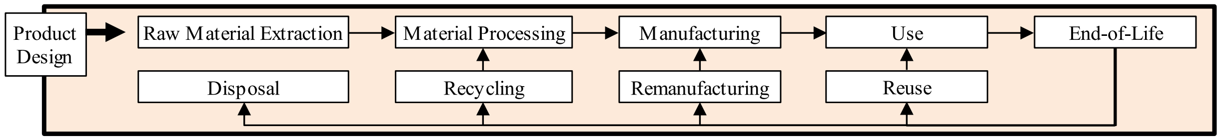

Fig. 3. Cradle-to-grave product life cycle (adapted from (Raoufi et al., 2017a).

tools are presented to the user (Fig. 5). The methods provided in the questionnaire results are instances of the available methods and commercially software tools for each of the three different aspects of SEA. Several environmental assessment tools are considered in the proof-of-concept inventory as reported above. Life Cycle Cost Analysis (LCCA), Cost-Benefit Analysis (CBA), and Break-Even Point (BEA) are included to evaluate economic aspects. As noted above, there are few established methods and software tools available for assessing social impacts; however, a list of evaluation frameworks is provided to help the user identify an appropriate social impact analysis method.

4.4. Step 4: conduct sustainable engineering analysis

Once the questionnaire was completed for the hexacopter, the most applicable methods and software tools were identified. Three economic impact assessment methods, i.e., LCCA, CBA, and BEA were identified by using the questionnaire. From these, LCCA was deemed the most appropriate for evaluating the economic impact of the hexacopter; CBA and BEA would be more appropriate for comparative studies between multiple products. To perform LCCA, cost data was collected from across the hexacopter's life cycle. The volume of ABS material required for making one hexacopter (47.2 cm^3), which includes process yield, would cost $0.21 (Premier Plastic Resins, 2017). Considering the average U.S. labor hourly compensation reported by the BLS (U.S. Bureau of Labor Statistics, 2017a), the total labor cost for injection molding of the ABS components for one hexacopter is $0.60. Using the average price of electricity reported by the U.S. Energy Information Administration (EIA) (U.S. Energy Information Administration, 2017), injection molding electricity costs would amount to $0.02 per hexacopter. Considering the usable capacity of a standard 40-ft shipping container (2398 ft^3) (Container Solutions, 2017) and the volume of the hexacopter package (0.17 ft^3), the average transportation cost to deliver one packaged hexacopter from the manufacturing plant to retailers is $0.021 (World Freight Rates, 2017).

To evaluate the use cost of the hexacopter, the purchase price ($70) of the copter (ROA Hobby, 2017) and the annual electricity cost for charging the battery ($0.18) were determined. Electricity prices are reported by the EIA (U.S. Energy Information Administration, 2017). Finally, costs of different EOL scenarios were investigated. The default scenario considered recycling, incineration, and landfilling to account for 33%, 13%, and 54% of disposed products, respectively, based on typical municipal solid

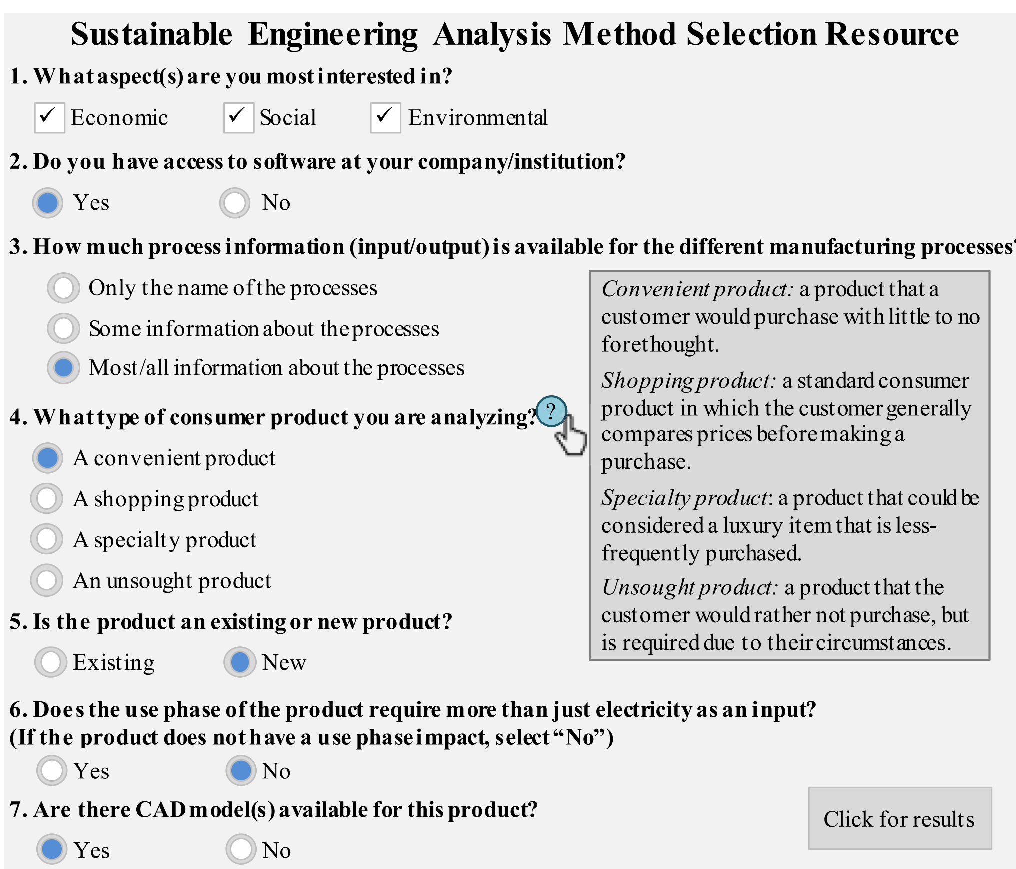

Fig. 4. A sample of completed questionnaire for hexacopter study based on user design and manufacturing information.

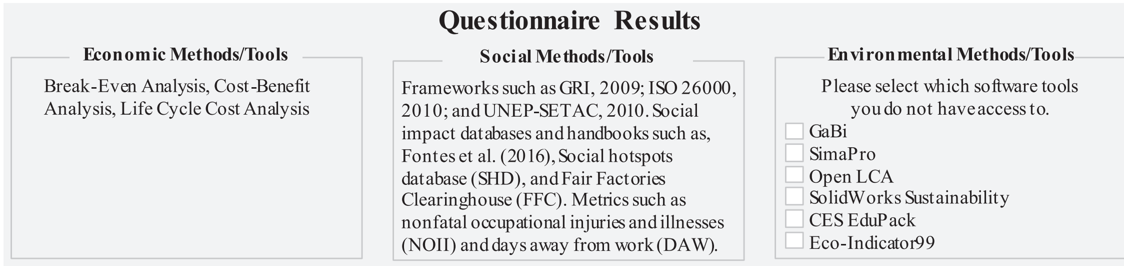

Fig. 5. Rank-ordered methods and software tools to conduct sustainable engineering analysis for hexacopter.

waste disposal practices reported by the U.S. Environmental Protection Agency (EPA) (2016). Average EOL hourly labor cost ($20.56) was calculated by multiplying the percentages by their associated labor cost (U.S. Bureau of Labor Statistics, 2017b). Since labor time for disposal is not known, actual disposal costs per product cannot be determined, though these are likely very low on an individual product basis. However, relative changes in hourly costs can be explored for different EOL scenarios. The economic impact assessment results of the initial design are summarized in Table 3.

The next analysis performed for the hexacopter looked at the social impact of the product. The resulting NOII and DAW values for manufacturing and transportation activities on a functional unit basis (one hexacopter charged once a week for a use duration of one year) is presented in Table 4. Since the average transportation time from the manufacturing plant to the retailers has a higher duration compared to the manufacturing cycle time, transportation activities have higher NOII and DAW values.

Another reason for this difference stems from the associated RDAW for transportation and manufacturing. While $RNOII_{mfg}$ and $RNOII_{trans}$ are similar for each, $RDAW_{mfg}$ is less than $RDAW_{trans}$, which results in a similar number of injuries and illnesses, but fewer days away from work in manufacturing. The social impact analysis of the EOL scenarios need further research. In addition to the lack of information about the time required for each operation, there is uncertainty about the number of products disposed and actual EOL treatment modes. Thus, rather than calculating NOII and DAW metrics for the EOL scenarios, the changes in RNOII, RDAW, and MDAW for each scenario are reported herein.

An environmental LCA was the final assessment conducted in evaluating the sustainability performance of the hexacopter. From the results of the questionnaire, it was found that GaBi, SimaPro, and openLCA were the most applicable tools (high fidelity) since design and manufacturing information was available. Based on its availability to the authors for this work, SimaPro was selected as the LCA tool to be used. SimaPro includes various environmental impact assessment methods, such as ReCiPe 2008, Impact 2002+, and IPCC 2013 GWP, which empower non-experts to conduct a range of analyses. We selected the TRACI 2.1 environmental impact assessment method, which is a multi-indicator method that utilizes ten metrics, i.e., ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion. The characterized impacts for each TRACI impact category are presented in Table 5. It can be seen that recycling at the EOL phase has negative impact values (an environmental benefit), which means promoting recycling would assist in reducing life cycle environmental impacts.

The environmental impact assessment results based on the normalization factors provided by Ryberg et al. (2014) are reported in Fig. 6. Normalized impact categories provide the opportunity for the analyst to better understand the relative contribution of each impact category. Raw material production, use, and incineration have the highest environmental impacts of all the life cycle phases. They are responsible for 33%, 11%, and 38% of the total environmental impacts, respectively. The other phases account for only 18% of total environmental impact. Carcinogenics (mainly due to raw material production) and ecotoxicity (mainly due to incineration) are shown to be the highest contributors to the environmental impact of the hexacopter, accounting for 49% and 33% of the total environmental impacts, respectively. The negative values in the figure indicate the sequestration of each impact category by end-of-life scenarios.

To compare results of a high-fidelity software tool (SimaPro) with a lower fidelity tool, SolidWorks Sustainability was identified. The CAD model of the hexacopter was imported into the software to conduct an environmental impact analysis. SolidWorks

Table 3
Economic impact assessment (LCCA) results for the initial design of the hexacopter.

	Category					
	Raw material	Transportation	Manufacturing	Use	End-of-life	Total
Cost	$0.21	$0.021	$0.62	$0.18	$20.56	$21.59

Table 4
Social impact analysis for manufacturing and transportation activities of the initial design (*U.S. BLS (2015) data).

Activity	Rate of nonfatal occupational injuries and illnesses (RNOII)*	Rate of days away from work (RDAW)*	Median days away from work (MDAW)*	Nonfatal occupational injuries and illnesses (NOII)	Days away from work (DAW)
Manufacturing	4.6	2.7	10	3.83E-02	2.25E-01
Transportation	4.5	3.2	20	7.22E-02	1.03E+00
Landfill	3.5	2.3	9	–	–
Incineration	2.0	1.1	9	–	–
Recycling	5.1	3.4	9	–	–

Table 5
Characterized environmental impact assessment results for the initial hexacopter design (SimaPro).

Category	Unit	Matl.	Mfg.	Trans.	Use	Recycling	Incineration	Landfill
Ozone depletion	kg CFC-11 eq.	7.7E-10	5.0E-08	3.7E-09	1.8E-11	−3.6E-10	−9.6E-10	1.5E-10
Global warming	kg CO_2 eq.	3.0E-01	9.6E-02	1.4E-02	1.0E+00	−4.1E-02	2.5E-02	3.3E-03
Smog	kg O_3 eq.	1.0E-02	5.4E-03	2.4E-03	6.6E-02	−1.7E-03	−3.1E-04	7.7E-05
Acidification	kg SO_2 eq.	8.9E-04	5.9E-04	9.2E-05	8.7E-03	−1.1E-04	−3.0E-05	3.7E-06
Eutrophication	kg N eq.	2.3E-04	3.9E-04	2.7E-05	1.2E-04	−1.7E-04	−1.4E-05	4.9E-04
Carcinogenics	CTUh	1.5E-08	3.5E-09	4.0E-10	1.3E-09	−1.5E-09	4.4E-10	1.5E-10
Non-carcinogenics	CTUh	1.4E-08	1.5E-08	4.3E-09	2.7E-08	−3.6E-09	1.7E-08	2.8E-08
Respiratory effects	kg PM2.5 eq.	8.9E-05	9.8E-05	1.2E-05	4.3E-04	−2.4E-06	−6.8E-06	4.9E-07
Ecotoxicity	CTUe	9.1E-01	5.2E-01	1.3E-01	2.7E-01	−1.6E-01	9.6E+00	1.7E+00
Fossil fuel depletion	MJ surplus	9.1E-01	1.1E-01	3.3E-02	5.1E-01	−2.3E-01	−8.4E-04	1.4E-03

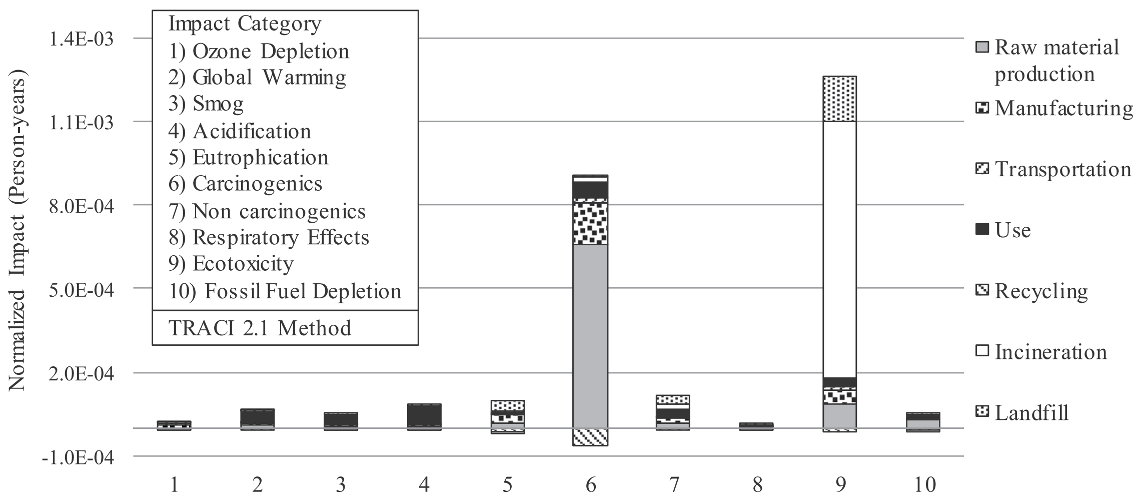

Fig. 6. Normalized environmental impact assessment results for the initial hexacopter design (SimaPro).

Sustainability provides four environmental metrics: energy consumption (MJ), carbon footprint (kg CO_2 eq.), air acidification (kg SO_2 eq.), and water eutrophication (kg PO_4 eq.).

The results are presented in Table 6 and show that the raw material extraction phase has the largest energy consumption and associated carbon footprint among all the other phases of the product life cycle. Moreover, it has the largest water eutrophication. The use phase has the largest air acidification impact among the other phases. The EOL phase in SolidWorks Sustainability has only three scenarios, i.e., recycling, incineration, and landfill. Compared to SimaPro, which provides detailed information about environmental impacts of each EOL scenario, SolidWorks Sustainability provides composite EOL results. The difference between these two LCA software tools supports how methods with different fidelity are sorted in the questionnaire based on the weighting of questions.

4.5. Step 5: analyze assessment results and make recommendations

Upon completion of the SEA, the assessment results will be evaluated to help achieve the goal of the study, which, in this case, is to improve the sustainability performance of a hexacopter. Thus, based on the foregoing analysis, three recommendations are made: (1) change the transportation mode, (2) reduce material use, and (3) take back hexacopters at their end of life. To satisfy the first recommendation, the transportation mode to deliver the raw material from the supplier to the manufacturer was changed from road to rail. Utilizing a one rail car, 147,000 hexacopters can be transported, while a 40-ft truck can transport 14,000 boxes, reducing the unit cost significantly.

The second recommendation is to reduce the use of material, which can be achieved by reducing part mass (e.g., a 20% reduction). Using less material helps to reduce costs across the life cycle. Based on the new design, the total cost of material required for making the hexacopter would be $0.17. The transportation cost will not change since it is dependent on the transportation capacity (mass of packaging and pallets), not the mass of each product. It should be noted that the second recommendation investigates the impacts of less material use, not changes in transportation mode. Thus, to investigate the impacts of using less material on sustainability performance of the initial design, the truck transportation mode is used in the second recommendation, as used in the initial product design scenario. Using less material would improve

Table 6
Environmental impact assessment results for the initial design of the hexacopter (SolidWorks Sustainability).

Category	Unit	Matl.	Mfg.	Use	Trans.	End-of-Life
Energy Consumption	MJ	5.6E+00	1.4E+00	2.3E+00	1.9E-01	2.6E-02
Carbon Footprint	kg CO_2 eq.	2.4E-01	9.4E-02	1.6E-01	1.3E-02	3.5E-02
Air Acidification	kg SO_2 eq.	8.1E-04	6.3E-04	1.1E-03	5.8E-05	1.8E-05
Water Eutrophication	kg PO_2 eq.	1.0E-04	2.3E-05	4.0E-05	1.3E-05	4.4E-05

manufacturing cost by decreasing the cycle time, which requires less electricity during the manufacturing process and less labor. Finally, EOL impacts would be reduced since 20% less material would be processed in the EOL phase.

Evaluating the third recommendation, product takeback, involved developing a revised EOL treatment scenario. In the revised scenario, it was assumed that recycling and incineration increased proportionally to 40% and 16%, respectively, by decreasing the landfilled fraction to 44%. This revised breakdown provides an opportunity to reclaim more material through recycling as well as reclaiming more embedded energy through incineration. The economic impact assessment results of each recommendation, as well as the impact of implementing all of the recommendations together are presented in Table 7. Shading in Table 7 indicates the phases impacted by each recommendation.

Next, social impact assessment was conducted for the redesigned hexacopter. $RNOII_{trans}$ and $RDAW_{trans}$ vary with transportation mode and play key role in reducing NOII and DAW values. Thus, to deliver final products from the manufacturing location to the retail locations, the transportation mode is changed from road to rail in the first recommendation, since rail shipping has lower rates of injuries, illnesses, and lost work days compared to the road transportation mode (U.S. Bureau of Labor Statistics, 2015). The results of the change of transportation activity are presented in Table 8. Moreover, in the second recommendation, reducing the mass of material in a hexacopter, resulted in reduced NOII and DAW. These social impacts were reduced by 99% and 20% by using rail shipping and reducing material use, respectively.

The total amount of municipal solid waste (MSW) in the U.S. in 2014 was 234 million metric tons (US EPA, 2015). Considering the production volume as 100,000 hexacopters per year, the total mass of EOL hexacopters collected is assumed to be 5,000 kg, annually. It is assumed that they reach their EOL at a steady rate, which is miniscule in comparison to typical waste disposal rates. Due to the lack of information about the EOL options, NOII and DAW are calculated parametrically based on the duration of each EOL processing route (Eqs. (6) and (7)). Changes in NOII and DAW values are reported in Table 8.

$$NOII_S = BR_S \cdot \left(\frac{5\times10^3}{234\times10^9}\right) . RNOII_S . \left(\frac{T_S}{200000}\right) \tag{6}$$

$$DAW_S = \left(\frac{RDAW_S}{RNOII_S}\right) . NOII_S . MDAW_S \tag{7}$$

In Eq. (6), $NOII_s$ presents the number of injuries and illnesses for each EOL scenario and *s* is the index for each scenario, i.e., *inc*: incineration, *dis*: disposal, and *rec*: recycling. BR_s is the breakdown of EOL treatment options, which in the initial design are 11%, 54%, and 35% for incineration, disposal, and recycling, respectively. T_s is the duration of each scenario, which is considered as parameter in the calculations. DAW_s, presented in Eq. (7), is the number of days away from work for each scenario. $RNOII_s$, $RDAW_s$, and $MDAW_s$ are presented above, in Table 4. Based on the scenarios presented in the third recommendation, the associated social impacts of the recycling and incineration scenarios would increase by 21% and 23%, respectively, while the social impacts of the landfilling scenario would decrease by 19%. Simultaneous consideration of all recommendations is presented in the last column of Table 8.

Finally, an environmental impact analysis was conducted to evaluate the sustainability performance of the redesigned hexacopter. The characterized environmental impacts when considering all three recommendations simultaneously using TRACI 2.1 in SimaPro are presented in Table 9. Similar to the environmental impact assessment provided in the fourth step of the methodology, the results of the new assessment are also normalized. The effect of all three recommendations on environmental impacts are reported in Fig. 7.

In addition to considering all the three recommendations simultaneously, the effect of each recommendation on the environmental performance is investigated. The results are presented in Table 10 and the numbers provide the total value of each impact category considering all phases of the product life cycle. Shading in Table 10 indicates the phases impacted by each recommendation.

The LCA software used in the fourth step of the methodology was SolidWorks Sustainability. The environmental impact

Table 7
Economic impact assessment results for each recommendation of the redesigned hexacopter.

Category	Initial Design	Recommendation 1 (Transportation mode)	Recommendation 2 (Material use)	Recommendation 3 (End-of-life)	Recommendations 1, 2, and 3
Raw material	$0.21	$0.21	$0.17	$0.21	$0.17
Transportation	$0.021	$0.003	$0.021	$0.021	$0.002
Manufacturing	$0.62	$0.62	$0.5	$0.62	$0.5
Use	$0.18	$0.18	$0.18	$0.18	$0.18
End-of-life	$20.56	$20.56	$16.45	$20.49	$16.39
Total	$21.59	$21.57	$17.32	$21.52	$17.24

Table 8
Social impact assessment results of each recommendation for the redesigned hexacopter.

Impact	Initial Design	Recommendation 1 (Transportation mode)	Recommendation 2 (Material use)	Recommendation 3 (End-of-life)	Recommendations 1, 2, and 3
$NOII_{mfg}$	3.83E-02	–	3.07E-02	–	3.07E-07
DAW_{mfg}	2.25E-01	–	1.80E-01	–	1.80E-06
$NOII_{trans}$	7.22E-02	2.43E-04	–	–	0.04E-07
DAW_{trans}	1.03E+00	3.65E-03	–	–	0.07E-06
$NOII_{inc}$	2.78E-14*t_{inc}	–	–	3.42E-14*t_{inc}	3.42E-14*t_{inc}
DAW_{inc}	1.38E-13*t_{inc}	–	–	1.69E-13*t_{inc}	1.69E-13*t_{inc}
$NOII_{dis}$	2.02E-13*t_{dis}	–	–	1.65E-13*t_{dis}	1.65E-13*t_{dis}
DAW_{dis}	1.19E-12*t_{dis}	–	–	9.73E-13*t_{dis}	9.73E-13*t_{dis}
$NOII_{rec}$	1.80E-13*t_{rec}	–	–	2.18E-13*t_{rec}	2.18E-13*t_{rec}
DAW_{rec}	1.08E-12*t_{rec}	–	–	1.31E-12*t_{rec}	1.31E-12*t_{rec}

Table 9
Characterized environmental impact assessment results for the redesigned hexacopter (SimaPro).

Category	Unit	Matl.	Mfg.	Trans.	Use	Recycling	Incineration	Landfill
Ozone depletion	kg CFC-11 eq.	5.5E-10	3.6E-08	8.8E-10	1.3E-11	−3.1E-10	−8.4E-10	8.6E-11
Global warming	kg CO_2 eq.	2.1E-01	6.9E-02	1.7E-02	7.1E-01	−3.6E-02	2.2E-02	1.9E-03
Smog	kg O_3 eq.	7.5E-03	3.9E-03	3.8E-03	4.7E-02	−1.4E-03	−2.8E-04	4.5E-05
Acidification	kg SO_2 eq.	6.4E-04	4.2E-04	1.1E-04	6.2E-03	−9.5E-05	−2.7E-05	2.1E-06
Eutrophication	kg N eq.	1.7E-04	2.8E-04	2.3E-05	8.7E-05	−1.5E-04	−1.2E-05	2.9E-04
Carcinogenics	CTUh	1.1E-08	2.5E-09	3.2E-10	9.1E-10	−1.3E-09	3.8E-10	8.9E-11
Non-carcinogenics	CTUh	1.0E-08	1.1E-08	7.0E-10	1.9E-08	−3.1E-09	1.5E-08	1.6E-08
Respiratory effects	kg PM2.5 eq.	6.4E-05	7.0E-05	1.5E-05	3.1E-04	−2.1E-06	−5.9E-06	2.8E-07
Ecotoxicity	CTUe	6.5E-01	3.7E-01	2.0E-02	1.9E-01	−1.4E-01	8.5E+00	9.8E-01
Fossil fuel depletion	MJ surplus	6.5E-01	7.6E-02	7.6E-03	3.6E-01	−2.0E-01	−7.4E-04	8.2E-04

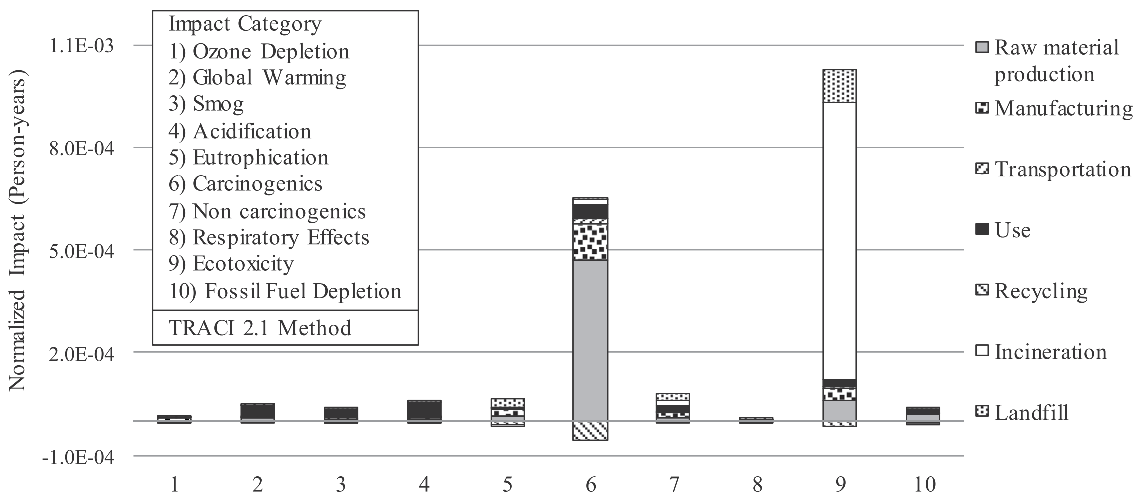

Fig. 7. Normalized environmental impact assessment results for the redesigned hexacopter (SimaPro).

assessment results from this lower fidelity tool are presented in Table 11 when considering all the three recommendations simultaneously. Compared to the results for the initial design (Table 6), impacts in all categories are improved for each phase of the product life cycle.

In Table 12, the relative change in selected environmental impacts compared to those for the initial design are reported for each recommendation and for a case that would implement all three recommendations.

5. Discussion of results

Evaluation of the SEA results for the hexacopter case study found that the life cycle costs would reduce by 0.1% by changing the transportation mode for the final product from road to rail (Recommendation 1); by 19.7% when reducing material use (Recommendation 2); and by 0.3% in changing the EOL strategy (Recommendation 3). By implementing all three recommendations at the same time, life cycle costs would be reduced by 20%. Evaluation of the hexacopter redesign scenarios for social impacts indicated a reduction in illnesses/injuries and days away from work of 20% by changing the transportation mode and 99% by reducing material use. By implementing product takeback at EOL (reducing landfilling), social impacts of landfilling would reduce by 19%, while social impacts would increase by 21% and 23%, respectively, for recycling and incineration activities. With regard to the environmental impact assessment, using the “high-fidelity” software tool (SimaPro) it was found that changing the transportation mode from

Table 10
Characterized environmental assessment results of each recommendation for the redesigned hexacopter (SimaPro).

Impact (units in Table 9)	Initial Design	Recommendation 1 (Transportation mode)	Recommendation 2 (Material use)	Recommendation 3 (End-of-life)	Recommendations 1, 2, and 3
Ozone depletion	5.4E-08	5.1E-08	3.8E-08	5.3E-08	3.6E-08
Global warming	1.4E+00	1.4E+00	1.0E+00	1.4E+00	1.0E+00
Smog	8.2E-02	8.5E-02	5.9E-02	8.2E-02	6.1E-02
Acidification	1.0E-02	1.0E-02	7.2E-03	1.0E-02	7.3E-03
Eutrophication	1.1E-03	1.1E-03	7.7E-04	9.5E-04	6.8E-04
Carcinogenics	2.0E-08	2.0E-08	1.4E-08	1.9E-08	1.4E-08
Non carcinogenics	1.0E-07	9.9E-08	7.3E-08	1.0E-07	6.9E-08
Respiratory effects	6.2E-04	6.3E-04	4.4E-04	6.2E-04	4.5E-04
Ecotoxicity	1.3E+01	1.3E+01	9.3E+00	1.5E+01	1.1E+01
Fossil fuel depletion	1.3E+00	1.3E+00	9.5E-01	1.3E+00	9.0E-01

Table 11
Environmental assessment results for the redesigned hexacopter (SolidWorks Sustainability).

Category	Unit	Matl.	Mfg.	Use	Trans.	End-of-Life
Energy Consumption	MJ	3.6E+00	8.8E-01	2.3E+00	1.1E-01	1.6E-02
Carbon Footprint	kg CO_2 eq.	1.6E-01	6.0E-02	1.6E-01	7.8E-03	2.1E-02
Air Acidification	kg SO_2 eq.	5.2E-04	4.1E-04	1.1E-03	4.1E-05	1.2E-05
Water Eutrophication	kg PO_2 eq.	6.4E-05	1.5E-05	4.0E-05	6.4E-06	2.3E-05

Table 12
Changes in selected impacts for hexacopter redesigns under different recommendations (SolidWorks Sustainability).

Impact	Initial Design	Recommendation 1 (Transportation)	Recommendation 2 (Material use)	Recommendation 3 (End-of-life)	Recommendations 1, 2, and 3
Energy Consumption, MJ	9.50E+00	−1.4E-02	−2.6E+00	−2.0E-03	−2.6E+00
Carbon Footprint, kg CO_2 eq.	5.42E-01	−1.0E-03	−1.4E-01	−2.0E-03	−1.4E-01
Air Acidification, kg SO_2 eq.	2.60E-03	+6.0E-06	−5.4E-04	no change	−5.3E-04
Water Eutrophication, kg PO_2 eq.	2.20E-04	−3.0E-06	−6.5E-05	−8.0E-06	−7.2E-05

road to rail would reduce ozone depletion and non-carcinogenics, but increase smog and respiratory effects (other impacts are predicted to remain unchanged). As expected, reducing material use would reduce environmental impacts in all categories. Moreover, in the revised EOL strategy, ozone depletion, eutrophication, and carcinogenics impacts are predicted to decrease relative to the initial EOL breakdown. Lastly, simultaneous consideration of all three recommendations demonstrated a reduction of environmental impacts in all categories. Using the “low-fidelity” software tool (SolidWorks Sustainability), it was found that the first and the third recommendations would not lead to significantly improved environmental performance compared to the initial design. However, the second recommendation is predicted to have better environmental performance than the initial scenario. The next section summarizes the findings and discusses several potential future research directions.

6. Conclusions

The objective of this research is to enable non-experts to identify the most appropriate methods and software tools prior to conducting SEA. At its core, our methodology relies on an interaction matrix to classify and rank an inventory of available SEA methods and software tools based on their relevance to available design data. The proof-of-concept questionnaire and supporting interaction matrix, as well as a graphical user interface (GUI), were implemented using MATLAB to demonstrate the methodology. A hexacopter design case study was presented using low- and high-fidelity LCA tools, along with low-fidelity economic and social assessment methods. This approach allowed us to compare the sustainability performance (e.g., economic and environmental metric types and values) of the initial hexacopter design and four design alternatives. In our demonstration, the relevance weights used to determine the appropriate SEA methods and software tools were assigned based on existing knowledge of the selected methods and tools. Upon conducting the SEA study for the hexacopter using available life cycle data, it was found that the assigned relevance weights enable non-expert users to differentiate between the available low- and high-fidelity methods and software tools.

Improving the sustainability performance of consumer goods during their manufacture, use, and end of life has been an increasing concern in industry. SEA approaches have been commonly used to evaluate the life cycle environmental, economic, and social impacts of products in an *ad hoc* manner. A number of analysis methods and software tools have been developed for individual analysis of each of the three aspects of sustainability. Prior to analyzing the sustainability performance for a product, the most appropriate method and software tool should be determined for evaluating each SEA aspect. However, due to the large number of software tools developed for conducting SEA, this selection process can be confusing and time-consuming for designers, especially to non-experts in sustainable engineering (Rossi et al., 2016; Zhang et al., 2013; Zijp et al., 2017). In this regard, two challenges were identified in the existing approaches, as reported in Section 2. First, selection approaches mainly focus on eco-design methods and tools (Buchert et al., 2017; Lindahl and Ekermann, 2013; Zijp et al., 2015). Second, few approaches have been developed to address the needs of non-experts in selecting the most appropriate SEA methods and tools; reported approaches focus on selection of tools for assessing environmental performance (Vargas Hernandez et al., 2012). The questionnaire-based methodology developed herein allows non-expert designers in both academia and industry to more quickly identify the most appropriate SEA methods and software tools available to them for evaluating their product design, avoiding non-value-added effort. Designers are presented a list of methods and tools that are ordered from most to least relevant to assist SEA analysis during product design.

To build upon the research presented in the foregoing, the following future directions have been identified. First, the relevance weights applied in the interaction matrix will need to be updated based on the judgement of a diverse group of SEA experts (e.g., using a Delphi study). Second, methods and software tools should be developed and incorporated into the questionnaire and the supporting interaction matrix for assessing broader social impacts. This includes incorporating indicators such as worker satisfaction, use of local employment, and impact on worker long-term health. Currently, due to the dearth of methods and software tools, the interaction matrix provides only a few options. To further develop the tool, new SEA methods and software tools need to be added to the inventory. In addition, we were able to adopt only two indicators for social impact assessment, necessitating the development and implementation of new social impact indicators, methods, and tools. It should be noted that the research herein developed the underpinning questionnaire specifically to assess consumer products. The tool could be extended to consider other product types. These modifications would improve the utility of related software applications that may be developed based on the outcomes of the research presented herein, and would better serve various user communities (e.g., students, novice designers, or small manufacturing enterprises).

Disclaimer

Certain commercial software products and consumer products are identified in this paper. These products were used only for demonstration purposes. This use does not imply approval or endorsement by the authors of this paper.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant Nos. CMMI-1350065 and DUE-1432774 at Oregon State University, DUE-1431481 at Wayne State University, and DUE-1431739 at The Pennsylvania State University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.016.

Nomenclature

BR_s	Breakdown of the end-of-life treatment scenarios
DAW_{mfg}	Days away from work for manufacturing
DAW_s	Days away from work for the end-of-life treatment scenarios
DAW_{trans}	Days away from work for transportation
$MDAW_{mfg}$	Median days away from work for manufacturing
$MDAW_s$	Median days away from work for the end-of-life treatment scenarios
$MDAW_{trans}$	Median days away from work for transportation
N_{trans}	Number of parts that can be transported by each vehicle
$NOII_{mfg}$	Nonfatal occupational injuries and illnesses for manufacturing
$NOII_s$	Nonfatal occupational injuries and illnesses for the end-of-life treatment scenarios
$NOII_{trans}$	Nonfatal occupational injuries and illnesses for transportation
PV	Production volume
$RDAW_{mfg}$	Rate of days away from work for manufacturing
$RDAW_s$	Rate of days away from work for the end-of-life treatment scenarios
$RDAW_{trans}$	Rate of days away from work for transportation
$RNOII_{mfg}$	Rate of nonfatal occupational injuries and illnesses for manufacturing
$RNOII_s$	Rate of nonfatal occupational injuries and illnesses for the end-of-life treatment scenarios
$RNOII_{tran}$	Rate of nonfatal occupational injuries and illnesses for transportation
T_{mfg}	Manufacturing process time
T_s	Duration of end-of-life treatment scenarios
T_{trans}	Transportation time

References

Alsaffar, A.J., Raoufi, K., Kim, K.-Y., Kremer, G.E.O., Haapala, K.R., 2016. Simultaneous consideration of unit manufacturing processes and supply chain activities for reduction of product environmental and social impacts. J. Manuf. Sci. Eng. 138, 101009.1-101009.18. https://doi.org/10.1115/1.4034481.

Buchert, T., Halstenberg, F.A., Bonvoisin, J., Lindow, K., Stark, R., 2017. Target-driven selection and scheduling of methods for sustainable product development. J. Clean. Prod. 161, 403–421. https://doi.org/10.1016/j.jclepro.2017.05.067.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J.G., Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. J. Clean. Prod. 107, 615–625. https://doi.org/10.1016/j.jclepro.2015.05.009.

Ciroth, A., 2012. Software for life cycle assessment. In: Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products. John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 143–157.

Claessens, M., 2017. 4 Types of Consumer Products and Marketing Considerations. Mark.-Insid (accessed 15.5.18). https://marketing-insider.eu/4-types-of-consumer-products/.

Clarivate Analytics, 2018. Web of science (accessed 1.10.18). https://clarivate.com/products/web-of-science/.

Container Solutions, 2017. ISO shipping container size and dimension specifications | Container Solutions (accessed 18.11.17). http://containersolutions.net/specifications/.

Dassault Systems, 2013. SolidWorks sustainability (accessed 9.5.17). http://www.solidworks.com/sustainability/.

Dreyer, L.C., Hauschild, M.Z., Schierbeck, J., 2006. A framework for social life cycle impact assessment. Int. J. Life Cycle Assess. 11, 88–97.

Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Ann. - Manuf. Technol. 61, 587–609. https://doi.org/10.1016/j.cirp.2012.05.002.

Eastwood, M.D., Haapala, K.R., 2015. A unit process model based methodology to assist product sustainability assessment during design for manufacturing. J. Clean. Prod. 108, 54–64. https://doi.org/10.1016/j.jclepro.2015.08.105.

Elkington, J., 1997. Cannibals with Forks: the Triple Bottom Line of 21st Century Business. Capstone Publishing Ltd, Oxford, UK.

Fisher, M.L., 1997. What is the right supply chain for your product? Harv. Bus. Rev. 75, 105–117.

Garretson, I.C., Mani, M., Leong, S., Lyons, K.W., Haapala, K.R., 2016. Terminology to support manufacturing process characterization and assessment for sustainable production. J. Clean. Prod. 139, 986–1000. https://doi.org/10.1016/j.jclepro.2016.08.103.

GeoMidpoint, 2018. Geographic midpoint calculator, find your personal center of gravity (accessed 25.5.18). http://www.geomidpoint.com/.

Goedkoop, M., Spriensma, R., 2001. The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment, third ed. PRé Consultants, Amersfoort, The Netherlands.

Goedkoop, M.J., Indrane, D., de Beer, I.M., 2018. Product Social Impact Assessment Handbook - 2018 (No. Version 4.0). The Roundtalble for Product Social Metrics, Amersfoort, The Netherlands.

Google, 2017. Google maps (accessed 9.5.17). https://www.google.com/maps/.

Granta Design Ltd., 2017. CES EduPack 2015: Eco Audit (accessed 8.5.17). http://www.grantadesign.com/products/ecoaudit/.

GreenDelta GmbH, 2013. OpenLCA (accessed 30.12.15). http://www.openlca.org/.

Gunasekaran, A., Spalanzani, A., 2012. Sustainability of manufacturing and services: investigations for research and applications. Int. J. Prod. Econ., Sustain. Dev. Manuf. Services 140, 35–47. https://doi.org/10.1016/j.ijpe.2011.05.011.

ROA Hobby, 2017. 65drones Alien X6s mini hexacopter with HD Camera in headless mode for Beginners. 65Drones (accessed 18.5.17). https://www.65drones.com/products/alien-x6-mini-hexacopter-with-hd-camera.

Hutchins, M.J., Gierke, J.S., Sutherland, J.W., 2009. Decision making for social sustainability: a life-cycle assessment approach. In: Technology and Society, 2009. ISTAS '09. IEEE International Symposium on. Tempe, Arizona, USA, pp. 1–5. https://doi.org/10.1109/ISTAS.2009.5155902.

International Organization for Standardization [ISO], 2006. Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006).

Jørgensen, A., Bocq, A., Nazarkina, L., Hauschild, M., 2007. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13, 96–103. https://doi.org/10.1065/lca2007.11.367.

Khan, M.T.H., Raoufi, K., Park, K., Reza, T., Psenka, C.E., Jackson, K.L., Haapala, K.R., Kremer, G.E.O., Kim, K.-Y., 2017. Development of learning modules for sustainable life cycle product design: a constructionist approach. In: Proceedings of the ASEE Annual Conference & Exposition, June 25-28, Columbus, Ohio, United States.

Kremer, G.E., Haapala, K., Murat, A., Chinnam, R.B., Kim, K., Monplaisir, L., Lei, T., 2016. Directions for instilling economic and environmental sustainability across product supply chains. J. Clean. Prod. 112 (Part 3), 2066–2078. Embedding Sustainability Dynamics in Supply Chain Relationship Management and Governance Structures. https://doi.org/10.1016/j.jclepro.2015.07.076.

Lindahl, M., Ekermann, S., 2013. Structure for categorization of EcoDesign methods and tools. In: Nee, A.Y.C., Song, B., Ong, S.-K. (Eds.), Re-Engineering Manufacturing for Sustainability. Springer Singapore, pp. 117–122.

Lu, T., Gupta, A., Jayal, A.D., Badurdeen, F., Feng, S.C., Dillon Jr., O.W., Jawahir, I.S., 2011. A framework of product and process metrics for sustainable manufacturing. In: Advances in Sustainable Manufacturing. Springer, Berlin, Heidelberg, Germany, pp. 333–338.

Ness, B., Urbel-Piirsalu, E., Olsson, L., Anderberg, S., 2007. Categorizing tools for sustainability assessment. Ecol. Econ. 60, 498–508.

Parris, T.M., Kates, R.W., 2003. Characterizing and measuring sustainable development. Annu. Rev. Environ. Resour. 28, 559–586. https://doi.org/10.1146/annurev.energy.28.050302.105551.

PRé Consultants, 2013. SimaPro (accessed 9.5.17). https://www.pre-sustainability.com/simapro.

Premier Plastic Resins, 2017. PC/ABS (accessed 18.5.17). http://www.premierplasticresins.com/pc-abs-natural-1500-lb-gaylord.html.

Ramani, K., Ramanujan, D., Bernstein, W.Z., Zhao, F., Sutherland, J., Handwerker, C., Choi, J.-K., Kim, H., Thurston, D., 2010. Integrated sustainable life cycle design: a review. J. Mech. Des. 132, 091004–1 to 091004–15. https://doi.org/10.1115/1.4002308.

Raoufi, K., Haapala, K.R., Jackson, K.L., Kim, K.-Y., Kremer, G.E.O., Psenka, C.E., 2017a. Enabling non-expert sustainable manufacturing process and supply chain analysis during the early product design phase. In: Procedia Manufacturing, 45th SME North American Manufacturing Research Conference, NAMRC 45, June 4-8, LA, USA, pp. 1097–1108. https://doi.org/10.1016/j.promfg.2017.07.100.

Raoufi, K., Haapala, K.R., Kremer, G.E.O., Kim, K.-Y., Psenka, C.E., Jackson, K.L., 2017b. Enabling cyber-based learning of product sustainability assessment using unit manufacturing process analysis. In: Proceedings of the ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. ASME, August 6-9, Cleveland, Ohio, USA, pp. 38–48. https://doi.org/10.1115/DETC2017-68249.

Raoufi, K., Manoharan, S., Haapala, K.R., 2019a. Synergizing product design information and unit manufacturing process analysis to support sustainable engineering education. J. Manuf. Sci. Eng. 141, 021018–021032. https://doi.org/10.1115/1.4042077.

Raoufi, K., Park, K., Hasan Khan, M.T., Haapala, K.R., Psenka, C.E., Jackson, K.L., Kremer, G.E.O., Kim, K.-Y., 2019b. A cyberlearning platform for enhancing undergraduate engineering education in sustainable product design. J. Clean. Prod. 211, 730–741. https://doi.org/10.1016/j.jclepro.2018.11.085.

Rossi, M., Germani, M., Zamagni, A., 2016. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J. Clean. Prod. 129, 361–373. https://doi.org/10.1016/j.jclepro.2016.04.051.

Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Technol. Environ. Policy 16, 329–339. https://doi.org/10.1007/s10098-013-0629-z.

Seto, K.E., Panesar, D.K., Churchill, C.J., 2016. Criteria for the evaluation of life cycle assessment software packages and life cycle inventory data with application to concrete. Int. J. Life Cycle Assess. 1–13. https://doi.org/10.1007/s11367-016-1060-6.

Sharma, B., Steward, B., Ong, S.K., Miguez, F.E., 2017. Evaluation of teaching approach and student learning in a multidisciplinary sustainable engineering course. J. Clean. Prod. 142, 4032–4040. https://doi.org/10.1016/j.jclepro.2016.10.046.

Thinkstep, 2013. GaBi Software (accessed 8.5.17). http://www.gabi-software.com/america/index/.

Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J.W., Kara, S., Herrmann, C., Duflou, J.R., 2012. Toward integrated product and process life cycle planning—an environmental perspective. CIRP Ann. - Manuf. Technol. 61, 681–702. https://doi.org/10.1016/j.cirp.2012.05.004.

U.S. Bureau of Labor Statistics, 2015. Incidents rates for non-fatal occupational injuries and illnesses (accessed 9.12.15). https://www.bls.gov/news.release/osh2.t01.htm.

U.S. Bureau of Labor Statistics, 2017a. International Comparisons of Hourly Compensation Costs in Manufacturing, 2012 (accessed 18.5.17). https://www.bls.gov/fls/ichcc.htm.

U.S. Bureau of Labor Statistics, 2017b. Waste treatment and disposal - may 2016 OES industry-specific occupational employment and wage estimates (accessed 14.11.17). https://www.bls.gov/oes/current/naics4_562200.htm.

U.S. Census Bureau, 2018. City and Town Population Totals (accessed 29.5.18). https://www.census.gov/.

U.S. Energy Information Administration, 2017. SAS output (accessed 17.11.17). https://www.eia.gov/electricity/annual/html/epa_02_07.html.

U.S. Environmental Protection Agency, 2016. Municipal solid waste | wastes | US EPA (accessed 11.9.17). https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/.

US EPA, O., 2015. Studies, Summary Tables, and Data Related to the Advancing Sustainable Materials Management Report. US EPA (accessed 17.11.17). https://www.epa.gov/smm/studies-summary-tables-and-data-related-advancing-sustainable-materials-management-report.

Vargas Hernandez, N., Okudan Kremer, G., Schmidt, L.C., Acosta Herrera, P.R., 2012. Development of an expert system to aid engineers in the selection of design for environment methods and tools. Expert Syst. Appl. 39, 9543–9553. https://doi.org/10.1016/j.eswa.2012.02.098.

Wilhelm, M., Hutchins, M., Mars, C., Benoit-Norris, C., 2015. An overview of social impacts and their corresponding improvement implications: a mobile phone case study. J. Clean. Prod. 102, 302–315. https://doi.org/10.1016/j.jclepro.2015.04.025.

World Freight Rates, 2017. Freight calculator (accessed 9.8.16). http://worldfreightrates.com/freight.

Zhang, F., Rio, M., Allais, R., Zwolinski, P., Carrillo, T.R., Roucoules, L., Mercier-Laurent, E., Buclet, N., 2013. Toward an systemic navigation framework to integrate sustainable development into the company. J. Clean. Prod. 54, 199–214. https://doi.org/10.1016/j.jclepro.2013.03.054.

Zijp, M., Heijungs, R., van der Voet, E., van de Meent, D., Huijbregts, M., Hollander, A., Posthuma, L., Zijp, M.C., Heijungs, R., van der Voet, E., van de Meent, D., Huijbregts, M.A.J., Hollander, A., Posthuma, L., 2015. An identification key for selecting methods for sustainability assessments. Sustainability 7, 2490–2512. https://doi.org/10.3390/su7032490.

Zijp, M.C., Waaijers-van der Loop, S.L., Heijungs, R., Broeren, M.L.M., Peeters, R., Van Nieuwenhuijzen, A., Shen, L., Heugens, E.H.W., Posthuma, L., 2017. Method selection for sustainability assessments: the case of recovery of resources from waste water. J. Environ. Manag. 197, 221–230. https://doi.org/10.1016/j.jenvman.2017.04.006.