

A Win-Win Strategy to Integrate Sustainability Objectives in Product Design – An Educational Approach

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Abstract—Most existing educational design approaches focus on discipline-specific modules, while those based on a generic product concept rarely target sustainability goals. With the increasing interest in sustainability and education for sustainable development, it is necessary to rethink product design approaches to target both customer needs and community requirements for sustainability. The main goal of the integral design approach proposed in the present work is to create a broader picture that integrates the design process, life cycle analysis, and role of each design and life cycle player. A wider management scheme that sets a clear road map of the contribution of all players is introduced. This scheme is based on a win-win strategy between different players to promote mechanisms to enhance sustainability and minimize risks and socioeconomic footprints.

Keywords—engineering design, sustainability, life cycle analysis

1 Introduction

Achieving sustainability goals through engineering design depends on establishing practical common interests between designers, clients, and users, as well as governmental, industrial, and social entities. Thus there is a need to develop a product design approach that increases depth and effectiveness of the design process to promote sustainability objectives within the common interests of the product stakeholders. The new design approach should aim at establishing guidelines for effectively defining sustainability-related objectives in the early stages of the design process. It should also provide tools to assess and monitor the impact of a product/artifact on sustainability and help in selecting the best alternative design in the concept design stage of the designing process.

However, due to lack of information and limited understanding of the overall picture of the life cycle of the artifact and its impact on global societal sustainability, designers do not have the capabilities needed to address sustainability-related objectives. There is also a need to frame common interests between clients and sustainability-promoting entities. This should be carried out through educational design approaches that impact future decision-making tools. Nevertheless, most existing

educational design approaches focus on discipline-specific modules, while those based on a generic product concept rarely target sustainability goals.

The present work aims at defining a methodology to achieve sustainability goals by creating design objectives, means, and management plans to practically promote sustainability. This methodology mainly depends on tracking, measuring, assessing, and monitoring the flow of energy, material, and other sustainability-related factors.

2 Sustainability in engineering education

Sustainability has become an increasingly important point of concern for the society in general and the engineering profession in particular [1]. The origins of the debate about sustainable development have been associated with the publication of the report entitled ‘Limits to Growth’ issued by the Club of Rome in 1972 [2] and the United Nations’ Conference on the Human Environment held in Stockholm in 1972. Nevertheless, the origin of the concept can be traced back to 300 years ago, to the work of Hans Carl von Carlowitz on sustainable forestry in 1713 [3]. However, there is a general agreement among researchers that the World Commission on Environment and Development report of the year 1987 [4] has mainstreamed the concept of Sustainable Development (SD). The best-known definition of sustainable development is that mentioned in this report, stating the following: “SD is a development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”.

The Education for Sustainable Development (ESD) concept was first established in 1992 with a world-wide recognition of Agenda 21 and its chapter 36 on education, adopted at the United Nations’ Earth Summit in Rio de Janeiro [5].

In the past three decades, several associations and higher education institutions focusing on sustainability issues were established [6]. The earliest in this field can be traced back to the Talloires Declaration signed in 1990 by 12 founding members, and expanded over the years to include more than 500 signatories from 55 countries as by the year 2016.

According to a European Union research [7], over 80% of the product-related environmental impacts can be influenced during the design phase. As a result, there have been increasing calls for designers and clients to adopt more sustainable practices to help businesses reduce the environmental impacts associated with their products and services. Studies carried out from 1998 to 2006 show that, on average, for every ton of consumed products in the UK, 10 tons of fuel and materials have been used, which rises to 100 tons if water is included [7]. Consequently, it is crucial to integrate sustainability into existing industrial design practices and narrow the gap between the engineering design process and the impact of the artifact’s life cycle on sustainability.

There is general acknowledgment of the fact that design should be at the heart of the engineering curriculum, taking into consideration that design is one of the core activities that professional engineers have to undertake. Not only accreditation agencies, such as ABET Inc. and EUR-ACE, but also the professional engineers’ societies necessitate that the requirements for design be at the core of professional engineers’

education. For several decades, traditional approaches in teaching design within engineering courses have focused on discipline-specific modules. These approaches accentuate the need for detailed specification of components within the design process, and the textbooks reflect this by including detailed methodologies for components sizing. Recently, more product design approaches, involving the generation of a general product concept, and the steps that are involved in producing and choosing between competing design alternatives were introduced. Educational models such as project-based learning were also used.

The design process, depicted in Figure 1, starts with problem definition, which generates a set of revised measurable objectives and constraints and the management strategy for the whole design process. This stage is followed by concept design, which lists the functions of the artifact and the means to reach this function and design specifications. The preliminary design is used to test and evaluate the selected design according to modeling and prototyping. The final design is then optimized in the detailed design stage before communicating the detailed design to clients, customers, and managers.

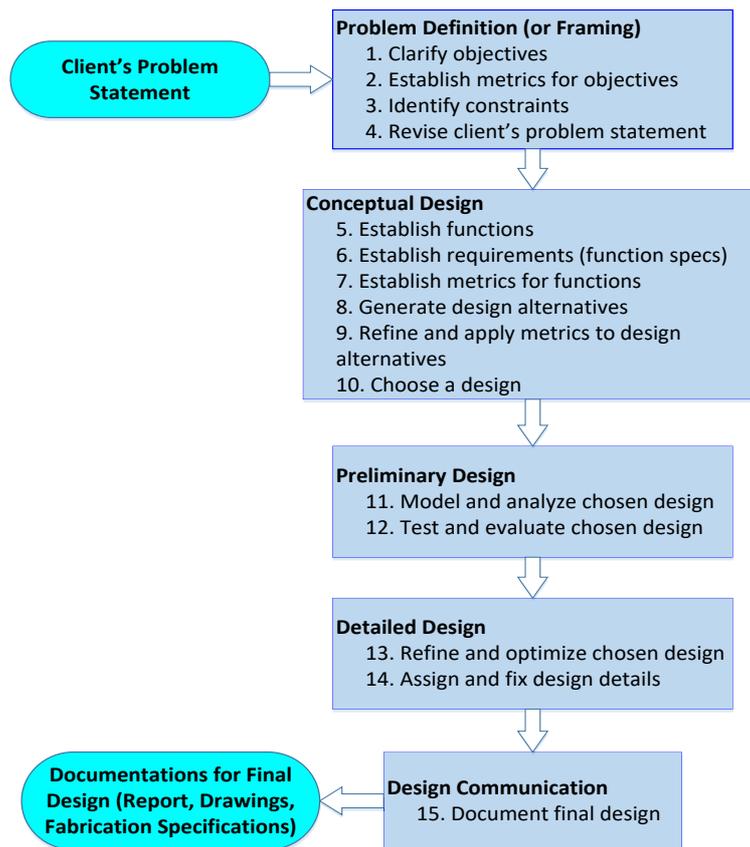


Fig. 1. The design process (modified from [8]).

The engineering design process plays a vital role in achieving design objectives. These design objectives are not limited to technical and financial issues only, but they should also be extended to cover environmental, social, economic, and cultural targets. The key players in the design process are the client, designer, and users, and the set of objectives should target common interests of the three players.

3 Life cycle analysis

Life cycle analysis is essential to embed sustainability measures in the design process and train future engineers to tackle sustainable development of the society. The life cycle of an artifact starts with the extraction of raw materials and delivery to the components' manufacturers. Components are then transported to the assembly factories and distributed to the end users where artifacts are operated and undergo maintenance. Finally, the artifact is considered a waste, which is either recycled or disposed. Figure 2 shows the main stages of the life cycle of an artifact [9].

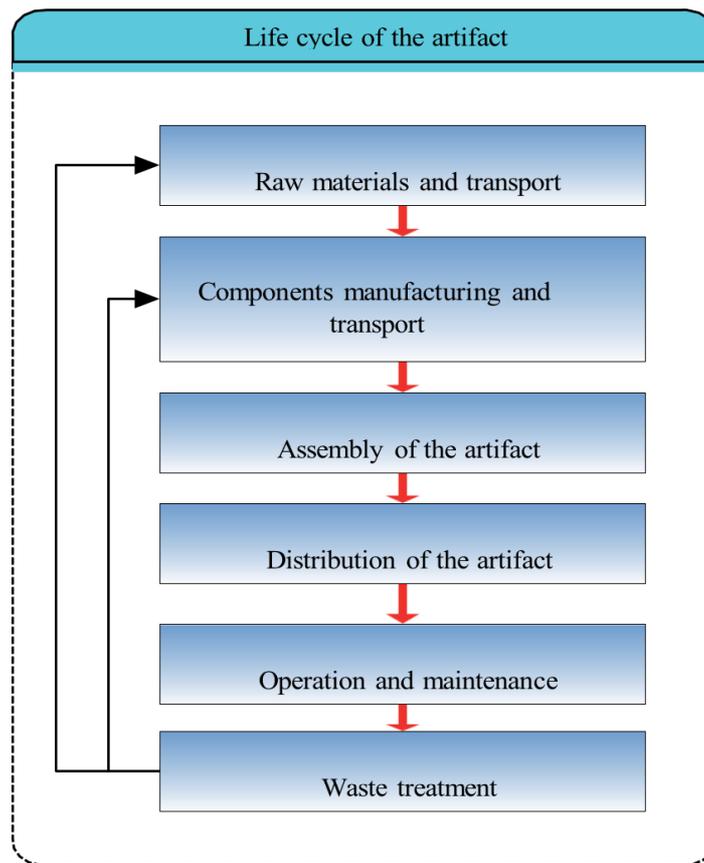


Fig. 2. . Life cycle of an artifact.

The engineering design process determines the expected life cycle of the artifact, from selection of the materials to the final waste treatment stage. Design objectives and selection of the best alternative to achieve these objectives can alter the artifact's life cycle.

There is a mutual interaction between the life cycle of an artifact and socioeconomic and environmental sustainability. The artifact's life cycle involves an ecological footprint, through energy consumption, water consumption, and waste disposal, and it also has a direct social impact on achieving comfort and high living standards, creating jobs, and affecting cultures. In addition to that, there is an economic impact for investments in its different stages.

Sustainability is not only related to achieving sustainability goals but also to achieving them through a sustainable robust process and the design process can control the entire life cycle to meet these goals.

4 Integral life cycle and design process overview

The engineering design process and the life cycle of the artifact have mutual impact, and this, consequently, impacts sustainability. Many players are involved in the life cycle, including the designer, client, manufacturer, governmental entities, social entities, and users of the artifact. Each of them plays a vital role in achieving sustainability goals.

In the engineering design process, the designer lists a set of measurable design objectives that reflect his understanding of the problem and the client's problem statement expressed in the RFP (request for proposal). These objectives could address the sustainability goals by assigning a higher relative weight to the sustainability-related objectives.

The client triggers the start of the design process through the problem statement that reflects his significant interests. He also plays an essential role in revising the design objectives with the designer. If the sustainability goals are evident in the client's statement, they will have a positive effect on the impact of sustainability.

While producing the artifact, the manufacturer contributes directly to its life cycle and related sustainability issues. Each step in the life cycle of the artifact consumes certain amounts of non-renewable energy resources and water. The products of each phase of the life cycle give rise to a measurable quantity of greenhouse gas emissions, water consumption, chemicals release, and socioeconomic impacts on workers and their jobs. Reducing the amount of greenhouse emissions and chemicals releases will reduce the ecological footprint of the artifact. Creating more jobs with minimum health risk will also enhance the economic and social impact on the community.

Governmental entities put a set of laws and regulations that may target the sustainability goals, either by minimizing the footprint of the product life cycle or by adding taxes to carbon price. Environmental laws and taxes regimes play an important role in promoting sustainability. On the other hand, governmental entities can easily map the inputs and outputs of each step of the life cycle and encourage or discourage different possible alternatives.

Social and non-governmental entities provide a remarkable impact on sustainability by monitoring governmental policies towards it, in addition to the socioeconomic impacts of the manufacturing facilities.

Finally, the users of the artifact play a vital role in promoting sustainability through their buying decisions selectivity and the actions they take towards recycling the artifact.

Rethinking the product design for sustainability is necessary. The primary goal is to create a broader picture that integrates the design process, life cycle analysis, and role of each design and life cycle player. It is also essential to introduce a more general management scheme that sets a clear roadmap for the contribution of all players. The efficient management scheme should be based on a win-win strategy between different players to promote mechanisms to enhance sustainability and minimize risks and socioeconomic footprints.

5 Managing sustainability data

Understanding the barriers to achieving the sustainability goals mainly depends on understanding the role of each player and their interest in creating a win-win strategy. The link between the central players mentioned above should be explicitly defined in the processes of artifact design and production.

The primary barrier is the lack of integrated management plan that assures the effective involvement of all players towards the sustainability goals. Poor communication between the main players also contributes to the barriers.

For each step of the artifact's production life cycle, the lack of ecological footprint data and socioeconomic data makes it difficult for the designer to choose alternative life cycle steps that have important positive impact on sustainability. The designer needs some indices to compare between alternatives for the same phase of the life cycle. These indices must reflect the following:

- Quantity of greenhouse emissions per artifact;
- Amount of chemicals produced per artifact;
- Amount of water consumed for producing an artifact;
- Amount of recycled waste per artifact;
- Percentage of renewable energy used per artifact;
- Number of workers required to produce an artifact;
- Percentage of occupational health and safety risk issues per artifact.

Lack of such information prevents the designer from choosing the best life-cycle alternatives for an artifact to achieve sustainability goals. Governmental entities are thus required to provide the designer, as well as the society as a whole, with sustainability-related data and the indices mentioned above for each step of the life cycle. In addition, communication between the designer and the governmental entities could be enhanced by creating an accessible pool of data that reflects the indices for alternative life cycle solutions.

Constructing the pool of data mainly depends on developing an accountability system for all the facilities and factories that may contribute to production of any artifact or component. The indicators of sustainability should be assessed for each facility or factory. These data should be maintained and updated and remain open to the public:

- Access to the facilities and factories sustainability indices;
- Labelling the artifact with a sustainability index.

Labeling the artifact with a sustainability index will allow the user to share the responsibility towards sustainability, while the sustainability index will reflect the total outcome of the artifact's life cycle. The designer and the client can thus label the artifact with the life cycle index to promote its selling and marketing.

6 Creating a financial value for sustainability

Creating a financial value for sustainability is a common interest of key players, and several arrangements could contribute to that:

- Constructing a tax reduction regime for the manufacturers according to their use of renewable energy;
- Adding a vulnerability cost related to the emission of greenhouse gases, water consumption, chemicals released into the environment, and health effects on workers;
- Constructing a tax reduction regime for the quality of managing workforce;
- Providing the client and the designer with the tax reduction information for alternative life cycles;
- Constructing a tax reduction regime for the recycling facilities;
- Creating a channel for users to sell used components and establishing a hub between the users and the recycling facilities.

The challenge of creating a financial value for sustainability mainly depends on the policies and regulations and the commitment of the society towards it. The financial value of sustainability should be compared to the financial value of repairing any harm associated with anti-sustainability actions. Establishing a metric for measuring this value will be of great benefit to reveal the financial value of sustainability. The financial value of anti-sustainability performance depends on several components:

- Government expenditure to mitigate the effects of climate change and global warming, including evacuation, reallocation, compensation for loss of properties, and similar actions;
- Increase of total expenditure in health care programs due to ecological footprint of unsustainable industrial growth;
- Expenditure in rebuilding the environment including third-party liability and insurance agreements.

Satisfying customer needs, being the main target of designers, may differ from satisfying community needs. Most design methodologies, such as the six-sigma method, for example, consider defects in the design and production processes to be related only to critical-to-quality (CTQ) issues. The quality is defined according to customer satisfaction regardless of the vulnerability of the production process and/or long-term risks associated with anti-sustainability practices in producing the artifact. Although minimizing waste is one of the six-sigma method goals, being a customer satisfaction driven method may cause some unsustainability implications.

As mentioned in [10], six-sigma is a disciplined, data-driven methodology to eliminate defects by constantly striving towards six standard deviations between the mean and the nearest specification limit in any process. This goal is accomplished through the use of two six-sigma sub-methodologies: DMAIC which targets improvement of an existing process that falls below specification and DMADV which is used to develop a new process at six-sigma quality levels.

Applying the six-sigma method could ensure minimizing defects per a million opportunities. This will help ensure customer satisfaction. Nevertheless, the need for defining community needs and considering them as additional customer needs should also help in reducing defects related to the sustainability issue. The role of the management team is to assure minimizing defects about both customer needs and community requirements. Emission of greenhouse gases in the production process, for example, could be improved to reduce emissions and related carbon taxes.

7 Teaching engineering design for sustainability

During the engineering design courses, students follow the steps of the design process for a given client statement. In the problem definition stage, a set of design objectives are developed, including sustainability-related ones such as environmentally benign objectives that are difficult to be measured in the absence of suitable metrics due to lack of information about the artifact's life cycle aspects. In fact, creating metrics for sustainability objectives depends on the availability of information, including:

- Sustainability impact of one component through its expected life cycle, including greenhouse gas emissions per produced component;
- Socio-Economic footprints of producing one component through different life cycle options and alternatives.

Due to lack of this information, students cannot address or monitor the impact of designing an artifact on sustainability. In the concept design phase students develop a set of functions and different means to realize these functions. The selection of the best function-means combination depends on meeting the objectives addressed in the problem definition stage, and selecting a particular means may lead to selection of a different product life cycle with different impacts on sustainability. The presence of information about available production life cycles helps the students compare between different means to achieve sustainability goals.

In the preliminary design stage, students model the selected means combinations to test the performance of the artifact. Computer software and prototyping help the students test the performance of the artifact and calculate the percentage attainment of the objectives under consideration. Prototyping may not reflect the complete life cycle of producing an artifact, and it is not easy to assess the sustainability goals by testing the artifact.

8 Rethinking the educational approach

It is important to integrate the design process of an artifact with its production life cycle and integrate other players in the management plan, including the manufacturer and governmental entities. Constructing sustainability indices for the production life cycle and the artifact's components and maintaining a pool of data are both required to unify the efforts toward sustainability. Students should have access to data related to life cycle sustainability and recycling. This will help them satisfy not only the needs of the client and the users but also environmental, societal, and economic needs. The accessibility of data will help design teams to state measurable sustainability-related objectives and to select the less harmful alternatives.

Engineering educational programs target social, economic, and environmental outcomes. Due to lack of practical design experience and their impact on sustainability, most programs just address the issue of sustainability as a remedial approach. Restructuring the design process to include the life cycle of the artifact will assist the goals of the program to achieve a higher level of learning integrated with higher exposure to sustainability issues.

A proposed integrated engineering design process and the product life cycle of the designed artifact are shown in Figure 3. The integrated diagram shows the flow of information between different players to manage and combine the design process and the product life cycle. Table 1 shows the main differences between the traditional design process and the combined design-life cycle approach. Introducing the design for sustainability will have a significant impact on building cultures of engineers. Students can track not only the customer needs but also the community needs through constructing measurable objectives. They will have an opportunity to practice sustainability knowledge management and more efficient quality methods that achieve the satisfaction of both customers and the community.

Selecting the design alternative based on measurable sustainability objectives will help them understand how to control the unsustainability threats and become part of future sustainable development strategies. The combined design-life cycle approach was recently introduced in a project-based design course for freshmen to help students identify measurable sustainability objectives instead of stating vague points such as being “environmentally benign”, “use of recyclable materials”, etc. This also helps students better understand the role of different players in promoting sustainability in a manageable practical way.

9 Combined design-life cycle pedagogical approach

Two courses have been used to implement and assess the new combined design-life cycle approach starting Spring 2018, namely, “Introduction to Engineering Design II” and “Nuclear Engineering Senior Design Project.” Both courses are project-based active cooperative design courses [11-12].

Table 1. Comparison between the design process and the combined design-life cycle approach

Design concern	Design process	Combined design-life cycle
Players	Customer, client, designer	Customer, client, designer, manufacturer, governmental entities, social entities
Charter	The project charter includes general sustainability-related objectives	The project charter includes specific, measurable sustainability-related objectives
Critical-to-quality determinant	Addresses customer needs	Addresses both customer and community needs
Design optimization	Tracking the added value to the customer	Tracking the added value to both customers and the community
Selecting alternatives	Based on qualitative sustainability-related objectives	Based on quantitative sustainability-related objectives
Carbon cost	Cannot be tracked	Can be tracked
Socioeconomic impact	Cannot be measured	Can be measured
Sustainability knowledge management	Not applicable	Applicable

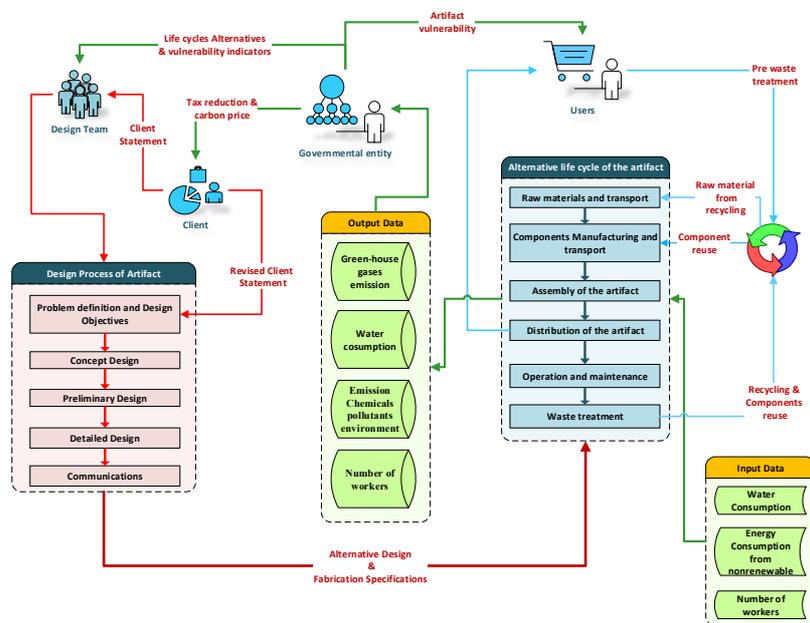


Fig. 3. Combined design-life cycle diagram

Introduction to Engineering Design II is a college core course, which is mandatory for all engineering disciplines. A rubric shown in Table 2 is used to assess ABET outcome #2 by addressing key performance indicators (KPIs) that reflect the attainment of the outcome. According to the ABET definition of outcome #2, the student work samples should demonstrate the student's ability to apply the engineering design process to produce solutions that meet specified needs, taking into consideration public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Table 2. KPIs for ABET outcome #2.

Design stage	Key Performance Indicators (KPIs)
Problem definition	The student should be able to clearly state the problem to be solved; identify potential customers and stakeholders; identify customer needs and constraints; identify applicable realistic constraints such as economic, environmental, social, political, and ethical ones, health and safety, manufacturability, and sustainability; convert needs and constraints to clear and measurable design objectives and specifications; describe the expected global, cultural, social, environmental, and economic impact of the design.
Design strategy	The student should be able to develop a workable design strategy, including a plan of attack, decomposition of work into subtasks, and development of a time plan; identify design functions; identify means to carry out each function taking into account technical and realistic constraints; develop a compelling business case and project charter.
Conceptual design	The student should be able to develop selection criteria based on design objectives, specifications, and constraints; develop several potential solutions such that each one meets the minimum requirements of the selection criteria and pertaining realistic constraints; use a decision analysis technique to select the best baseline design alternative.
Preliminary design	The student should be able to carry out modeling and discipline-specific analysis of the selected baseline design to ensure desired strength, stiffness, stability, and safe operation; determine shapes and assemblies of all components taking into consideration human-machine interface issues and aesthetics of the final product; select the appropriate material and standard equipment; carry out proof of concept using scale-down models, prototypes, and/or computer simulations; evaluate and refine the design using successive build and test iterations; consider reliability, maintainability, failure and effect analysis, and life-cycle sustainability; update schedule, budget, and business case.
Detailed design	define practical measures of effectiveness; identify engineering standards that will be used in the detailed design of the selected alternative; carry out a detailed design of the selected alternative; perform iterative analysis to achieve potential improvements; carry out an impact analysis of the solution including global, cultural, social, environmental, and economic dimensions.
Documentation	The student should be able to communicate final design and design procedure using necessary documentation and supporting material, including professionally prepared engineering drawings, technical specifications, and user manuals (if applicable).

As shown in Figure 4, instead of considering the classical design process, the combined design-life cycle approach is introduced to the students before the start of design activities. Some KPIs are used mainly to assess the students' attainment of design for sustainability issues. These KPIs are as follows:

- Identify applicable realistic constraints;
- Convert the needs and constraints to clear and measurable design objectives and specifications;
- Describe the expected global, cultural, social, environmental, and economic impact of the design;
- Carry out impact analysis of the solution, including global, cultural, social, environmental, and economic dimensions.

The first three KPIs are used to evaluate the students' attainment of outcome #2 in the problem definition stage, while the fourth is mapped in the detailed design stage. These KPIs are used to monitor the effect of introducing the combined design-life cycle approach to achieve sustainability goals via engineering design. Table 3 shows the improvements in attaining these KPIs before and after Spring 2018.

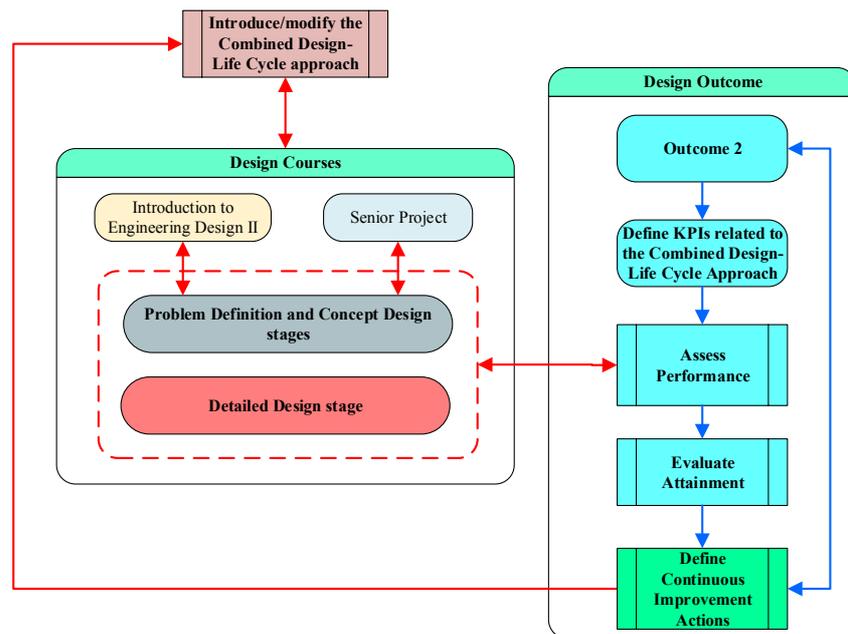


Fig. 4. Pedagogy of the combined design-life cycle approach.

In the Introduction to Engineering Design II course, students are introduced first to the design process, and teams are requested to select their project to solve a current or potential issue. After instructor's approval, students start to apply the design process, and by the end of the course they deliver an artifact.

Introducing a combined design process-life cycle approach at the beginning of the course has a significant impact on shaping the students' mindset towards sustainability of the community. Statistics have been gathered to compare the percentage of projects related to sustainability and to target the design to related issues. After introducing the combined design-life cycle approach, this percentage increased remarkably from 20% to 63%. In Spring 2018 most of the students' projects targeted sustainability issues; they included water saving, renewable power generation, power saving, and artifacts for people with special needs. Moreover, manufacturability became a major concern in the designed artifacts.

In the senior project, a client statement was delivered to the students to design a nuclear reactor for a mission to Mars. Students used more specific constraints that reflect their understanding of the combined design-life cycle approach and its effects on sustainability. Although the reactor is proposed to generate power on Mars, its components are to be manufactured on earth. The constraints stated by students were related to nonproliferation, using carbon dioxide for cooling instead of water, and using design components with high reliability and less produced greenhouse gas emissions during manufacturing.

Table 3. Attainment of outcome #2 before and after introducing the concept in Spring 2018.

KPI	Before Spring 2018	After Spring 2018
Identify applicable realistic constraints such as economic, environmental, social, political, and ethical ones, health and safety, manufacturability, and sustainability.	Constraints are general and did not track all aspects of sustainability. Examples: <i>Environmentally Benign.</i> <i>Promote Sustainability.</i>	Constraints are more specific and track many aspects of sustainability. Examples: <i>Create more jobs.</i> <i>Consume less water during manufacturing and use.</i> <i>Consume less fossil fuel during manufacturing and use.</i> <i>Use recyclable materials.</i>
Convert the needs and constraints to clear and measurable design objectives and specifications.	Metrics are qualitative, such as: <i>Low, Medium, and High.</i>	Metrics are quantitative, such as: <i>Water consumption should not exceed 1 liter per 10 manufactured artifacts.</i>
Describe expected global, cultural, social, environmental, and economic impact of the design.	Impact of design is expressed in general terms and does not reflect community needs.	Impact of design is specific and related to community needs.
Carry out an impact analysis of the solution including global, cultural, social, environmental, and economic dimensions.	Impact analysis is qualitative and, in many cases, could not be measured to reflect achieving sustainability-related goals.	Impact analysis is quantitative and reflects specific factors such as the number of jobs per artifact and total water and power used per manufactured artifact.

Some perceived problems needed to be taken into consideration. Students complained about the lack of data regarding water and power consumption in producing artifacts. Although many artifact components are not manufactured locally, more collaboration is needed between our academic institute and the local industrial and governmental authorities to build a sustainability database for future designers.

On the other hand, some projects exceeded the target cost per produced artifact as compared to alternative designs that target the same problem. This included high cost

of using solar panels to empower the generator. Students were introduced to carbon emission trading, climate change, and other sustainability issues. Nevertheless, collaboration between governmental authorities, industry, academia, and the public is still a far reached goal.

10 Conclusion

A new integrated artifact design process and product life cycle methodology is developed to permit practically achieving the sustainability goals. This product design methodology allows future designers to efficiently satisfy and implement the sustainability goals of the society while satisfying the classical client/customer needs. Two project-based active cooperative learning design courses have been used to implement and assess the new approach starting Spring 2018. Results obtained indicate better attainment of performance indicators related to sustainability with better awareness of sustainability issues. Nevertheless, collaboration between governmental authorities, industry, academia, and the public is still unachievable in order to reach a win-win situation. But preparing future designers and industry leaders through integrating the proposed approach in design pedagogy is expected to reduce the current gap. This will support the current effort of establish cooperation between different key players.

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