# SUSTAINABLE SOFTWARE ENGINEERING: CURRICULUM DEVELOPMENT BASED ON ACM/IEEE GUIDELINES

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**Abstract:** Climate change risk and environmental degradation are the most critical issues of our society. Our technology influenced daily lifestyle involves many software and apps which are used by large society and their use is increasing than ever before. Sustainability is a significant topic for future professionals and more so for software engineers due to its impact on the society. It is significant to motivate and raise concern among students and faculty members regarding sustainability by including it into Software Engineering (SE) curriculum. This paper presents how sustainability can be included in various courses of the SE curriculum by considering ACM/IEEE curriculum guidelines for SE curriculum, literature review as well as various viewpoints so that SE students can attain the knowledge of sustainable software engineering. It also includes assessment of key competences in sustainability for proposed units in SE curriculum.

**Key words:** Sustainability, Sustainable Software Engineering, Curricula, Curriculum Development, Software Engineering.

## 1. INTRODUCTION

Software has become an integral part of our everyday life and gradually impacting human being and society. The current industrial growth and adoption of ICT more and more threaten the future of sustainability and cause environmental issues [1, 2]. Sustainability is becoming a crucial concern in information technology and software towards our future. Sustainability management is one of the upcoming movements in the 21st century but, until now, it could not get as much attention as it should be by software engineering. Furthermore, ICT has a major role in sustainable development, specifically in software and green computing [3]. It is important that environmental concerns should be addressed in the development, implementation and operation of softwares. In this respect, the contribution of ICTs for energy and environmental sustainability has attracted attention of both researchers and professionals [1] as software contributes significantly to every aspect of our lives.

Dick et al. [4] proposed first definitions for sustainable software and sustainable software engineering in 2010 which has become the foundation for later explanation. According to Ray et al. [5], the term 'sustainable' applies to both the longer life and greener aspects of software. Brooks et al. [6] found three dimensions to sustainability: environmental, economic and social. These are interrelated and these should be selected in such way towards optimum arrangement and alliance. Sustainable software is defined as the software whose direct and indirect negative influence on economy, society, human beings, and environment that result from development, implementation and usage of the software are minimum [7]. Green software generates the minimum amount of e-waste during its operation and development [8].

Sustainable software engineering is developing software through a sustainable software engineering process which meets sustainability purpose in considering human beings, society, and environment from software implementation and operations. Sustainable software

engineering (SSE) is based on the foundation of designing and developing software by taking into consideration various dimensions of sustainability which are economic, environmental, individual, social and technical ones [9, 10]. A number of recent studies were performed to find out how sustainability is identified and included in software engineering process towards sustainable software development [11] which can reduce its environmental impact on society.
In many research studies, sustainability and energy efficiency are observed as crucial expertise for future software engineers [12-15]. However, a recent survey by Manotas et al. [16] of 3860 software professionals from Google, ABB, IBM and Microsoft reveal that present higher educational programs do not prepare these professionals to undertake sustainability, although they are inclined to learn about it [16]. Also in their survey they noticed extensive significance of greenability and sustainability. Another study on teaching sustainability in software engineering also supports that sustainability is not included in the software engineering (SE) courses and the present focal point is on energy efficiency issues [12-14]. Scientists have recently recognized that issue related to sustainable software engineering should be part of the discipline towards future of human beings..
Software engineers presently perform many tasks that may ensure sustainability, for instance, Agarwal et al. [3] consider the capabilities and gain of green software and suggested more efficient algorithms will take less time to execute and it leads to sustainability. However, sustainability is considered as an additional feature in many software projects as software engineers are tied by time-to-market pressure and are often less inclined to administer sustainable methods and techniques [17]. For now, apart from cost, factors such as environment, social and human sustainability are required to be considered in any planning, implementation and running initiative related to software systems [18]. Organizations are now beginning to understand that not only cost efficiency, but also long-term and continued prosperity can be gained from sustainability. Therefore, apart from factors like cost, time, and quality, sustainability has also become one of the significant objectives to achieve when developing, configuring, operating and working software systems. Therefore, there is a need to support the transition to sustainability and incorporate it into software systems and other underlying business processes [19].
Green and Sustainable Software Engineering (GSSE) is the art of developing green and sustainable processes [20]. Sustainable software process takes care its objectives and impact on human beings, society, economy, and environment that derive from its solution and deployment [21]. Presently, the effect of IT on sustainable advancement – in particular, on software - is an emerging issue due to global concern on climate change. Education sector has to contribute significant role in ensuring future software engineers understand sustainability dimensions and integrate it into SE curriculum. Gibson et al. [22] supported that educational sector has an important part to play towards future software professionals who can understand sustainability issues in software development. Therefore, there is need to integrate sustainability in Software Engineering discipline curricula. Gibson et al. [22] further observed that it is mentioned just once even in ACM/IEEE guidelines and twice in SWEBOK with respect to software economics area. They argued in current scenario there is need of sustainable software engineering education guidelines and components required in such curricula for future software engineers. Therefore, this paper advances effort in this direction. This paper extends our previous work [23] by following ACM/IEEE guidelines for SE curriculum along with authors' long academic experience to first list and categorize relevant SE courses offered in SE programmes. Later sustainability related units are introduced in existing SE courses followed by assessment of these units with respect to key competences in sustainability.
The rest of the paper is organized as follows: In Section 2 related work to describe relationship between software quality and sustainability along with initiatives to include sustainability in SE higher education programmes are presented. Section 3 introduces curricula development on sustainable software engineering. Section 4 includes points of discussion. Finally, it concludes along with a brief viewpoint for future direction.

## 2. RELATED WORK

### 2.1. Software quality and sustainability

Sustainability is usually referred as a non-functional requirement in software systems [19]. Non-functional requirements are also known as quality requirements. Interestingly organizations have recognized sustainability in quality issues, for instance, maintainability, usability, agility to update but could not include it due to time and budget constraints in software project management [24].

Amri and Bellamine Ben Saoud [25] proposed Generic Sustainable Software Star Model (GS3M) to examine sustainable software and noticed some studies consider sustainability as a part of quality, while others observe quality and sustainability as different concepts and use quality attributes to support sustainability. Calero et al. [26] and Calero [27] applied the hypothesis that sustainability is a factor of the software quality, thus, unified it as a quality characteristic with three other sub-characteristics: energy consumption, resource optimization and perdurability. Calero [26] also noticed that operationalization in this way includes introducing some modifications in the ISO quality standard ISO/IEC 25010 to support sustainability as a quality component. Albertao et al. [28] and Kern et al. [29] also identified quality attributes to define sustainability. Interestingly, Albertao et al. [28] formulated software project sustainability characteristics into development-related features (modifiability, reusability, portability, and supportability), usage-related attributes (performance, dependability, usability, and accessibility) and process-related attributes (predictability, efficiency, and project's footprint). Kern et al. [29] endorsed a quality model for sustainable software which construct sustainability criteria into three categories: common quality criteria which are well-known and standardized issues (such as efficiency, reusability, modifiability and usability); directly-related benchmark (such as energy efficiency, framework entropy, functional types, hardware obsolescence, adaptability, feasibility, accessibility, usability and organization's sustainability); and indirectly-related yardstick that demonstrate effects of software on other products and services and cover the effects of use as well as systemic effects such as the fit for aim, elegance and reflectivity.

### 2.2. Sustainability in SE curricula

Sustainable software engineering is getting limelight among professionals and researchers [7, 15]. However, researchers have noted that sustainability is under-represented in the curricula [11], hence the need to include the concept of sustainability in the university curriculum of computer science, software engineering and information systems. Mann et al. [30] presented a framework for educators to design sustainability-centred education while Sammalisto and Lindhqvist [31] observed on the integration of sustainability in higher education based on different sustainability dimensions like environmental, economic, social and technical. Gibson et al. [22] studied requirements engineering significance in ensuring sustainability in software development in UK. Groher and Weinreich [32] studied how sustainability is perceived by software professionals in projects and found that professionals mainly linked it with maintainability and extensibility of software. Renzel et al. [33] contributed a detailed strategy of projects for sustainable software engineering.

Chitchyan et al.[34] reviewed sustainability related with Software Product Line Engineering (SPLE) and suggested main focus on technical and social sustainability issues along with social sustainability related to organization. Lutz et al. [35] also specified characteristics of sustainability in SPLE. Mohankumar and Anand Kumar [36] proposed green based model for sustainable software engineering. Recently Penzenstadler et al. [37] proposed a blueprint for a course on software engineering for sustainability.

### 2.3 Key competences in sustainability

Major challenges in the incorporation of sustainability in the university education are in the field of teaching [38-41]. Therefore identifying key competences in sustainability may be the first step towards sustainability inclusion in higher education [42]. Wiek et al. [43] defines competence as a functionally linked complex of knowledge, skills, and attitudes that enable

successful task performance and problem solving. Competence is a quality developed through practice and not an end state [44].
In 2002, Organisation for Economic Co-operation, Development (OECD), identified key competencies needed for an individual to lead an overall successful and responsible life and for contemporary society to face present and future challenges [45].The OECD key competencies are divided into three categories: subject and methodological, social and personal. The OECD study on key competencies and comprehensive educational objectives reveals sustainability's significance for the future [46]. Subsequently, multiple studies have introduced key competencies for education for sustainable development in the formal education sector to help assess the learning outcomes of pupils and an overview is provided in the Table 1.

Table 1. Key competencies for education for sustainable development

| | **Key competencies** |
|---|---|
| De Haan [47] | Foresighted thinking;<br>Interdisciplinary work;<br>Cosmopolitan perception, transcultural understanding and cooperation;<br>Participatory skills;<br>Planning and implementation skills;<br>Empathy, compassion and solidarity;<br>Self-motivation and motivating others;<br>Distanced reflection on individual and cultural models. |
| Barth [48] | Self-motivation;<br>Capacity for empathy, compassion and solidarity;<br>Reflection on individual;<br>Motivating others;<br>Participatory skills;<br>Foresighted thinking;<br>Interdisciplinary work;<br>Cosmopolitan perception, transcultural understanding and co-operation;<br>Reflection on cultural models;<br>Planning and implementation. |
| Sleurs [49] | Values and ethics;<br>Emotions;<br>System thinking;<br>Knowledge;<br>Action. |
| Roorda [50] | Responsibility;<br>Emotional intelligence;<br>System orientation;<br>Future orientation;<br>Personal involvement;<br>Action skills. |
| Wiek [43] | Interpersonal;<br>Anticipatory;<br>Systemic working;<br>Normative;<br>Strategic. |
| Giangrande [51] | Intrapersonal;<br>Interpersonal;<br>Future thinking;<br>Systems thinking; |

| | |
|---|---|
| | Disciplinary and interdisciplinary;<br>Normative and cultural;<br>Strategic. |

This study will assess proposed units integrated in SE courses based on the approach by Giangrande et al. [51] and Wiek et al. [43]. Wiek et al. [43] proposed a framework of key competencies in sustainability by categorizing competencies into clusters which was found to be useful by Giangrande et al. [51] who further extended the framework.

## 3. SUSTAINABLE SOFTWARE ENGINEERING CURRICULA OUTLINE

Sustainability knowledge should be integrated in a curriculum by linking the concept of sustainability to a particular field of study [31] rather than offering separate courses on sustainability. Considering the suggestion, figure 1 presents an approach to integrate sustainability education in SE curriculum. First, ACM/IEEE guidelines for SE curriculum development has been followed to include an initial set of courses SE students should take in order to later practice their profession successfully. ACM/IEEE guidelines 2014 for SE curriculum development consists of a set of SE competencies that every SE graduate must know and provides guidance to academic institutions and accreditation agencies about the knowledge and skills fundamental to software engineering education [52]. Subsequently, additional courses have been included to reflect the current SE education based on the advancement in SE education. Further, the final set of courses are organized in different categories based on the structure of academic programs in the major universities: Fundamental courses of sustainability; core SE courses; technical electives; non-technical electives; project-based courses and industrial practice. Finally, the information gained from literature review along with authors long academic experience in SE discipline facilitated the inclusion of sustainability competence in the form of flexible units within existing courses of SE curricula.

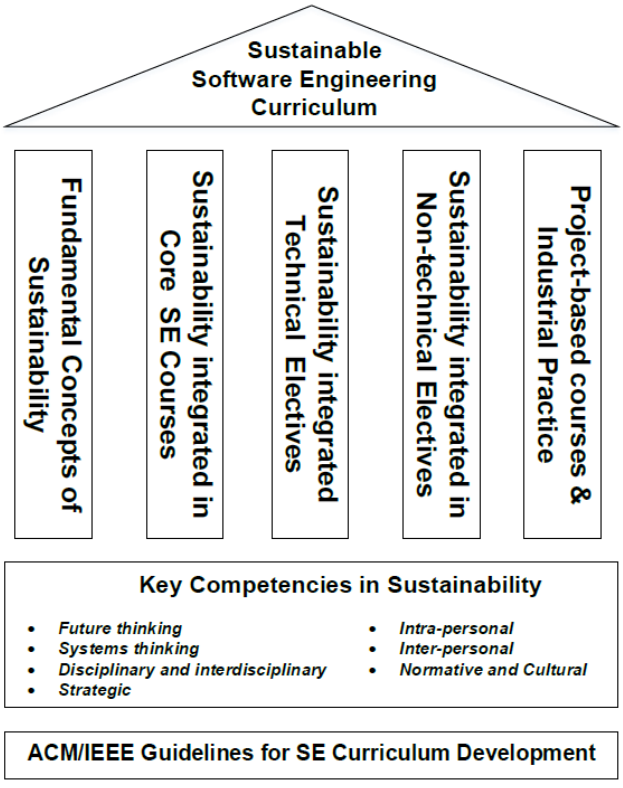


Figure 1. An approach for sustainability inclusion in Software Engineering Curricula

The program should include the following units in the existing courses of the SE curricula so that students can get sufficient exposure to different components of sustainability issues in software development life cycle.

### 3.1 Fundamental concepts of Sustainability

***Sustainability Theory:*** Understanding the concept of sustainability in software and its various parts, so as to be applied to different stages of software development and deployment and operations stages in the organization.

***Sustainability Analysis:*** Understanding of rigorous analyses of sustainability issues in software development, from cost estimation to project management, software maintenance and evolution. It should include, in general, software systems to be developed from a comprehensive perspective to sustainability and long-term consequences on the environment and the society.

### 3.2 Core SE courses

***Software Requirements Engineering:*** Sustainability inclusion in requirements elicitation and analysis process, understanding of sustainability to apply in requirements elicitation process which includes stakeholder modelling, goal modelling, process modelling, and system modelling.

***Software Architecture and Design:*** How to apply sustainability in different kinds of software architecture and design issues, for instance database, human computer interaction, and modules interconnection, and in software architecture development.

***Human-Computer Interaction Design:*** Human Computer Interaction (HCI) is part of many information technology and software applications. Therefore, sustainability issues should be included as component in this course. Nyström and Mustaquim [53] suggested that persuasive system design can influence users to behave and live more sustainably and should be related to sustainability of the environment. Sustainable HCI should address WCED's (World Commission on Environment and Development) sustainability view "… that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [54]. Sustainable system design principles can be included in Human Computer Interaction (HCI), software system design, and industrial software development project curriculum.

***Software Modelling and Analysis:*** Stakeholders requirements modelling towards understanding how to incorporate sustainability issues into the scenarios of requirements with the help of UML diagrams. It also includes trade-offs, conflict resolving in the requirements of different stakeholders, and system modelling by using available tools from sustainability perspective for complex software systems.

***Software Process:*** Software process improvement should include sustainable software engineering process, Agile and DevOps approaches. Also knowledge of applicable tools, methods and technologies to facilitate the sustainable software engineering process. Energy and resource utilization are the main components that impact sustainability and, therefore, should be determine from the initiation of the process. Eco-design of digital services towards ensuring reducing environmental impacts to develop digital services that are more sustainable consume less resources and energy and produce less waste. Further knowledge of relevant tools, process and technologies to facilitate the sustainable software development process.

***Software Verification and Validation:*** An optimized approach in ensuring sustainability in software engineering in software verification and validation process including different types of testing and operation of the software product. Specification systems and automated verification tools can be helpful in this regard.

***Software Quality Assurance:*** Software process improvement and quality assurance control, and operation of the software product. Configuration management tools and software inspection tools. Knowledge of standards of eco-design (ISO 14006, ISO 14062).

***Software Project Management:*** It includes planning phase, controlling phase, of sustainability activities along with sustainability policies to ensure an efficient process. Appropriate project management tools and agile methods management tools can facilitate in ensuring sustainability practices in software project management. Eco-design of digital services towards ensuring reducing environmental impacts to develop digital services that are more sustainable consume less resources and energy and produce less waste.

***Software Construction and Evolution:*** Software evolution is continuous process. Refactoring tools, automated testing tools, configuration management tools along with project management tools aid in ensuring sustainability in software construction and evolution.

***Software Security:*** Security and safety during the development of complex software systems is crucial. So security and safety are now integral part of he set of non-functional requirements which leads to software quality. ISO/IEC 25010:2011 included safety as an explicit characteristic in software while ISO/IEC 9126-1:2001 ensures security in software. Safety and security are called out and treated specifically because they are significant characteristics. Penzenstadler et al. [55] supported that the same is true for sustainability, specifically the dimension of environmental sustainability, and there is need to find suitable means to analyze, support, verify, and validate sustainability requirements in software engineering.

### 3.3. Technical Elective Courses

***Internet of Things (IoT):*** IoT has the ability to combat climate change and towards green environment. It could impact the sustainability in different areas such as use of water and energy efficiency. According to World Economic Forum IoT could be game changer for sustainability [56]. IoT helps in applying waste management strategies and in circular economy. IoT deployments can help in addressing many SDGs of UN. IoT technology can have tangible benefits to sustainability [56]. Many IoT initiatives may lead to accomplish sustainability in future [57]. So, students should be aware of such IoT applications which can apply to achieve sustainability as cases studies, white paper, discussion, seminar etc.

***Cloud Computing:*** Cloud computing provides more efficient use of computing power and is advantages for environmental sustainability. Application of cloud computing to ensuring social, business, and environmental sustainability. It can include discussions, case studies, seminar, projects, company visit etc.

***Web and Mobile Systems:*** Sustainability and page speed are correlated. When your website runs more efficiently it requires less processing power thus less energy and lower carbon footprint [58]. Also, sustainable design is efficient and accessible. Sustainable mobile apps and its users may contribute to achieving environmental goals and mobile devices are an enabler for sustainable actions due to its huge potential for scalability [59]. Mobile applications that have even a little effect on resource efficiency or the reduction of greenhouse gas emissions could result in a greater impact as these are used in daily life [59]. This can include concepts on social software interface with sustainability issues, green software development and usage practices, promote technologies, development frameworks and tools which facilitates sustainability in web and mobile systems development. These could be included as real life projects, cases studies, seminar and lectures from industry practitioners.

***Sustainable Data Center****:* Green data centers or sustainable data center as it will help in reducing carbon footprint, design and deployment of data store and applications to operate in

energy-efficient ways. Therefore, it should include real life case studies, seminar and discussions that how sustainability can be incorporated in this regard.

***Tools for Software sustainability:*** Tools must be introduced to assist different stages of software development (requirements, design, testing, configuration management etc.) towards ensuring sustainability. This can be a part of a sustainable or green software engineering laboratory program.

### 3.4. Non-technical Elective Courses

***Global Professional Practice/Social Responsibility:*** Global professional practice should include environmental issues related with software engineering products, uses and how carbon foot print, CO2 emissions, global warming is matter of concern and students should be aware and about its consequences for society. These can be included as case studies, seminar, group discussion to analyze environmental degradation cases and towards exploring mitigation plan, identifying global environmental challenges, sustainable software, energy management, Green computing standards in context of software applications.

### 3.5. Project-based Courses and Industrial Practice i.e. internships

***Project based courses:*** Most of the universities have final year projects or thesis for students to explore real world challenges. Universities sometimes also require their students to do industrial internships of one to two months so that students can get experience in professional projects in real settings. Sustainability can be included as a learning outcome for such courses. Projects involving sustainability in software engineering during summer internships or such mini projects as part of the course.
The following table 2 presents how integration of these units into current curriculum will help SE professionals to acquire key competencies in sustainability.

**Table 2.** Assessment of key competence in sustainability with respect to proposed units in SE curriculum

| Units | Key competencies in sustainability [43, 51] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Intra-personal | Inter-personal | Future thinking | Systems thinking | Disciplinary and interdisciplinary | Normative and cultural | Strategic |
| *Sustainability theory* | X | | X | X | X | | X |
| *Sustainability Analysis* | X | X | X | X | X | | X |
| *Software Requirements Engineering* | X | X | X | X | X | | X |
| *Software Architecture and Design* | | X | X | X | X | | X |
| *Human-computer interaction design* | | X | X | X | X | X | X |
| *Software Modelling and Analysis* | | X | X | X | X | | X |
| *Software Process* | | X | X | X | X | | X |
| *Software Verification and Validation* | | X | X | X | | | X |
| *Software Quality Assurance* | | X | X | X | | | X |
| *Software Project Management* | | X | X | X | | | X |
| *Software Construction and Evolution* | | X | X | X | X | | X |
| *Software Security* | | X | X | X | | | X |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Internet of Things (IoT)* | | | X | X | X | | X |
| *Cloud Computing* | | | X | X | X | | X |
| *Web and Mobile Systems* | | X | X | X | X | | X |
| *Sustainable Data Center* | | | X | X | | | X |
| *Tools for Software Sustainability* | | X | X | X | X | X | X |
| *Global Professional Practice/Social Responsibility* | X | X | X | X | X | X | X |
| *Project based courses* | | X | X | X | X | X | X |

## 4. DISCUSSION

Sustainable software engineering is an emerging paradigm and significant for the society in terms of the environment. Sammalisto and Lindhqvist [31] argued that a proper feedback system is required between educators and University administrators to show the value and significance of the integration of sustainability. Torre et al. [11] observed in top 10 universities curriculum analysis that none engineering courses explicitly addresses sustainable software engineering and studied status of green sustainable software engineering. They conducted survey where vast majority of respondents (97%) view there is need for more courses related to sustainability.

The present industrial production and more and more use of ICT bring endanger the prospective sustainability and lead to environmental problems [1, 2]. In a recent study, Salam and Khan [60] classify 20 success elements towards the evolution of green and sustainable software. Out of these, green software design and efficient coding is the most significant factor (71%) and power-saving software methods (70%). Mahmoud and Ahmad [20] proposed green model for sustainable software engineering. Naumann et al. [61] proposed sustainable software engineering process and quality models and suggested nine successive stages: Requirements, Design, Unit Testing, Implementation, System Testing, Green Analysis, Usage, Maintenance, and Disposal. Lami et al. [62] found that sustainability related processes are missing in ISO/IEC 12207 and proposed three sustainability processes: Sustainability Management Processes, and Sustainability Engineering Process and Sustainability Qualification Process.

The purpose of SSE is to curtail the power footprint of computers as well as minimize other environmental impacts related with software systems. Software is now a pervasive part of the society as even mobile phone and social media users are in billions. It is the responsibility of software engineering educators to prepare the SE professionals by providing them with skills to meet the expectations of the software industry [63]. Therefore, it is significant to include sustainability in courses for future software engineers so that it can be achieved while developing, deploying and maintaining all kinds of software in the future. Professional practices should be included in the SE curriculum [64] and professional practices can include sustainability component. Moreover, sustainability has the potential to attract more students to SE discipline area due to its indispensable significance for future [65]. Programs that address environmental sustainability in information technology area are sometimes also referred as green information technology. Green IT refers to information technology and system initiatives and programs that address environmental sustainability [66] and manage energy consumption as well as waste associated with the use of hardware, software which tend to have a direct and positive impact on sustainability [67].

The proposed curriculum development can be easily customized and introduced as part of an undergraduate- or graduate-level software engineering curriculum. Since only a limited number of undergraduate and graduate programs on sustainability have been introduced in the last decade in certain institutions, the curricula proposed here can be a useful contribution to the body of knowledge for software engineering educators. As requirement specifications are the base input for software architecture and design therefore requirements have an impact on sustainability. With increasing global concern regarding our climate, the time has come to include "Sustainability" as a non-functional requirement towards quality software for future generations.

## 5. CONCLUSION AND OUTLOOK

Due to climate change in last decade and proliferation of information technology, software and apps in daily life in society, there is crucial need to develop and deploy green software. Therefore, there is need to provide training to future software engineers in such a manner that they will be able to include sustainability in each stage of software development life cycle. Here important units of sustainability inclusion in software engineering curricula have been described according to recent ACM/IEEE curriculum guidelines for SE curriculum along with literature review on sustainable software engineering approaches, concepts and tools. Software engineering undergraduate and graduate programs should include at least one foundation course on sustainability in their curriculum. This study also includes appraisal of key competences in sustainability for proposed units in SE curriculum.

This work can be extended by a survey and interviewing software engineering professionals to know in more detailed manner how SSE course can be developed and improved in future towards more practical-oriented approach so that future software engineers will be able to produce eco and sustainable software.

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