How to Integrate Environmental Challenges in Computing Curricula?

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ABSTRACT

This paper advocates for the integration of environmental aspects in computing curricula, with a focus on higher education. We created knowledge-based curriculum specifications in order to help teachers who wish to add knowledge foundation on computing impacts. This document lists topics and references that can be integrated into curricula. We implemented it in several higher education institutions. This paper reports on our experience and feedback. We also discuss recommendations to overcome obstacles that, from our experience, are often faced when modifying computing curricula to integrate environmental challenges.

CCS CONCEPTS

• **Social and professional topics** → **Sustainability**; **Computer science education**; **Model curricula**.

KEYWORDS

computing curricula, environmental challenges, sustainability

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1 INTRODUCTION

As our societies are facing environmental challenges of a global scale [3], the role of Higher Education Institutions should be to prepare their students to make informed decisions, in particular to mitigate and adapt to climate change. Yet, as several studies show, the integration of these issues in most curricula is still slow, in particular in computing [12, 21]. Torre *et al.* [21] present the result of a survey from 33 academics regarding the teaching of green and sustainable software engineering in higher education. This study illustrates that sustainability is under-represented in the curricula. Gibson *et al.* [12] perform a study on novice (young) software developers showing that while they are well aware of the need for sustainability in general, the issues of sustainability in software development are not fully understood.

Traditionally, Computing[1] programs have largely eluded environmental issues, unlike other domains where these questions arise more naturally. When they are addressed, they are usually more oriented towards using computing as a solution to environmental problems than evaluating the impact of ICT on the environment [20]. Moreover, when sustainability is included in a curriculum, it is in general by focusing on energy efficiency [14, 21]. More recently Mishra and Mishra [18] have proposed a sustainable software engineering curriculum that relies on software development life cycle (direct impacts). Yet, the environmental impacts of ICT are more complex, either in terms of carbon footprint, resource depletion or toxicity [16, 17], while its utility is debated: the environmental benefits of ICT must be balanced with its direct and indirect impacts [11]. In this context, we believe that Computing curricula in higher education should integrate environmental challenges in a more complete way. Students have to be aware of the environmental issues and the role of ICT, and the higher education system

[1]This includes Computer Science (CS) and Information Technology (IT) as disciplinary fields; Information and Communication Technology (ICT) will refer to the part of the computing technosphere and its concrete impacts.

should make them capable of taking decisions with environmental challenges in mind [10].

With this objective in mind, we addressed the following question. *Which topics should a computing curriculum include to properly take into account environmental issues?* We mostly focused on higher education curricula.

We may observe that most teaching specifications, such as the ACM Computing Curricula 2020 [10], favor competence-based learning. Moreover, competence specifications already exist for Sustainability as well as for the ICT professional sector. For instance, the European Digital Competence Framework 2.0 [8], which aims at evaluating the digital competence of citizens, includes a competence "4.4 Protecting the environment: To be aware of the environmental impact of digital technologies and their use.", with several proficiency levels. Another example is the European e-Competence Framework[2] which provides a reference document of 41 competences of professional use of Information and Communication Technology (ICT). It includes a Sustainable Development competence (*A*8) which involves being able to estimate the impact of ICT solutions in terms of eco-responsibilities including energy consumption, to advise business and ICT stakeholders on sustainable alternatives that are consistent with the business strategy, and to apply an ICT purchasing and sales policy which fulfills eco-responsibilities. It also gives some knowledge and skills associated to the competence.

In spite of these references and skill bases, it seems that the difficulty of creating courses on this theme is still a potential blocking point. Torre *et al.* [21] give three main reasons for this: lack of awareness, lack of existing teaching material and the high effort it requires to teach sustainability.

Through our experience, we observed three additional difficulties: first, the systemic nature of the ICT sector which requires interdisciplinary teaching; second, computing educators ("faculty members or teachers of a computing academic unit within a school or university" [10]) have to get familiar with very different topics, from different disciplines; finally, we could not find any curriculum addressing environmental issues of the whole ICT sector yet.

For all these reasons, and in particular to cope with this last point and to answer the question of which topics should be included in a curriculum, we chose to focus on a knowledge-based approach, which is thought to be complementary to an approach that would be based on professional skills and competencies. For this purpose, we have proposed a Knowledge-Based Curriculum Specification (available in French in [7] and in English[3]) that aims at providing useful concepts and references to help educators in computing creating their own courses. In this paper we will present this document and share our experiences on its integration into existing curricula at several higher education institutions.

There are different ways of integrating environmental issues in existing curricula. Molthan-Hill *et al.* [19] provide a conceptual framework with 4 categories describing possible integration of climate change education (CCE) into higher education: *Piggybacking*, which consists in including CCE in existing modules and courses, by giving examples at the margin such as using environmental datasets or case studies; *Mainstreaming*, which also consists in including CCE within existing structures, but with the emphasis on a broader cross-curricular perspective, for example requiring that every module in a given degree addresses CCE; *Specializing*, which consists in creating specialized modules, courses or degrees for CCE; and *Connecting*, which consists in creating transdisciplinary modules or courses. They also collected data about existing integration in 45 countries, based on the results of a survey. We will see that we experimented different strategies in the various institutions where we implemented the curriculum specification.

Our contributions are the following:

- We present knowledge-based curriculum specifications for computing education programs, mostly aimed at higher education programs.
- We show how it was implemented in several higher education institutions.
- We discuss the integration of environmental challenges in existing computing programs, answer some doubts that teachers might have and provide some hints to solve issues raised by teachers.

2 PRESENTATION OF THE KNOWLEDGE-BASED CURRICULUM SPECIFICATIONS

This section presents the Knowledge-Based Curriculum Specifications document that we designed to help higher education institutions integrate environmental impacts into their computing curricula.

The document was designed according to the following principle: it lists dedicated topics that should be addressed in a computing curriculum, and for each topic, gives main concepts and references. References can be used to gather knowledge before preparing a lecture or as resources for student projects. The work presented here does not intend to provide pedagogical content (precise subjects, course titles, exercises...) for professors, but only a a set of topics that should be considered for integration in curricula.

It was created based on a few professors' experience in teaching these subjects. Its development required to address several difficulties. Some of them are related to the definition of the perimeter that should be addressed in computing curricula. First, understanding the direct impacts implied by hardware devices manufacturing and the use of services lead us to introduce some ecological and technical notions in the curricula. Second, ICT has not only direct impacts but also indirect effects, which requires an understanding of lots of social aspects. Finally, ICT is related to lots of sectors. As a consequence, we had to deal not only with technical aspects but pluri-disciplinary ones. Articulating them and structuring the document can be done in different manners, the issue being to produce a readable and comprehensible structure so that readers understand why each aspect is important.

Our final document is divided into four main parts. The first one addresses global environmental issues, with a focus on those concerning most particularly the ICT sector, i.e. primary resources and energy. Then, environmental impacts of ICT are described, first with first-order impacts due to ICT equipment life cycle, and then with second- and third-order impacts, i.e. the changes that

[2] https://www.ecompetences.eu/
[3] Knowledge-based curriculum specifications to integrate environmental challenges in computing curricula, available at this link

Evolution of the environmental impacts of ICT *Beyond the impact of ICT at a given moment, it is necessary to understand the dynamics of the sector impacts in a context where a drastic reduction of our impacts is recommended by international organizations such as the IPCC.*

Notions:

- Development of the digital infrastructure: number of equipments, data volumes...
- Growing share of global GHG emissions
- Technical improvements: efficiency, intensity, Moore's law and Koomey's law, PUE, battery autonomy, Landauer's principle, etc.
- Predictions vs. projections. Projections made from models should not be considered as predictions. They do not capture, far from it, all the complexity of socio-technical evolutions.
- Prospective scenarios for ICT: knowing and criticizing prospective scenarios including an ICT component: SMART 2020 and 2030 from GeSI, BIO Intelligence Service 2008, The Shift Project, Fing, ADEME, etc.

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Figure 1: Extract from part II of the knowledge-based curriculum specifications document

ICT induces in other sectors or user behavior. The third part describes methodologies and tools to measure the impacts: life cycle assessment (LCA), greenhouse gas (GHG) protocol, tools to measure energy consumption etc. The last part presents Green ICT (how to reduce ICT's impacts) and ICT for Green (how to use ICT to reduce the environmental impacts of other sectors). First column in Table 1 summarizes the document's organization.

Figure 1 presents an extract of the specifications, about the evolution of the impacts. As can be seen from this extract, writing this specification has been driven by several principles. Rather than giving precise numbers and orders of magnitudes (that can evolve in time), we favored describing concepts and trends, and giving pointers for further reference. Moreover, our approach is not supposed to be driven by activism of any kind. This is why we carefully chose the references to include. These references are thought to be as much as possible scientific or technical works, produced by recognized persons or entities.

3 EXAMPLES OF IMPLEMENTATION IN HIGHER EDUCATION

The specifications we discussed in Section 2 were used in several higher education institutions (HEIs) (see caption of Table 1 for details). We now present an overview of these teachings and how the curriculum has been used, then we detail important lessons that we learned from these works.

3.1 Implementations of the curriculum

Table 1 shows which parts of the specifications were used in each HEIs curriculum. The levels correspond to the Bologna process structure.[4] The first 3-year Bachelor cycle (undergraduate) is denoted as B1, B2, B3 for years 1, 2 and 3 respectively. Similarly, we use M1 and M2 to refer to the second 2-year Master (graduate) cycle and D for the doctoral cycle.

The table reveals first an heterogeneous distribution of the curriculum's four parts across the institutions and degree years. Part II on the impacts has been the most covered (67 % and 100 % for direct impacts) followed by part I on context (41 %). The last two parts on taking actions have been less covered because of various reasons: lack of existing contents and references (all items, especially part IV); time needed to seriously approach them in programs (all items), lack of necessary pluri-disciplinary skills (especially last item).

Each teacher has its own knowledge and area of expertise. Some of us were specialists of these topics, others were not and had to learn new subjects.

Each HEI had its own number of credits and associated teaching hours to implement the curriculum. Following Moltan-Hill *et al.*'s terminology [19], we mostly integrated the specifications by specializing and piggybacking. In HEI1 and HEI7 for instance, specialized modules were created for each year of the computing curriculum, with a larger scope about environmental issues in the Bachelor year, and focusing more on ICT in the Master years. In HEI3, a specific module dedicated to social and environmental issues in ICT has been created in Master 2 level. In HEI6 the curriculum was integrated by connecting through a new module of seminars called "major ecological issues" for first year students that encompassed various topics (impacts of ICT, climate change, economy, biodiversity).

Furthermore, each educator also has her own preferred teaching methods. The curriculum was therefore implemented in different ways: lectures only (when only few hours were allocated), lectures+labs, lectures+projects, lectures+labs+projects. Labs are either in the form of measurements (energy consumption or carbon footprint computations), literature study or analysis of study cases. Projects were chosen by students. They included a complete analysis of a topic (e.g. 5G, autonomous vehicles) or more specific topics (computing power usage effectiveness of servers of a datacenter).

[4] https://ehea.info/page-three-cycle-system

Table 1: Integration of the specifications in computing curricula of different Higher Education Institutions (each HEx represents an institution : HEI1 = ENSIIE, HEI2 = University of Bordeaux, HEI3 = Grenoble INP - Ensimag, HEI4 = Polytech'Lille of University of Lille, HEI5=INSA Lyon, HEI6=Marseille, AMU, HEI7=EPISEN). B = Bachelor, M = Master, D = Doctorate. The number indicates the degree year.

Topics	**B1**	**B3**			**M1**			**M2**				**D**
	HEI6	HEI1	HEI2	HEI7	HEI1	HEI4	HEI7	HEI1	HEI3	HEI5	HEI7	HEI2
Part I - Context												
Environmental issues		x	x	x				x	x	x	x	x
Sustainability frameworks		x	x	x								x
Primary resources				x						x		x
Energy	x	x	x	x				x		x		x
The global economic and production system				x								
ICT Sector: evolution, infrastructure, usages	x		x	x			x		x	x		x
Part II - Understanding: Environmental impacts of ICT												
Direct impacts	x	x	x	x	x	x			x	x		x
Indirect impacts	x		x	x	x	x			x	x		x
Other impacts: geopolitical, social...	x		x	x		x			x	x		
Evolution of the impacts	x				x	x				x		
Part III - Taking action: measuring impacts												
Methodologies			x		x	x						x
Tools and indicators for measuring electrical consumption					x		x			x		
Part IV - Taking action: Towards responsible ICT												
Green IT			x			x	x	x				
ICT standards and labels	x									x		
ICT for Green			x				x	x				
Why and how can organizations integrate ICT's impacts?						x						

In HEI2-B3 for instance, lectures were given following the overview from Table 1. They always included a time for debate. Each week, students had a homework with to illustrate the lesson and increase their critical thinking: measuring their own carbon footprints, the carbon footprint of their own computers and smartphones, the time spent on their devices, finding rebound effects and website analyses. Finally the last weeks of the semester were entirely dedicated to a group project aiming at identifying, from a literature review, positive and negative aspects of a chosen topic. This work was achieved with the submission and a presentation in front of the whole class.

3.2 Main experience feedback

We now report a list of advice from our teaching experiences.

Make students act. The most straightforward approach to address global ecological considerations is to only give formal courses. Because the facts may be frightening or stressful, it is important to put students in action. It can be measuring, coding, experimenting. But it can also be writing, speaking, communicating. It is particularly important because, contrary to most fields taught in computing curricula that are mostly based on mathematical/formal theories and engineering (where one builds objects), ecological concerns are highly complex natural and social systems, where experts try to understand nuts and bolts using partial information, identify trends rather than producing extremely precise numbers. Creating the conditions for students to speak and debate is thus particularly interesting.

Propose solutions. In relation with the previous point, we now try in our programs not only to assess the various ecological impacts of digital sector but also to discuss solutions for students to be actors, in their professional life, of changes for a more sustainable world. This is not easy, but the technical skills necessary to evaluate ecological impacts (LCA, carbon accounting, energy measurement...) are in increasing demand as all organizations have to reduce their climate impact [1].

Choose subjects that directly concern students. In the various exercises we propose, we observe that choosing some that are directly in relation with students' environment (the campus, their school, their friends...) increases a lot their motivation. For instance, the subject "What should be the education program of your school in 2035?" has particularly motivated students.

Tackle political concerns. Parts of the curriculum we build concern more political or economical subjects than technical ones. But these aspects must be tackled. Leichenko and O'Brien [15] argue for adopting an anthropocene perspective when teaching climate change, which "involves questioning accepted norms, rules, institutions, policies, and practices that perpetuate unsustainable resource use". Other books argue that neutrality in science does not even exists [23]. One way to address these issues can be to consider historical dimensions of science/technology in general and digital expansion in particular. In our experience, the reaction of students with regards to these aspects may be quite different from one to another. The challenge here is to initiate discussions in the class.

Make students feel legitimate. Often, graduate people in computing (and other scientific fields) seem to believe that their role in the society is purely technical, and that important decisions are made at higher levels. We think it is important to send the message that people having technical skills have a role to play in the thoughts about the place of technology in the society.

Recall some basic scientific knowledge. At all levels, it seems important to make some revisions on various knowledge that students should have but are not so comfortable with:

- Exponential/linear/logarithmic progression. Lots of ecological concerns can only be understood if people are at ease with orders of magnitude. A recent work by Bol, Pirson and Dekimpe [6] is a good example of how various mathematical laws (e.g. Moore's law) combine to finally result in an increase of ICT's impact. Besides, simple models such as the prey-predator one [5] can provide a nice framework to understand the use of natural resources, production peak phenomenon and better recycling on materials' run out [22].
- Various notions around electricity: power, energy, intensity etc. The link between energy and GHG emissions is particularly important, but we had to deal with it from scratch as it is rather unexpected that computing students have been exposed to it before.
- Classical notions in complex systems (fixed point, feedback loop, homeostasis, nonlinear dynamics...) are central in understanding climate changes issues and evolving ecosystems. They are usually hard to grasp by students with limited knowledge in physics.

4 DISCUSSION

In this section, we describe some difficulties that we have faced, and issues that had to be discussed when we dealt with the integration of environmental issues in computing curricula.

4.1 Is it my role to teach around sustainability?

One of the main objections when talking of teaching environmental aspects is related to the role teachers think they have.

One point is that a lot of computer scientists seem to think they do not have the legitimacy to speak of non-technical aspects of computing. Our answer to this point is that computer scientists constantly acquire new technical skills, either because they are in charge of new educational modules, or because computing evolves. Based on our experience, we think that important ecological aspects can be approached in a reasonable amount of time in a computing program (although it may require to make difficult pedagogical decisions, as discussed later). We also believe that computer scientists are particularly well placed because they can make bridges between technical aspects of computing and ecological considerations; for instance talking of the relation between code optimization and energy consumption, the power trade-offs and limits involved in computer architecture or even the energy-consuming necessity of computing in mining digital assets (Bitcoin for instance).

Another objection, subtly different, is that it is not computer scientists' role to teach these aspects. We actually think it is because (i) digital sciences are hugely involved in the (good and bad) ecological impact of human being, so it is important to integrate these issues in computing education and (ii) most of the time, it is nobody else's role in the institutions. As stated in the ACM Code of Ethics and Professional Conduct [2] (Section 1.1 Contribute to society and to human well-being, acknowledging that all people are stakeholders in computing), *"In addition to a safe social environment, human well-being requires a safe natural environment. Therefore, computing professionals should promote environmental sustainability both locally and globally."*. Other sections of this code of conduct encourage computing educators to take responsibility to teach computing impacts: *"A computing professional should… (2.5) Give comprehensive and thorough evaluations of computer systems and their impacts, including analysis of possible risks, (2.7) Foster public awareness and understanding of computing, related technologies, and their consequences"*.

Last but not least, there seems to be different points of view in the role of the training course itself, and therefore of the teachers: should a higher education program focus on getting students ready for work, or tackle holistic considerations? Our opinion on this matter is that it should do both, and preparing our students to the systemic changes to come is critical even for their professional life.

4.2 How to make room in the educational program?

Another critical point of discussion is related to the means: how to make room for these teachings in the existing, overloaded, education programs?

A first step consists in convincing colleagues of the importance of these issues. Different arguments were useful to us:

(1) First of all, approaching things from a technical view is really convincing. For instance, being able to perform energy measurements of a digital equipment is a skill often really appreciated by colleagues and students.
(2) Second, some pressure for a change in the teachings now comes from the students themselves. Various calls, such as [9], encourage all actors in society – public authorities, businesses, individuals, associations – to play their role in the major transformation needed for a sustainable society. Students organizing for sustainability international [13] was created to ensure that all university graduates are given knowledge and competences about sustainability. Citing them or asking the students associations to support the changes can help in the prioritization of contents.

(3) Finally, some colleagues may not be aware of the extent of the environmental issues, or not feel informed enough to discuss them. Various contents now exist to raise awareness of environmental issues, for instance the Climate Fresk [4].

In our experience, the major underlying difficulty is in fact to initiate collective discussions, in particular across different disciplines. Too often, new courses are introduced only when someone leaves and someone with the competences is available. But too few people have skills in relation with ecological considerations, making this functioning inefficient. And more importantly, rather that making room for just a few hours, the whole program may have to be redesigned for ecological considerations to be efficiently approached (see next Section).

4.3 What place must be given to environmental challenges in the educational program?

One question that often arises is: does it make sense to have a 10 hours course on environmental challenges when the whole program is oriented towards producing more goods and services? Answering this question is difficult, and we do not have formal answers to what is the good balance, and what would be an ecologically coherent curriculum. We must work on this aspect and develop a mainstreaming or connecting curriculum [19] that would integrate environmental aspects of ICT in the whole program rather than just in a small part of the program.

Lastly, we have to recall that ecological aspects are only one of the social, societal, and ethical implications that ICT is concerned with (fairness in AI, surveillance capitalism, filter bubble...). It is clear that connections have to be made between those different aspects. Exploring connections between them and ecological ones in our curricula is a work-in-progress.

4.4 Shall we also teach universities staff?

In order to efficiently tackle ecological aspects of computing in the educational programs, it may be useful to train the staff of universities, depending on their profession:

- Training the other computing educators to environmental issues is critical for a successful integration of these issues into the programs. Of course, they may decide not to talk about these in their own courses, but it would have several benefits: only informed educators can themselves teach ecological issues to their students; only teachers aware of the urgency of the environmental situation can be convinced that integrating these issues into computing programs is crucial.
- It would be great if teachers of other domains had some notions on environmental impacts of computing, because it would allow to make some bridges between courses. For instance, increasing demand of metals in ICT may concern chemists/physicists (which elements) and mathematicians (how to model the trends) and raise shared questions about thermodynamic limits and implications for the production.
- Training the IT staff of the university is a good way to promote sustainable practices inside the university itself and to disseminate these practices when these people change employer.
- Training the administrative staff of the university might have less visible impacts on the students education. However it can still have other indirect beneficial impacts. Beyond the benefits induced if administrative staff members implement good environmental practices at work, it can also help building a strong environmental culture at the university. The question of culture is critical, as the more people are convinced of the importance of environmental aspects, the more likely they will be able to initiate a transition and to induce important changes in the programs. Our own experience (e.g. at HEI3, HEI6 and HEI7) shows that embarking everyone in the process is essential to its success.

In relation with this question, providing contents for continuous training may be useful, but we do not have experience on this subject.

Finally, the general issue is to make colleagues have common vocabulary and notions so that they can discuss together and build common visions of the education program.

4.5 How to go from knowledge to useful skills?

Our curriculum is oriented towards acquiring knowledge, but not acquiring *skills*. This is a perspective of our work that we have just initiated. Relations with companies will be crucial here. CSR (Corporate Social Responsibility) policies will likely be useful.

5 CONCLUSION

In this paper we have described our experience of integrating environmental challenges in existing computing curriculum at higher education institutions. We report which topics where taught from a document that we wrote to define knowledge-based curriculum specifications, and share some findings that we found important when sharing the experience at different HEIs.

With this paper, we wanted to encourage computing educators to talk more about environmental aspects. Our experience shows that they are ways to face obstacles and that, even if it is a personal investment to learn new topics, it is essential to do it and thanked by students.

The main objective of this work is to facilitate the integration of pedagogical content on the theme of ICT impacts in training programs, in order to change practices in the sector. It gives rise to many perspectives for the community: evaluation of the diffusion of the theme in the institutions; evolution of the curricula in generalist or specialized courses; and appropriation by the students.

AUTHORS' CONTRIBUTIONS

AL and KM coordinated the work on the curriculum specifications and the paper. AL, KM and AB wrote the first draft of the paper. The other authors reviewed the whole paper, proposed improvements, and added citations. All authors read and approved the final manuscript.

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