Enhancing Sustainable Software Engineering Methods through SECoMo

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Abstract. Sustainability is a globally important topic in today's world. Its most prominent aspect is ecological sustainability, but it also concerns social and economic issues. Many factors come into play that have a negative impact on sustainability, for example an increase in energy consumption or pollution. The Information and Communication Technology (ICT) sector contributes to these negative factors as well, for examply by the growing energy consumption of ICT hardware. But Software can also have negative impacts on ecological sustainability, thus it is important to consider how to increase the software sustainability. The growing field of Sustainable Software Engineering deals with the questions of how to develop sustainable software and how to develop it in a sustainable way. Existing research proposes a number of sustainability metrics, measurement tools or process and life cycle models, but despite this variety of approaches, it seems that sustainable approaches of Software Engineering (SE) are not yet well established in practice. The Software Eco-Costs Model (SECoMo) approach is a new estimation approach in this field which allows to estimate and represent the ecological costs of software already from an early stage on in a software project. It enables stakeholders to have an early understanding of the sustainability impact of a software and to make design decisions accordingly.
The purpose of this seminar thesis is to consider how SECoMo can be integrated with other existing sustainable software engineering approaches and how it can contribute to improving the integration of such approaches in practice.

1 Introduction

In 2015, the United Nations (UN) introduced the *Sustainable Development Goals* [32] in order to raise awareness for the concept of Sustainability: they include the fight against poverty, protecting the planet and granting prosperitiy for everybody [19]. The goals emphasize how important the topic of Sustainability has become for the world, and that taking action affects everybody: "governments, the private sector, civil society"[19, p. 1] and every private person.
Identifying existing negative influences on Sustainability is the first step towards reducing them and revealing the great potential for positive impacts everybody can achieve. Accordingly, many industries in the private sector have taken on their responsibility and have started to reduce their negative ecological impacts on Sustainability. The Information and Communication Technology (ICT) sector is no exception: with its products and services it contributes to high power consumption and carbon dioxide emission [16] and thus has a negative effect on global warming [31] - but in the last few years, many efforts have been made to counteract these negative impacts, for example by improving energy efficiency of hardware products or by increasing the Sustainability of data centers. The focus of these efforts is mainly on reducing the negative impacts of hardware products, but software can have an impact on Sustainability aspects, too - not only by enabling people or processes using it to be more sustainable, but also as a product itself, for example during its development process. Efforts directed at improving software Sustainability during its development and usage phases are an important aspect of IT Sustainability.
In the growing research field of Sustainable SE there is a great number of scientific contributions covering ideas for example on Sustainability guidelines for software, models for sustainable development life cycles or specific energy measurement tools for certain types of applications. However there is a lack of an evaluation of these approaches in practice and more conrete models and metrics that can be applied in a great variety of software projects are missing. This paper aims at comparing a new approach in the field of Sustainable SEoftware Engineering, SECoMo [29], with the existing variety of models and approaches in the field. The goal is to work out how this approach for estimating the ecological costs of a software system can enhance existing approaches for sustainable software and its development, and how it can contribute to increase the practical adoption of Sustainable SE overall.
The relevant background topics for this seminar thesis, Sustainability and its relation to ICT, software in particular, are introduced and defined in the first section. In the following, the related work from the field of Sustainable SE is presented. In addition, the SECoMo approach is introduced and described with a focus on its general purpose and motivation. In the following section, SECoMo is considered in the context of Sustainable SE and analyzed regarding its ability to enhance existing approaches, in order to identify its benefits for the field of sustainable SE and its overall impact on the practical adoption. Lastly, limitations of SECoMo in the context of sustainable SE are presented and a conclusion of the paper is given.

2 Background

2.1 The Concept of Sustainability

Although it is clear that Sustainability is a concept of increasing importance in the world and impacts many areas of our daily lives, the definition of the term Sustainability itself is not as clear and not always consistent. There are various attempts at understanding and defining the concept of Sustainability, coming from different perspectives which influence the focus of the definition (e.g. the needs of humans or of nature [9]) and thus it can be hard to find a common understanding [12]. In order to successfully work towards a sustainable future, finding this common understanding is absolutely necessary, though [12].

Most attempts at defining the concept of Sustainability start with the definition of the concept of *Sustainable Development* in the so-called *Brundtland Report* in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[21, p. 4]. In addition, the requirements for sustainable development according to [21] are related to three different aspects: society, economy and environment. These three aspects are now widely accepted as "the three dimensions of sustainable development" [32, p. 1].

Based on this understanding of sustainable development and which dimensions it covers, the concept of Sustainability can be defined as *a holistic concept that embraces environmental, social and economic factors which lead to a decent life for the current generation while maintaining natural, social and economic resources so that future generations are not limited in living the same decent life.*

2.2 Sustainability and ICT

The ICT sector has a major influence on economies, societies and even people's daily life. It is obvious that ICT plays an important role in the context of Sustainability, too: on one hand, as negative contributor to global warming, due to its increasing carbon dioxide emissions; on the other hand it has a great potential for positive impacts, by reducing the energy consumption of its own products or as an enabler to achieve energy efficiencies in other sectors [31].

The energy consumption of hardware is the main direct impact ICT has on Sustainability. While direct impacts are often quite obvious, indirectly caused effects of ICT (like the ability to enable improvements in other industries) are often overlooked, even though they can have even greater impacts in the long run. A more fine-grained differentiation of the effects of ICT, which is often used in the literature ([11]; [17]), distinguishes between three types: First-order effects, second-order effects and third-order effects [5]. While first-order effects refer to direct impacts "of the physical existence of ICT" [11, p. 2], like resource consumption during the production or usage phase of hardware, second-order effects describe rather indirect effects that are caused by using ICT, like the optimization of processes which might lead to resource conservation [17]. The third-order effects refer to impacts observable on a long-term scale, like the

"adaptation of behaviour (e.g. consumption patterns) or economic structures" [11, p. 2] which themselves have influence on different aspects of Sustainability.
If ICT can have negative and positive impacts on Sustainability on so many different levels, the question that comes to mind is: What are concrete approaches so that ICT can actually be used "in the service of sustainability"[10, p. 5]? According to Hilty et al. [10], there are a couple of relevant approaches in the field of ICT that contribute to Sustainability, with Green IT being the most well-known one. Green IT deals with ecological sustainability of ICT products and has been continuously adapted by companies and organizations since the term was coined in a Gartner Report [16] in 2007. It covers the concepts of Green *In* IT and Green *By* IT [10]. While Green In IT refers to ICT as resource consumer and carbon emission producer itself and deals with improving the environmental sustainability of ICT hardware [6], Green By IT aims at improving the environmental sustainability in related areas (other products or processes) by using ICT as the enabler [10]. Green In IT approaches take impacts of the whole life cycle of ICT products into account, which is important in order to achieve holistic environmental sustainability [10]. Green IT is related to first- and second-order effects of ICT, but as a strategic concept adapted by many organizations, it has the potential to create long-term, third-order effects, too.
Even though ICT products consist not only of hardware artifacts but also software artifacts, the main focus of Green In IT is usually on improving the sustainability of ICT hardware, and often Green By IT approaches do not take the impacts of software artifacts fully into account.

2.3 Sustainability and Software

Software artifacts actually play an important role in the relationship of ICT and Sustainability: Although it may seem that software as the immaterial part of ICT products does not have an impact on Sustainability and "is automatically green" [1, p. 3], this naive assumption is made too rashly. For example, when software is developed, the process requires a lot of physical resources; when software is used, it can support sustainable causes and projects; and it can even have third-order effects like changing user behavior towards more sustainable practices (like video conferencing instead of business travel [3]). If software is regarded as "the ultimate cause of hardware requirements and energy consumption" [15, p. 1], it becomes clear that it is also indirectly influencing energy efficiency aspects.
Considering all these direct and indirect impacts, software definitely needs to be taken into account regarding ICT Sustainability considerations. Accordingly, for the ICT subfield of SE there is a need to include Sustainability topics. But so far, such considerations are not a part of traditional SE methods [23]. This is critized by a growing number of authors ([23]; [1]; [3]), as the awareness for the importance of Sustainability in SE grows. The emerging field of *Green* or (more holistically) *Sustainable Software Engineering* aims at filling this gap by providing approaches that deal with sustainable software and its engineering. Sustainable SE thus constitutes another important apporach how to use ICT in the service of Sustainability.

In the literature, there does not yet exist one common definition of Sustainable Software and Sustainable SE [33]. Nevertheless, for the purpose of this paper the following definition of Sustainable Software is chosen, as it best relates to the three dimensions of Sustainability:

> "Sustainable Software is software whose direct and indirect negative impacts on economy, society, human beings, and the environment resulting from development, deployment, and usage of the software is minimal and/or has a positive effect on sustainable development" [8, p. 3]

Accordingly, Sustainable SE provides the systematic methodology to develop Sustainable Software. It is defined by Naumann et al. as

> " [...] Sustainable Software Engineering is the art of developing [...] sustainable software with a [...] sustainable software engineering process. Therefore, it is the art of defining and developing software products in a way, so that the negative and positive impacts on sustainable development that result [...] from the software product over its whole life cycle are continuously assessed, documented, and used for a further optimization of the software product" [17, p. 3]

This definition provides a holistic description of the idea of sustainable SE, especially due to its focus on the impacts the software product has over its whole life cycle. In this context, Penzenstadler [23] provides a categorization of Software Sustainability aspects that reflects the variety of impacts software can have. It differentiates between four aspects: the development process aspect, the maintenance process aspect, the system production aspect and the system usage aspect [23]. This categorization will be used in the following in order to describe and categorize existing contributions in the field of sustainable SE.

3 Related work in Sustainable SE

3.1 State of Research

According to a Systematic Literature Review (SLR) conducted in 2012 [22], most of the research activity in the field of sustainable SE has started in the beginning of the 2010s and has significantly increased since then. This is underlined by the follow-up study from 2014 [26], which identified around 40 relevant publications that were added just in between the two studies. In summary, the main insights provided by the studies are the following: While there are many contributions over the last years that relate to software and Sustainability in some way, most research still goes into "domain-specific, constructive approaches" [22, p. 5], and general reference approaches that can be applied to the whole domain of sustainable SE are missing [22]. The study from 2014 identified already more contributions with a focus on general aspects of SE processes and Software Design [26], but also found that most covered application domains are still only remotely connected to SE [26]. Moreover, a lack of case studies and experience reports

about applications of proposed approaches and methods in practice was identified [22], which shows that the research field is still mostly shaped by academia and the practical view is missing [26].
The following aspects stand out in current research because they are targeted by many authors and are thus the most relevant issues of the field currently:
There is a need for a unified definition of the concepts of sustainable software and the role of Sustainability in SE. This need is apparent and mentioned by many authors ([33]; [4]; [6]; [24]). The general opinion is that despite the variety of attempts, it is not possible to identify a commonly accepted definition yet, due to the recency of the research field, but also due to the complex nature of the concept of software sustainability [33]. This lack of a defined common ground is critical, because until a widely accepted definition is established, most efforts in the field will be likely to "remain insular and isolated" [33, p. 5] and thus hinder the practical adoption of Sustainable SE.
Integrating Sustainability as a software quality attribute by making it a Non-Functional Requirement (NFR) in official SE standards is emphasized by many authors as well ([27]; [3]; [1]). This step would account for the central role sustainability plays today [27] and help to integrate Sustainability "early in the lifecycle of software development and influence design decisions" [28, p. 2], but there are still appropriate analysis and assessment methods missing as well as policies and standards ([27]; [33]).
In general, as also found by the SLR, the field is missing concrete reference models and methods that can provide holistic frameworks to actually perform sustainable SE [22] and thus provide guidance to Sustainable SE researchers and practicioners. In addition, the need for concrete, unified metrics that enable to measure the actual impact of software on sustainability is also evident. To meet this demand, more and more contributions from the past five to six years aim at providing concrete models and metrics to be used in the context of sustainable SE. The most relevant ones will be presented in the next section.

3.2 Overview of existing contributions to Sustainable SE Practices

Sustainability metrics and measurement methods Many contributions to sustainable SE focuses on methods and tools to measure energy consumption of software. There are several tools and measurement frameworks for tracking or measuring energy consumption of software, like *GreenTracker* [3], *PowerIndicator* [18] or *PowerAPI* [20], that all have different focus aspects. PowerAPI for example enables the monitoring of energy consumption of an application during runtime [20]. Other approaches introduce mathematical metrics like the energy efficiency measures proposed by [7] and [13] - they consider the relative energy consumption of applications and measure it on a low level, which makes it possible to "find resource intensive parts of programs and improve them" [13, p. 1]. The required effort to test and use these metrics is quite high [13], and the metrics are very specific, which indicates that it is not likely that these metrics can be applied in practice soon.

Kern et al. [15] propose another interesting metric and the respective calculation method for the carbon footprint of a software project. This sustainable SE contribution from 2015 aims at finally providing a practical approach for measuring the environmental impact of software which can be integrated in a software development process [15]. The basic idea is to calculate the respective current footprint of the development process of a software project or of the software product itself [15]. The metric itself is expressed as kg CO_2 per person month and is calculated based on rather high-level inputs like number of working days or number of employees [15].
Nearly all of the existing metrics and measurement methods focus exclusively on power and energy consumption and thus mainly target environmental sustainability. Nevertheless, there are efforts to consider software impacts in relation with other dimensions of Sustainability, like the Sustainability properties and related metrics provided by Albertao et al. [2]. Based on existing software quality measures, eleven software Sustainability properties were derived, which include aspects like Usability, Efficiency or the Project's Footprint [2].

Software life cycle, process and other software sustainability models A great variety of approaches exist that propose systematic models for sustainable SE. Many of them rather target side aspects of sustainable SE like the ICT impact assessment model [11] or the Sustainability goals reference model [25]. The very important types of systematic models for sustainable SE are models with a focus on the Software Development Life Cycle (SDLC) and general process models, as they give guidance on how to actually realize the development. Most of these models concentrate on enhancing existing traditional models with activities and best practices that improve the sustainability of the software development process itself in all its phases. Examples are the models by Agarwal et al. [1] and Shenoy and Eeratta [30], which include aspects like simply reducing resource usage like paper [30], but also consider activities like writing energy-efficiency code [1]. Furthermore, they emphasize the need to integrate Sustainability considerations in the requirements phase and to use respective measures to ensure sustainability and software quality ([1]; [30]).
The systematic sustainability model that currently seems to be most important in research area, as it is highly referenced in many related contributions, is the *GREENSOFT* model [17]. This "reference model for green and sustainable software and its engineering" [17, p. 1] is a comprehensive model that combines many aspects of sustainable SE and can be considered to be the best starting point for applying sustainable SE to practical projects at the moment. It consists of four parts or levels: a *life cycle model* that is used to assess the impact of the software during its different phases; a set of *sustainability criteriy and metrics*; different procedure models (like for development or administration); and a collection of further recommendations for different stakeholders [17]. Overall, this complex model aims at providing information on sustainable software, its engineering, use, administration and so on for different stakeholders and is thus a very important contribution to the research field. But nevertheless, it is not yet the perfect model that enables to integrate sustainability in practical projects right

away: The development procedure model for example concentrates on describing how to manage sustainability during the development process (for example with sustainability reviews [17]), but it does not specifically say how to realize it with the actual development. For this, the integration of approaches is needed that for example specify how to calculate certain sustainability metrics or allow the estimation of processing time or energy consumption in early stages [17].

3.3 Adaption of sustainable SE in practice

As the previous sections show, Sustainability in SE is a relevant research field with increasing acadmic interest and many contributions. Nevertheless, as various authors point out, there is a lack of practical evaluation of existing apporaches and of experience reports ([22]; [26]), and many existing methods and metrics are not yet suitable to be used in practice. This lack of practical evaluation is a sign for the very limited adoption of sustainable SE practices in non-academic areas. As Kern [14] points out, the field itself is not yet open for non-academic contexts - but this is absolutely relevant in order for sustainable SE to actually make a difference. Reasons for this problem are on one hand the still missing common ground in the field (see section 3.1; [14]) but also the fact that practioners are not yet included in the discussions [14].
Kern proposes ideas how to open up the research field in order to increase the adoption of sustainable SE practices in the industry and the public sector [14], and names two possible ways forward: either starting with including software delevopers in the discussion and use them to evaluate existing ideas, or starting with raising awareness for the issue with private users in order to come up with new ways how to characterize sustainable software [14]. The first idea seems to be a logical step forward given the issues of the field, but in the author's opinion, there is still one issue impeding this: As long as there is still a lack of concrete models and metrics that can be easily adopted for a variety of different projects, the adoption and evaluation of existing sustainable SE approaches will continue to be limited to small, specific cases and will not reach a broader range of practitioners. The existence of reference models like GREENSOFT is already a step in the right direction by providing a framework for actual, sustainble software projects, but it is still missing concrete details for development processes, for example. Thus, what is needed to promote the field of sustainable SE are such concrete approaches that can still be applied for a variety of projects.

4 The SECoMo approach

The Software Eco-Cost Model (SECoMo) was introduced by Schulze [29] in 2016. This approach provides Software Engineers with generic models and metrics necessary to estimate and express the ecological costs a software system causes when it is used [29]. Thus, SECoMo represents a concrete estimation approach for the impact a software system has on ecological sustainability.
The main motivation behind SECoMo is to provide an approach that allows

to not only measure the ecological costs that are actually caused by a software system, but also to be able to estimate those costs upfront, for example already during the design phase of a software project in order to keep the costs for changes low [29]. In order to achieve this, SECoMo offers a set of mathematical models which allow to precisely calculate a variety of different eco-cost metrics, based on information that is already available in the design phase: specification models that describe the functionality, behavior and structure of the software system [29]. Furthermore, SECoMo is intended to be highly adaptable in order to allow the estimates to be calculated for different levels of details available - an early, an intermediate and an advanced level [29]. More information available allow for more accurate estimates to be made [29]. In addition to the mathematical models, SECoMo defines a set of eco-cost drivers in order to identify causes for certain ecological impacts and to better describe under which circumstances they occur [29]. The auxiliary models used in SECoMo provide information about these cost drivers, but can also be used to express the estimated eco-costs of the software system [29]. This way, SECoMo additionally offers a possibility to communicate estimated or measured eco-costs to stakeholders of a project which can use this information to make improved decisions [29].
Against this background, the SECoMo approach is intended to be used in the early stages of SE projects to create estimates about the ecological impact of a software system, so as to enable transparency about the sustainability aspect right from the start [29]. This again makes it possible for software engineers and other stakeholders to make decisions about changes to the software at the design stage which take the impact on ecological costs into account [29]. SECoMo can also be used in the context of defining requirements for a software system, for example in terms of specifying upper bounds for the eco-cost metrics that must not be exceeded, or even to calculate exact eco-costs if enough details are given, for example for the specific usage scenario of a software system [29].
SECoMo can be integrated in a software engineering project as soon as the necessary basis is available: the specification models describing how the software will be structured, which behavior it should follow and what functionalities it should provide. Then, the following steps of the SECoMo approach can be integrated in any step of the SE process - in the design phase already if early eco-cost estimations are required, otherwise in later iterations of the process to refine the initial estimates or to calculate the actual eco-cost values (for example in the testing phase):
1. Calibration of the models, in order to receive accurate values concerning the hardware energy consumption factors (resource factors) that are later needed as inputs to the mathematical models [29].
2. Preparation of the auxiliary models so that they include all information available regarding the relevant eco-cost drivers (on the intermediate and advanced level certain information can be derived) [29].
3. Calculation of the estimates for the different eco-cost metrics based on the available information and the specified parameter values, which specify aspects like user type or case [29].

5 SECoMo in the context of Sustainable SE

Classification of SECoMo in Sustainable SE The SECoMo approach can be classified as a sustainable SE approach, as it aligns with many of the basic ideas characterising the definition of sustainable SE (see section 2.3): SECoMo can be used within a **software engineering process** to support design decisions; it deals with attributes of **software products**, namely its ecological costs during the usage phase (part of the software **life cycle**); as an adaptive estimation and calculation approach it deals with **continuously assessing and documenting** eco-cost, which are relevant in the context of **negative and positive impacts on sustainable development**, mainly for environmental sustainability; and it has the general goal of **optimizing the software product**. While it is not an engineering process itself, it definitely classifies as a method that enhances and supports aspects of such a process with regards to Sustainability.
Moreover, SECoMo can be described as an approach that is directed at the impacts of software while it is used. Thus it falls under the category of **system usage aspect** approaches according to the Software Sustainability aspects categorization [23]. As stated by the author [24], the system usage aspect is the most relevant one as it has the biggest impacts, especially the more the software is used, thus SECoMo covers a very relevant area of Software Sustainability.
With regards to the current research and its most relevant issues, SECoMo can be assessed as follows: The approach itself does not contribute to finding a common definition of Sustainable SE, due to its specific focus on usage eco-costs. It does, however, provide useful metrics and measurement models that can be used for defining Sustainability requirements in a SE process (see section 4), and thus enhances the chances of making Sustainability a NFR in the furture. As for the third aspect of missing concrete reference models and metrics, the next sections will show how SECoMo can contribute to these aspects.

SECoMo and Sustainability Metrics Like the majority of the introduced metrics (see section 3.2), SECoMo focuses mainly on environmental aspects of Sustainability, the ecological costs of software in particular. The eco-cost metrics that are part of SECoMo range from a very fine-grained level to a high-level scope (e. g. from execution costs for a single operation to those for a concrete scenario [29]), and are thus suitable for a variety of different purposes for which eco-costs are regarded. Most of the presented metrics and measurements are only usable in a specific context ([18]; [7]).
What the SECoMo metrics do not provide are information about energy efficiency (like [7] and [13]), and as they are estimated or calculated without information about the concrete implementation, they can not directly be used to identify resource intense coding parts. But the SECoMo metrics can give even more useful insights, as they can be calculated before any implementation is even considered and still give information on which parts of the software might be very resource intense (for example the execution of a certain operation, or updating a certain data type [29]).
The goal and motivation of SECoMo actually resembles those of the presented

carbon footprint calculation method by Kern et al. [15]: they share the motivation of providing a concrete method to calculate the environmental impact of a software product, that can be integrated in software development processes in a reasonable way ([15]; [29]). Moreover, the authors intend to create awareness and transparency for the aspect of software energy consumption [15] (which SECoMo aims at, too, mainly with regards to the stakeholders [29]). Finally, Kern et al. emphasize that the benefit of their method lies in its ability to finally integrate sustainability aspects early in the software development and design process [15] - which is one of the main benefits of SECoMo, too [29].
The differences between the two approaches lie in the flexibility of the metrics and their scope: The Carbon Footprint metric has a fixed unit and is thus restricted to a certain context, the SECoMo metrics can vary in the units they represent (for example CO_2 emissions, but also dollars [29]) and are thus far more flexible. Furthermore, they can adapt to many different contexts due to the variety of aspects from different dimensions they can cover [29], and they are not restricted to the high-level inputs the Carbon Footprint metric requires [15], but can be way more fine-grained [29]. In its scoep, SECoMo is more restricted that the Carbon Footprint calculation method: While the latter method can calculate the footprint of the software product itself and in addition the footprint of the development process[15], SECoMo only applies to the eco-costs caused by the software product itself [29].
Overall, these differentiation aspects underline the general benefits of the SECoMo eco-cost metrics in relation to existing sustainability metrics: they are more flexible and can be applied for different contexts and are thus more adaptive and they allow an early understanding of causes for inefficient energy consumption of a software product, as early as in the design phase.

SECoMo and Sustainable SE models As outlined in the section 4, SECoMo can be integrated into traditional SE processes by adding the estimation or calculation steps in the design phase or later phases. Thus, it should also be possible to integrate SECoMo into sustainable SE processes and SDLC models that are enhanced with sustainability activities (like the ones proposed by [1] and [30]).
A very interesting question is whether it makes sense to *add* SECoMo to the GREENSOFT model. According to [29], SECoMo fits to the GREENSOFT model in general. But as GREENSOFT is a reference model that comprises a variety of approaches [17], SECoMo can not simply be integrated *into* the model, but it needs to be considered at which level it makes most sense. The general concept of eco-costs in SECoMo relates to the first level of GREENSOFT, the life cycle model that is used to assess the impacts of the software in different phases [17] - eco-costs are impacts relevant in the usage phase. The Sustainability Criteria and Metrics as second level of GREENSOFT could be extended by adding SECoMo's eco-cost metrics as part of the environmental metrics. But where SECoMo actually fits best is the third level of GREENSOFT, the procedure models [17]: For the development procedure model, so far there only exists a process model which suggests ways to manage sustainability during the development process. What is missing is a concrete method how to include the

measurement of Sustainability aspects in this development procedure, and as the authors note themselves, additional aspects like for example early estimations of the energy consumptions may enhance their proposed model [17]. SECoMo thus is the perfect addition to the development procedure model of GREENSOFT, especially because it enables estimations at such an early stage like the design phase which makes resulting changes way cheaper [29].
So overall, SECoMo is a suitable method that can be integrated in existing SDLC models, but also could be added to the GREENSOFT model, as it enhances it by providing a concrete approach not only to measure sustainability metrics (here: eco-costs), but also to estimate these eco-costs early, before even the first deployable software is available.

Sustainable SE and SECoMo in practice The previous sections show that SECoMo can enhance and extend existing approaches of Sustainable SE in many ways. Based on this, SECoMo can also help to facilitate the actual practical adoption of such approaches and sustainable SE concepts in general.
First, by enhancing existing methods, like the GREENSOFT model, or as additional metric next to the Carbon Footprint metric [15], their application in practical cases is more likely as they are more concrete and flexible and it is easier to adopt them. Furthermore, the SECoMo approach itself is likely to be applied in practical projects due to its clear structure, the high adaptability and its ability to be integrated in existing SE processes. Thus it provides a suitable starting point for practitioners to start dealing with Sustainable SE topics and for academia to start integrating them in the discussion - a reasonable way to reach the goal of Sustainable SE applied in practice [14]. In addition to integrating practitioners in the discussion, Kern [14] proposes a variety of further ideas how to foster the adoption of Sustainable SE in practice, like formulating concrete rules and guidelines for sustainable software products or integrating sustainable SE concepts in teaching. SECoMo can be of benefit for these ideas, too, for example by providing the basic metrics on which guidelines are formulated, or as a suitable exemplary approach that can be used in teaching in order to give students an idea about the ecological footprint of software.

5.1 Limitations

Being an approach for estimation and calculation of software eco-costs, SECoMo has a focus on environmental sustainability and is thus mainly enhancing software Sustainability in terms of this dimension. It refers to economic sustainability in terms of reducing the costs for late changes to a software product in the development process, or the possibility to express eco-costs in a monetary unit [29], but this is only a minor concern. It could be criticized that in order to be considered a holistically sustainable approach, some kind of social sustainability component would be formally required. This formal limitation however is qualified by the fact that most existing sustainable SE approaches actually focus on environmental sustainability, thus SECoMo is not an exception.

Another critical aspect is the assumption that SECoMo can have a major impact on establishment of sustainable SE approaches in practical projects - this is after all mainly based on the concrete nature of the approach itself and the fact that it allows to be used even with only a small amount of input information available [29], which reduces the obstacles for a practical adoption of the method. In order to actually see if this assumption holds true, it is necessary to first perform further evaluation of the SECoMo approach itself.

6 Conclusion

In the context of Sustainability, ICT and especially software play a major role as contributor to negative impacts, but also as enabler for positive impacts. The research field of sustainable SE deals with approaches to ensure the Sustainability of software products during their whole life cycle. Over the past few years, the amount of contributions to the field has significantly increased, and many approaches exist that tackle different aspects of software Sustainability. But a common understanding and concrete guidance is still missing, and despite the growth of the research field, sustainable SE is still not established in practice.

The SECoMo approach introduced in this paper is a sustainable SE approach that focuses on software usage sustainability by estimating or calculating software eco-costs. It has the ability to enhance existing approaches in the field in various ways and might thus be suitable to help leading Sustainable SE to more adaption in practice: With regards to existing metrics, SECoMo provides a new set of eco-cost metrics that can be applied to various types of software development projects as they are more flexible and can cover a broad range of contexts. In comparison to existing sustainability models in the field, an important role that SECoMo can play is to enhance the already well-rounded GREENSOFT model with a concrete estimation approach for environmental sustainability aspects in order to make its development procedure model more concrete and thus more likely to be adapted in practice. Furthermore, it provides analysis and assessment methods for adding Sustainability as NFR. Over all, SECoMo introduces a new type of approach to sustainable SE with its ability to estimate eco-costs even before development phase has started. It constitutes a concrete and comprehensive approach that can be applied for a great variety of projects and is thus suitable to be adopted in real life projects and to promote sustainable SE, which would foster the integration of practitioners into the discussion about sustainable SE that is so far dominated by academia.

The future work on SECoMo will show whether it is indeed a suitable approach that can enable the adoption of sustainable SE in practice. The research field itself needs to open up to practitioners to finally include the practical view on Sustainable SE and to start with evaluating existing approaches in practice, and it needs to work on finding a common understanding of the underlying concepts. But the trend of adopting Green IT and Sustainability concepts in companies shows that these efforts might soon be worthwhile.

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