Sustainability and Longevity: Two Sides of the Same Quality?

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***Abstract*—This paper attempts to shed light on the relationships between the concerns of sustainability and longevity in software and requirements engineering. Disciplines related to longevity of information and of systems can bring interesting ideas and perspectives to the discussion of sustainability. At the same time, sustainability clearly is a crucial component and critical success factor in determining an actual system's longevity.**

While many isolated techniques exist, the various definitions of sustainability are not all aligned, and clarity on the concepts is needed to move forward. We argue that it is crucial to consider sustainability not just in the sense of lean software, green computing and functional requirements for improving environmental sustainability, but also consider how it applies to the systems under design in a holistic perspective. We discuss possible relationships and synergies and outline a set of research questions for sustainability as a design concern.

I. Introduction

The lack of long-term thinking in software and systems design has been a concern for at least two decades, since Parnas lamented the costs of aging software [1]. However, it is recently coming into increased focus from different angles [2]. The trade-off between short-term interest and long-term benefits manifests in a lack of sustainability with a variety of different symptoms and names - software aging [1], the digital dark ages [3], technical debt [4], lifecycle costs, but also negative impact on the environment of the system under design or outside the (budget planning) time horizon. The latter is the core aspect of what we commonly understand as sustainability: meeting 'the needs of the present without compromising the ability of future generations to satisfy their own needs' [5].

Neumann emphasizes that 'there is much to be gained from farsighted thinking that also enables short-term achievements.' [2]. However, in practice, aspects concerning end-of-lifecycle aspects, system durability, information security and sustainability are often considered as an afterthought or a low-priority requirement that can be sacrificed in the heat of the race towards deadlines. This leads not only to cost overruns and high lifecycle costs in software, but also manifests itself in systems that have negative impacts on their environment, be it in the social dimension (such as security flaws and privacy breaches), in the environmental dimension (such as high energy and other resource consumption) or in the technical dimension, where this often becomes manifest as a lack of resilience, adaptability, durability, longevity, or system sustainability.

Software aging has been one of the first terms used to describe one aspect of this phenomenon, the perceived brevity of useful system lifespans. In the last decade, increasing attention has been paid to the lack of longevity of the information *assets*, and the emerging fields of digital preservation and digital curation focus on the set of processes necessary to sustain digital information across social and technical boundaries. These fields have increasingly moved from focusing on the digital information objects to a broader systems perspective.

In Software Engineering, sustainability is a comparably new topic with several connotations [6]. On one side it relates to environmental sustainability with a focus on environmental informatics, green computing, and systems to support sustainability in the environment. On the other side it relates to sustainable systems design. Here, the perspective has focused on software architecture and systems evolution (see for example [7]).

Disciplines such as preservation and curation provide interesting angles of thought, experiences, and perspectives on sustainability, since they are by their nature taking a long-term perspective. These fields have started to conceptualize and articulate changes needed in software engineering to improve the sustainability of information and computation ecosystems. Their arguments mirror recent complaints about the lack of long-term thinking in software engineering [2].

This article tries to connect the dots in an attempt to identify synergies and possible paths forward. The purpose is to contribute to the emerging discussion on sustainability in requirements engineering and systems design with a perspective on long-term sustainability of systems that is informed by a closely related domain that sustainability research has not yet been connected to.

- We emphasize the similarities between conceptions of longevity and sustainability in recent literature, and clarify the distinctive relationships between the two.
- We shed some light on the sustainability of systems from a long-term information perspective.
- We highlight the crucial nature of early-phase understanding of such concerns and the role of requirements engineering in longevity and sustainability; and
- we pose a set of research questions that should contribute to the larger picture of sustainability research in requirements engineering and information systems design.

In doing so, we will focus for the most part on the sustainability of software and information systems, but also emphasize how this is closely related to the 'other side' of sustainability, the outward view of a system's impact on the environment, and that these facets can be successfully considered only in conjunction.

The article is structured as follows. The next section will introduce notions of information longevity and information systems longevity and discuss sustainability in digital curation and preservation. Section III discusses the implications of such sustainability perspectives on requirements engineering, and Section IV attempts to bring these perspectives together and outline possible avenues of research and practice that appear promising.

II. Sustainability or longevity?

The perspective of this article is influenced by a field whose very existence is built on the premise of sustainability: Digital curation and preservation emerged as disciplines to address the need to carry digital information into the future in authentic form, in reliable and trustworthy environments, to be accessible and understandable for a community of users - which is sometimes very narrow, but often as broad as the general public [8], [9]. Hence, their focus by definition is on future rather than present needs.

The next sections thus introduce key aspects of these domains with a focus on sustainability.

A. Information Longevity and Sustainability

The emergence of digital curation and preservation as fields was initially motivated by cases of information loss including satellite and census data stored on tapes [10] and expensive recovery projects such as the BBC Domesday disc [11]. As interdisciplinary fields, they are connected to digital archiving and records management, research data mangement, computer science and software engineering, information and knowledge management, and digital libraries, to name a few.

Graduating from preserving static bits of data stored on media to preserving the dynamic processes that provide meaningful information and interaction, the emerging conception of digital preservation as enabling computation [12], in particular across ecosystem boundaries, puts the notion of sustainability center stage. In that, it concurs with the notion of sustainable software as being designed to be 'long-lasting'[1]. The notion of 'long' is necessarily a relative one and can last from 7 years (a typical time horizon in legal compliance) to 5000 or more (a nuclear waste information management time horizon). In the standard reference model for long-term digital preservation, long-term is defined as 'long enough to be concerned with the impacts of changing technologies ... or with a changing user community.' [13].

Research and practice in digital longevity has initially focused on mitigation actions, techniques, and controls to address technological and socio-economic change and discontinuity, in particular the perceived threat of obsolescence [8]. Recently, the question has been raised whether obsolescence is a real threat in an increasingly networked ecosystem [14]. There is no conclusive evidence [15], [16], and a better understanding of the ecosystem is needed.

B. Sustainable infrastructure

From their origins in cultural heritage and eScience – in particular archives, museums and libraries and the space data and high energy physics domains – the concerns of digital longevity have become a major topic in fields ranging from eGovernment [17], [18] to digital libraries[2] [19] or environmental sciences [20], [21].

A particularly interesting application domain in this context is the one of digital scholarship, research infrastructures, and data science. This emerging 'fourth paradigm' of science as 'data-intensive scientific discovery' [21] holds tremendous promises, most visibly maybe in the environmental sciences where long-running data collections hold explanations for how the human presence impacts life on our planet, and what can still be done to avoid the worst [22]. From a number of core disciplines that have embraced this paradigm more openly than others, the word of open data and data sharing is spreading rapidly, as evidenced by the recent success of the Research Data Alliance[3] and its manifold interest and working groups.

The sustainability of the emerging global research infrastructures, which are as much social infrastructures as technical ones, should be a key concern. Speaking about the socio-technical nature of cyberinfrastructure, Edwards et al. argue that one cannot design such infrastructure top-down, that it grows in a bottom-up process instead. As such, the sustainability of dynamic ecosystems is a complex subject that may elude intentional design to some degree: 'Better, then, to deploy a vocabulary of growing, fostering, or encouraging in the evolutionary sense when analyzing cyberinfrastructure' ([23], p.12). These thoughts certainly have relevance when considering external sustainability as a design goal for systems.

C. Economically sustainable information

The discourse surrounding digital preservation and curation has increasingly moved from an ex-post treatment to emphasizing the fundamental importance of sustainability both on the levels of infrastructure, organizations, and ecosystems [24] and on the levels of software systems [12].

An influential report on sustainable digital information [24] analyzed the specific nature of digital information assets from an economic perspective and highlighted structural challenges. The authors point to a number of phenomena of wider relevance to the sustainability perspective, including the following.

- **Misalignment of demand** is a particular concern in a field whose existence is derived from future demand for access. Without preservation, there is no access; but without access, there is no need for preservation. Since most of the need occurs outside of most organization's

[1]https://sustainability.wiki.tum.de/Sustainable+Software

[2]Ross and Hedstrom explicitly use the term sustainability, although they do not define it.

[3]https://rd-alliance.org/node

planning horizon, there is little incentive for investment; and it is often difficult, if not impossible, to calculate the net present value of digital assets. Whereas for digital curation and preservation, the primary separator is time, for other areas it is social structure that separates sustainability stakeholders from system designers and decision makers.
- **Market failure** is a common effect of this misalignment: It often makes no economical sense for agents to engage in sustainable activities, since their short-term interests outweigh possible long-term benefits given their business drivers and the market structures they operate in.
- **Incentives and mechanisms**. Taking a broader perspective on sustainable information ecosystems, the report raises the question whether one can 'design institutions that create incentives for private individuals, acting in their own interests, to make choices and take actions that achieve the desired public purpose'. ([24], p. 94) It identifies a need for research into how *mechanism design* approaches employing game-theoretic concepts can provide a deeper understanding of the subject.

D. Information Systems Longevity and Sustainability

Increasingly, the perspective of research on digital longevity has shifted towards addressing the root causes and establish longevity as a design concern upstream in the systems lifecycle. We articulated this explicitly in [25], where we observed that many approaches and techniques exist in isolated perspectives that contribute to increase both information longevity and system longevity (and sustainability), but that there are no accepted perspectives on longevity as an overarching concern that would integrate and drive such techniques. We argued for interdisciplinary research efforts dedicated towards long-term perspectives on systems design from the inception onwards. In the conception of longevity as an information systems design concern brought forward in [25], longevity as a systems design concern is composed of three major concerns.

- **Information longevity** relates to the "ability to govern information independently of and across systems".
- The "**ability to sustain** the information system, across an unstable organizational and technological context, for as long as a defined set of conditions holds" is further linked to the qualities of system evolution and system resilience as key quality concerns.
- Finally, the existence of an **exit point** enables the system owner to "move the information base and the defined valid state changes.... to .. another system" when this is beneficial. [25]

We note that these observations and arguments show striking parallels to those voiced by [26], [27] from the perspective of software engineering for sustainability: The notion of sustainability corresponds to *relative sustainability* defined in [27] – the expectation that the organization context surrounding the solution space artifacts will be able to sustain the system for as long as needed, 'preserving the function of a system over a defined time span' [27]. It is in this context very interesting to note the usage of the term preservation for defining sustainability. However, the question arises if sustainability requires the exact notion of preservation – if a system evolves continuously to *better* provide its function and values to the environment without negative impact, that seems to be a very sustainable system without necessarily *preserving* its function in full.

On the other hand, it seems that the narrow interpretation of technical sustainability in [25] misses the wider social ecosystem facet of system sustainability, where technical system qualities can only be seen as co-determinants of sustainability.

The exit point addressed above corresponds to what Milic-Frayling calls the explicit consideration of end-of-life aspects of system design: Besides established software quality attributes, 'we need to include properties that pertain to the end-of-life of computing systems. These should include provisions for minimizing the expected effort and cost of sustaining digital assets produced by the system.' [12].

E. Synthesis

So what can digital curation, archiving and preservation – or digital stewardship, as it is sometimes called [33]– bring to the sustainability debate in requirements and software engineering?

Since curation and preservation by their nature take a long-term perspective, they can offer insights into the role that the longevity of information assets play in the sustainability and longevity of the system which they are part of. As such, advocates of sustainability in software and requirements engineering can find a natural ally in the domains of digital curation and preservation.

We noted that the conceptualizations of sustainability in software and requirements engineering are very similar in nature to the conceptualization of longevity as outlined above. If sustainability is defined as 'preserving the function of a system over a defined time span' [27], is there a difference at all between longevity, preservation, and sustainability of an information system?

For one, preservation may not be an adequate term to define sustainability, as it implies fixing an entity over time, whereas sustainability is a more open-ended and relational concept that refers to how systems influence each other. Longevity as an effect manifests only in time. As a design concern, it emphasizes the durability of the system itself and the crucial importance of thinking beyond that duration, recognizing the importance of external relationships. Sustainability is by nature of its origin concerned with contextual factors, but emphasizes the long-term aspects this perspective entails. The *observed effect* of long-living systems that have no negative impact on the environment is similar for both perspectives.

Long-term sustainability of information about a system is fundamental for understanding the sustainability of the system itself. The fundamental importance of designing sustainability into the infrastructure, organizations, and systems for digital curation and preservation makes these fields an interesting test case for approaches to sustainability.

It becomes clear that it would be counterproductive to focus definitions of sustainability on the external view alone, i.e. the absence of negative impact on the environment. A holistic perspective including both sides of the coin, as suggested for example by [27], is much more representative of the very nature of sustainability itself.

III. Implications for sustainability in requirements research

There is ample awareness of the need to address sustainability in academic literature, as evidenced recently for example in Special Issues of IEEE Software on Architecture Sustainability and on Green Software. However, this does not translate into practical success. As Neumann points out, 'We should anticipate the long-term needs that a system or network of systems must satisfy, and plan the development to overcome potential obstacles that might arise, even if the initial focus is on only short-term needs. This might seem to be common wisdom, but is in reality quite rare. Common requirements for ... adaptability, human safety, interoperability, long-term evolvability, trustworthiness, and assurance evaluations are generally much too weak.' [2] Why is this the case?

A crucial distinction has to be made between a solution-oriented *system quality* and a (problem-oriented) *concern*, i.e. an 'interest in a system relevant to one or more of its stakeholders' [28]. The latter does not simply translate into the former. For example, the sustainability *of* a system architecture as defined by Koziolek et al [29], [30], is clearly a system quality. However, sustainability of a complex socio-technical information system does not translate into a system quality easily. Similar to the notion of IS longevity outlined in [25], it is a design concern that will be relevant to certain stakeholders, not all of which are commonly involved directly in the requirements and design stages. It will raise the importance of specific capabilities and qualities in the system under design and will need to be addressed using specific viewpoints, methods, concepts and techniques.

It is this observation that emphasizes the crucial role of requirements engineering in sustainability: For the most part, some techniques required to address sustainability may already exist. They include patterns that increase architecture modularity and hence facilitate evolution, model-driven approaches to decouple long-living conceptual aspects from short-lived technical implementation aspects, trade-off analysis methods, and many others. By identifying relevant aspects and facilitating prioritization, requirements engineering can bring into focus those elements that are most critical; identify stakeholders and concerns and their relationships; establish which trade offs have to be considered; and thus ensure a focus on critical aspects with a real impact on sustainability in specific system scenarios.

However, for many systems, the concerns are not sufficiently identified as relevant and valuable, the implications are not well understood, and the techniques hence often not applied. Evidence on the effectiveness of these techniques over longer timespans is scarce.

Assessing the real gaps of engineering techniques in the light of sustainability requirements requires a solid understanding of sustainability concerns. This needs to build on solid conceptual foundations. Future studies need to go beyond claiming that sustainability is a relevant quality and clearly translate the concern in specific instances into relevant qualities to enable designers to address these concerns systematically. Initial studies such as by Mahaux [31] demonstrated the feasibility of addressing concrete sustainability concerns with existing requirements concepts and techniques. Penzenstadler argued that models from the sustainability domain can provide useful assistance in requirements engineering activities [32]. Larger efforts and a shared knowledge base are needed to establish common terminology, identify patterns, and deepen the understanding of the complex relationships between the design concerns, stakeholders, system capabilities and qualities, and possible patterns of addressing them.

IV. Conclusion and Outlook

A. Summary

We have attempted to highlight new relationships between digital longevity and sustainability, illustrating the relevance of sustainability in disciplines such as digital curation and preservation and highlighting approaches to sustainability in these disciplines.

It becomes clear that it is crucial to apply sustainability not just in the sense of lean software and functional requirements to support sustainability outside the system, but also consider how it applies to the systems under design. Not only are these the aspects that are under the control of the designer, they are also the opportunity to turn concepts onto our own field and evaluate the contributions first-hand. Promising approaches have been brought forward, but a common understanding is lacking, and a certain incoherence can be diagnosed between related, non-competing approaches with potential for synergy. This is of course a normal observation for an emerging field.

B. Research questions

In the following, we outline some questions that arise from the discourse. Instead of providing a comprehensive roadmap, this should be seens as a starting point for a broader discussion and engagement.

- **Trade-off decisions.** The different dimensions of sustainability (social, technical, human, and environmental) are interrelated. Real sustainability is only achieved where all areas overlap. This implies that over-investing to extend one aspect of sustainability will be wasteful unless excess sustainability from this or another dimension can be transferred to cover gaps in other dimensions. A typical case is a transfer of economic excess sustainability towards technical sustainability, investing into a software architecture renovation in order to address technical debt. Can early-phase models support robust design decisions considering these trade-offs?
- **Digital ecosystems.** The focus on early phases and the contextual understanding of a system requires a much

more profound understanding of ecological questions in dynamic ecosystems. For example, how do the life cycles of adjacent and indirectly connected systems and technology components affect the sustainability of a system under design? How do the lifecycles of digital ecosystems affect their environment?
- **The role of information longevity and curation.** In addition to system qualities, the question arises what role information longevity plays in supporting system sustainability, and how this goes beyond what is currently recognized as *data quality* in ISO SQUARE [34], [35].
- **The impact of long-term preservation.** Not only do many digital objects live much longer than originally intended today - and in multiple redundant locations - we also do not normally know the potential negative impact of creating or preserving them. It has been possible to provide an estimate of the carbon footprint of a Google search, but it is much more difficult to provide an estimate for the footprint of a new piece of digital data to be stored for 10 years or more.
- **Modelling.** Sustainability clearly calls for holistic perspectives. Lankhorst points out the shortage of support for assessing longer-term change in system architectures beforehand [36]. Can Enterprise Architecture be leveraged effectively for addressing sustainability concerns? Does a successful consideration of sustainability in software and systems design require new viewpoints?
  Recent contributions discussed the sustainability of architectural design decisions [37] and emphasized the role of decision viewpoints to support architectural design [7]. Do current viewpoints provide adequate support for decision making in sustainability? How can requirements engineering support a systematic and traceable consideration of sustainability aspects in architectural design?
- **Qualities.** How do inwards and outwards sustainability relate to system qualities? How can these relationships be analyzed systematically? While the contribution of performance efficiency to green computing is one obvious answer, it is clearly not the only connection that can be made. When considering longer timeframes, the relationships become more complex. We need a much more precise understanding of the relationships between both types of sustainability and specific software capabilities and qualities, underpinned by empirical studies.
  Generally, quality is used in a static sense, missing a designation of its evolution over the system lifetime. However, the desired system qualities will inevitably change over time. How can we anticipate likely changes with critical impact early?
- **End-of-life.** Under which circumstances should end-of-life concerns be considered? Can there be a case made for these that is convincing to decision makers and system designers in the initial stages of the system lifecycle?
- **Requirements patterns** for specific sustainability contexts and concerns could provide a helpful resource for the broader community of requirements engineers, enabling practitioners to introduce these concepts to their clients. First efforts have started to address this, but are limited to environmental sustainability features and not based on rigorous analysis [38]. Correspondingly, *design patterns* for particular solution schemes in well-contextualized situations will be a natural future step to enable broader takeup of tested solutions. Such patterns could likely be identified already in the domains of preservation and curation.
- **Practice.** As pointed out 15 years ago in a related context, '"The real problem", says computer designer Hillis, "is not technological. We have the technical understanding to solve problems such as digital degradation. What we don't have yet in our digital culture is the habit of long-term thinking that supports preservation..."' [3] If that is the case regarding sustainability, what are the inhibitors that prevent the concern from being successfully addressed, and how can requirements engineering contribute to an increased awareness of the importance and benefits of this concern?
- **Culture.** System designers often lack an understanding of the cultural and social determinants of sustainability on organizational, societal, and community levels. A shared understanding of key factors should provide a useful toolset for requirements analysis. This could first on specific highly interested communities such as green computing, research infrastructures, or digital curation. What are the cultural factors that influence the perception of relevance of sustainability in organizations? Can a systematic approach towards analyzing and documenting these in an RE process increase the effective consideration of sustainability concerns?

C. A sustainable software design manifesto?

Neumann, a vocal advocate for long-term thinking, calls for more systematic experimentation and more formality in design, but also emphasizes the importance of a 'holistic balance of human intelligence, experience, memory, ingenuity, creativity, and collective wisdom, with slow and fast thinking' [2], pointing to Kahnemann [39].

To facilitate the establishment of a stable and sustainable research agenda, a focal point of reference is needed, synthesizing the diverse aspects and providing an openly accessible, robust and clearly delineated reference point clarifying the scope, facets, objectives and challenges of the emerging research discipline and enabling the setup of interdisciplinary platforms of research and practice. It may be the right moment for a sustainable design manifesto for requirements engineering (or software engineering) as a focal point bundling objectives and perspectives in a coherent message of reference.

Analogous examples to consider are plentiful, in particular in the general area of sustainable design[4], but generally aimed at a non-academic, broad audience. On the software side, they include the Agile Manifesto[5] and the Business Rules mani-

[4] e.g. http://www.core77.com/reactor/04.07_chochinov.asp
[5] http://agilemanifesto.org/

festo[6], but also the SOA manifesto[7] and the Recomputation manifesto[8]. However, most manifestos have not been created in collaborative, open creation process with an explicit focus on sustainability. An example of a very collaborative approach can be seen in the Force11 manifesto on 'Improving Future Research Communication and e-Scholarship'[9] .

As Neumann points out, realistically, 'the real-world arguments for short-term optimization are likely to continue to prevail unless significant external and internal efforts are made to address some of the long-term needs.' [2] An open manifesto for forward-thinking sustainable software design, drafted collaboratively in an open and sustainable process, could set a milestone and provide the necessary focal point for joint future efforts.

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