Habilitation

Perspectives on Digital Sustainability

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by

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Summary

This habilitation thesis presents perspectives on digital sustainability, a novel concept connecting digitalization with sustainability. It explains why digital artifacts such as software or data have to meet technical characteristics of quality, transparency, semantics and multiple locations in order to serve society in the long term. However, these requirements are just necessary but not sufficient preconditions to consider digital artifacts sustainable. Their associated ecosystem of businesses, governments, and individuals must also meet the legal and organizational characteristics of open license, shared tacit knowledge, participation, good governance, and diversified funding. And, finally, sustainable digital artifacts must lead to ecological, societal and economical benefits.

This thesis statement is discussed in the introductory chapter of the habilitation. It connects and summarizes 13 refereed publications clustered in five perspectives on digital sustainability:

In the first perspective, the path of defining the concept of digital sustainability is summarized. This part starts with a publication that introduced an initial set of characteristics for digital sustainability (Stuermer, 2014). The following article connects digital sustainability with digital preservation (Stuermer and Abu-Tayeh, 2016). These studies have eventually led to an extended publication in a sustainability journal elaborating the basic conditions of digital sustainability in detail (Stuermer et al., 2017a).

The second perspective includes recent publications on open source software (OSS) research scrutinizing how patterns of digital sustainability are applied within the software development industry. One publication analyzes feature requests within the Eclipse OSS community (Heppler et al., 2016). The following article develops a maturity model of Inner Source, a special form of OSS development practices in an organization (Eckert et al., 2017). And one study in a computer science journal addresses different types of OSS governance by comparing independent and joint communities (Eckert et al., 2019).

The next perspective focuses on the procurement of information technology (IT) which involves critical topics of knowledge management and governance related to digital sustainability. Analyzing data crawled from the Swiss public procurement platform Simap.ch exposes lock-in effects, outsourcing decisions as well as multisourcing within the software industry. One article in this perspective introduces the methodology and the dataset pointing out the high level of direct awards within the IT sector (Stuermer et al., 2017b). Another publication tests hypotheses on contract choice in regard to knowledge specificity and task scope (Krancher and Stuermer, 2018a). And one study explains multisourcing decisions using a large dataset on public procurement of IT in Switzerland (Krancher and Stuermer, 2018b).

The subsequent perspective highlights open data and linked data as another form of sustainable digital artifacts. One publication proposes a framework permitting the measurement of the impact of open data (Stuermer and Dapp, 2016). Another article introduces linked open government data (LOGD), a kind of graph-structured open data stored in different kinds of platforms (Hitz-Gamper et al., 2019).

The final perspective extends the phenomenon of open data into the area of governmental services. By linking the concepts of public governance and open government one article shows how transparency and participation are achieved with digital tools (Stuermer and Ritz, 2014). Another publication includes an empirical analysis of the FixMyStreet open government platform in Zurich called “Züri wie neu” using open data and a user survey to identify the motivation of citizens using this digital tool (Abu-Tayeh et al., 2018).

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1. Introduction on Digitalization and Sustainability

Back in 2011 venture capitalist Marc Andreessen wrote the article “Why software is eating the world” arguing that information and communication technology (ICT) and in particular the software industry will transform the global economy (Andreessen, 2011). He was right: In the beginning of this decade the largest corporations were mostly oil and gas companies as well as banks and retailers. Today, in September 2019, only eight years later, the five most valuable companies are belong to the ICT sector: Microsoft, Amazon, Apple, Google (Alphabet), and Facebook have a joint market capitalization of 4.3 trillion USD – significantly more than the 3.9 trillion USD gross domestic product (GDP) of Germany, the fourth largest economy of the world. This illustrates the economic dominance private technology companies have gained in recent years and it emphasizes the tremendous power controlled by a few individuals.

At the same time the ecological effects of the increasing use of digital technologies are growing rapidly. Recent estimations assume that the share of ICT in global greenhouse gas emissions has increased by 50% in only five years, rising from 2.5% in 2013 to 3.7% of global emissions in 2018 (Ferreboeuf, 2019). These are more greenhouse gas emissions than those of the entire civil air transport, which amounted to about 2% in 2018 according to the report of the Shift Project (Ferreboeuf, 2019). In addition this report concludes that the total energy consumption for the production and use of digital technologies currently rises by 9% per year and is expected to reach around 3800 TWh in 2020. Because the digital energy consumption is increasing much more rapidly than the global value its share grew from 1.9% in 2013 to 2.7% in 2017, and is expected to reach 3.3% in 2020 and possibly 6% in 2025.

The growing power of ICT corporations and the ecological impact of digital technology indicate two major challenges of the ongoing digital transformation particularly in relation to sustainability. The aim of this habilitation is thus to develop a novel connection between digitalization and sustainability addressing privatization of digital knowledge as well as environmental effects. Thus, the first section presents a definition and overview of each concept followed by three different aspects of their combination: Describing the similarities and differences between “sustainability *of* digitalization” and “digitalization *for* sustainability” eventually leads to the concept of “digital sustainability”.

The second section presents the thesis statement substantiating it with the articles of this habilitation. It connects the basic conditions of digital sustainability with the publications grouped along the five perspectives of digital sustainability, namely open source software, procurement of information technology, open data and linked data as well as open government. The third section provides a summary of the 13 habilitation articles, and the final section contains the conclusions and an outlook for future research in the area of digital sustainability.

1.1. Digitalization

The amount of data and software is increasing enormously. In 2014, Facebook users alone created 4 petabytes (4’000’000 gigabytes) per day (Wiener and Bronson, 2014). The data stored currently on this planet in digital form is estimated at 33 zetabytes (33’000’000 petabytes), expected to grow up to 175 zetabytes until 2025 (Reinsel et al., 2018). Therefore, big data researchers are working constantly to find ways of handling the massive data while still making sense of them by descriptive, predictive, and prescriptive analytics (Sivarajah et al., 2017).

This trend is being called different names: “Digitization”, “digitalization”, “digital transformation”, “digital revolution”, or “digital transition”. These terms are often used interchangeably in current practitioner-oriented and even research literature. Nevertheless, there exist in fact clear distinctions between some of the terms. It all goes back to the 90’s: In his book “Being digital”, Nicholas Negroponte in 1995 coined the term “digitization” to describe the conversion of analog information and processes into digital format in a technical sense (Negroponte, 1995). This definition is supported still today as it describes the process of dematerialization and decoupling of information from physical carriers using digital technologies (Legner et al., 2017).

On the other hand, “digitalization” refers to the sociotechnical process of adopting these technologies in an organizational and societal context (Tilson et al., 2010). Similar to this understanding some scholars use “digital transformation” to focus on changes on the organizational level (Berghaus and Back, 2017), while others refer to the transformation of entire industries (Ustundag and Cevikcan, 2018) and business models (Loebbecke and Picot, 2015) through digitalization. As such, some scholars argue that “digitalization” and “digital transformation” in fact describe the same phenomenon (Riedl et al., 2017). A recent literature overview of 282 research articles on “digital transformation” resp. “digital disruption” defines it as “a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies” (Vial, 2019). Thus this thesis uses "digitalization" as a term that encompasses a holistic view of all changes that arise from the growing technical possibilities of software and data as well as the digital networking of people and machines.

1.2. Sustainability

Similar to the vast topic of digitalization, the area of sustainability is also attracting a great deal of attention in academic research today even though the subject has a long history. The original definition of “sustainability” can be derived from 18th century forestry, when it was obvious that only as many trees should be cut as will grow back (Von Carlowitz, 1713). A more recent definition was provided by the Brundtland Report “Our Common Future” in 1987 (Brundtland et al., 1987): “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” It presents an understanding no longer connected directly with the physical world only but with all needs of current and future generations. This definition of “sustainable development” thus follows the goal to create intra-generational and inter-generational equity, the twin principles of sustainability (George, 1999).

In the 1990s the term “triple bottom line” coined by John Elkington introduced the notion that sustainability has to meet three goals: economic prosperity, environmental quality and social justice (Elkington, 1997). This view even convinced managers, consultants, and investors, thus bringing the concept of sustainability into the corporate world. Although the triple bottom line was and still is disputed (Norman and MacDonald, 2004), it remains a relevant concept to measure sustainable development e.g. through corporate social responsibility (CSR) initiatives (Painter-Morland, 2006).

Today, however, sustainability is primarily associated with the 17 Sustainable Development Goals (SDG) of the United Nations (UN General Assembly, 2015). Based on the principles of “planetary boundaries” (Rockström et al., 2009) the United Nations have extended their Millennium Development Goals (MDG) into the categories of the triple bottom line: economic development, environmental sustainability, and social inclusion (Sachs, 2012; Griggs et al., 2013). Thus, the SDG represent today’s globally agreed on agenda to fight poverty, protect the planet and ensure prosperity for all (Blanc, 2015).

1.3. Three aspects of digitalization and sustainability

While the two issues of digitalization and sustainability elaborated above are both complex and subject to constant change, their combination often leads to even more misunderstandings. There exist three different aspects how digitalization and sustainability relate to each other: In the first aspect, “sustainability of digitalization”, critics of digitalization highlight the energy consumption and electronic waste production of digitalization, thus pointing to its negative consequences (Kuntsman and Rattle, 2019). In a second aspect, “digitalization for sustainability”, experts in information and communication technologies (ICT) recognize the potential of digitalization for addressing climate change and supporting other issues of sustainable development (Seele and Lock, 2017). This habilitation introduces and focuses on a third aspect of digitalization and sustainability, “digital sustainability”, the sustainability of digital artifacts such as data and software. These three aspects are elaborated next.

A) Sustainability of Digitalization

“Sustainability of digitalization” covers the ecological effects caused by ICT, also called “life-cycle impact” (Hilty and Aebischer, 2015). A new report of the Shift Project assumes the share of ICT in global greenhouse gas emissions has increased by 50% from 2013 to 2018, rising from 2.5% to 3.7% of global emissions (Ferreboeuf, 2019). In particular, the total energy consumption of data centers, networks, Internet of Things (IoT) sensors and end user devices is currently rising by 9% per year and is expected to reach about 3800 TWh in 2020. In a worst-case scenario researchers even predict digital technologies to claim 51% of global electricity consumption in 2030 (Andrae and Edler, 2015). The main reason for this growth is the expectation that improvements in energy efficiency are not likely to keep up with the rate of global Internet traffic increase (Andrae, 2019).

One particular problem involves electricity and data demand peaks caused by media consumption in evening hours (Morley et al., 2018). In general, streaming of online videos is estimated to generate 80% of the global traffic on the Internet thus causing the largest share of energy consumption and carbon emissions (Efoui-Hess, 2019). Other challenges in ICT are hardware production and disposal. On the production side, ICT equipment requires various metals such as gallium, germanium, indium and rare earths elements (Chancerel et al., 2015). Once the hardware is disposed, these metals usually get lost in a large pile of electronic waste (Widmer et al., 2005) estimated today at 50 million tons per year (Kaya, 2016).

It is obvious that buying less powerful devices lowers electricity consumption and using electronic equipment as long as possible reduces waste (Ferreboeuf, 2019). Such technical strategies to reduce energy consumption and evade other ecological issues related with ICT are provided by “Green IT” principles (Murugesan, 2008; Velte et al., 2009; Esfahani et al., 2015). Sophisticated technological ways to save energy are for example Content Delivery Networks (CDNs) which lower the required Internet traffic by storing frequently used data packages on local servers. Such technologies reduce the distance and consequently the amount of data traffic thus saving electricity (Lee et al., 2011).

B) Digitalization for Sustainability

Digital transformation may also facilitate sustainable development despite its negative effects elaborated above. Defined as “ICT for sustainability” (Hilty and Aebischer, 2015) or “digitalization for sustainability” (Seele and Lock, 2017), research has identified multiple ways how digital technologies may reduce greenhouse gas emissions, lower energy consumption in general or improve public welfare and justice. These include video conferencing to reduce travelling to international conferences (Coroama et al., 2012), software to create a market within organizations to limit the number of business flights to reduce CO_2 emissions (Maranghino-Singer et al., 2015), using big data for smart energy management (Zhou et al., 2016), or fight corruption and increase tax compliance with digital tools (Fanea-Ivanovici et al., 2019).

Since 2010 the concept of the “smart city” has attracted the attention of academic scholars and practitioners (Meijer and Bolívar, 2016). It involves the use of technology to achieve sustainability in cities. An analysis of the numerous smart city frameworks developed in recent years points out many similarities with the concept of urban sustainability (Ahvenniemi et al., 2017). Therefore SDG 11 “Make cities and human settlements inclusive, safe, resilient and sustainable” is strongly linked with the smart city discussion (Klopp and Petretta, 2017) representing a relevant area of technology used for sustainability.

The challenge remains to determine how digitalization affects sustainability on the bottom-line. Is “IT for Green” bringing more benefits than causing problems (Faucheux and Nicolaï, 2011)? Teleworking demonstrates the so-called “rebound effect” (Greening et al., 2000): For example, energy is saved because people do not have to commute to work every day. However, this leads to an increase of the possible work distance. So, when these people do have to go to work the overall travel distance might be even greater (Coroama and Mattern, 2019). Another example is the “myth of the paperless office”: Sellen and Harper (2003) found back in the early days of the Internet that the use of email within an organization increased the amount of paper use by 40% on average. Such ecological paradoxes are frequent in the case of technological advances (York, 2006) leading to so-called rebound effects in ICT (Gossart, 2015). Thus, the overall impact of digitalization on sustainability remains an open question.

C) Digital Sustainability

So far literature on sustainable development sees technology as a means to an end (Mansell and Wehn, 1998; Weaver et al., 2000; Unwin and Unwin, 2009; Stafford-Smith et al., 2017). However, the increasing role and dependence on digitalization raises new issues of how to manage the large amount of data and software involved, particularly since digital innovations mostly stem from the private sector (Dolata, 2018). The primary goal of privately-owned enterprises controlling most of the global digital knowledge is to raise the shareholder value by increasing users' dependence on their technology by means of vendor lock-in (Zhu and Zhou, 2012). This usually leads to proprietary data silos and monolithic IT systems (Johansen et al., 2014) where individuals and organizations lose control over their data and software.

In contrast, trends such as the open source (Raymond, 2001), open community network (Flickenger, 2002), open content (Forte and Bruckman, 2005), open data (Janssen et al., 2012) and open hardware (Powell, 2012) movements show alternative ways to innovate and collaborate within the digital space. In the last 30 years, hacker communities and civic tech groups have emerged as reliable partners for technological developments showing high commitment and non-profit motivation for providing services to society thus increasing the public value of digitalization (Von Krogh et al., 2012; Micholia et al., 2018). While, for instance, corporations have incentives to follow “planned obsolescence” strategies in order to stimulate repeated purchases by customers (Bulow, 1986), open source and open hardware communities strive to make their products last as long as possible (Rosner and Ames, 2014; Kostakis et al., 2018) by applying open source design principles (Bonvoisin, 2016).

In addition, open source software and open standards-based data formats are well-suited for long-lasting data storage and retrieval called "digital preservation" (Madalli et al., 2012). It is well known that suitable software is necessary to interpret documents and that it is also a problem to have the appropriate operating system and hardware to run this software (Rothenberg, 2000). Rothenberg (2000) suggests using emulators in order to run old software tools on new systems. Another approach to have long-term support for software tools is suggested by Gamalielsson and Lundell (2014) who conducted research about the sustainability of open source communities. In their empirical analysis of OpenOffice.org, LibreOffice and Apache OpenOffice, they found that forking within open source communities is an important governance mechanism to decrease dependence on software vendors. Such social processes within open source communities are crucial for sustainable technical contributions because they limit the power of commercial interests (Crowston et al., 2008).

To provide a generic framework for the longevity of freely available data, software, and other digital artifacts including their associated communities, the concept of digital sustainability has been developed (Stuermer, 2014). It focuses on the sustainability of digital artifacts and their ecosystems that together deliver a valuable contribution to ecological, social and economic goals (Stuermer and Abu-Tayeh, 2016; Stuermer et al., 2017a). While the concept and its history are elaborated in more detail later in this thesis, a list of the ten basic conditions for sustainable digital artifacts is presented below (see Table 1). They constitute the core element of the concept, describing both the necessary conditions for the digital artifact itself as well as the requirements for its ecosystem. The tenth condition of the conceptual framework provides a link to sustainable development demanding contribution on an ecological, social, and economical level.

Digital artifact		
1	**Elaborateness**	The elaborateness of digital artifacts is determined by their modularity, integrity, accuracy, robustness, and other characteristics regarding the quality of their substance
2	**Transparent structures**	Transparent structures signify technical openness allowing access to the inner structures of digital artifacts, such as source code, standard specifications, content, or data structures
3	**Semantic information**	Semantic information makes complex digital artifacts more easily intelligible to humans and machines through comprehensible structures and meta data
4	**Distributed location**	Distributed location means data, software and other digital artifacts are stored and operated on multiple sites, e.g. through replicated data storage or peer-to-peer technology
Ecosystem		
5	**Open licensing regime**	Open licensing regimes grant everyone the right to use and modify digital artifacts at no cost and for any purpose, thus providing improvements and enhancements without limitation
6	**Shared tacit knowledge**	Shared tacit knowledge of digital artifacts means the availability of many individuals and organizations knowing because of their experience how to understand, use, and modify digital artifacts
7	**Participatory culture**	Participatory culture signifies permeability of contributions throughout the entire lifecycle of digital artifacts, enabling peer-review processes on all levels
8	**Good governance**	Good governance means the digital artifact and its ecosystem is not controlled by a single individual or organization, but governed in a decentralized way by its contributors and other stakeholders
9	**Diversified funding**	Diversified funding allows cost covering of infrastructures, contributions, and other spending from various financial sources instead of dependence on one or a few individuals or organizations
World		
10	**Contribution to sustainable development**	Contribution to sustainable development means sustainable digital artifacts must provide positive ecological, social or economic effects

Table 1: Basic conditions of sustainable digital artifacts (Stuermer et al., 2017a)

1.4. Overview of definitions

The sections above have discussed the terms “digitalization” and “sustainability” and presented aspects of their interrelationships. Since terminology applied in this thesis sounds similar but still requires a clear distinction the following Table 2 presents a list of definitions of these frequently used terms and concepts. Apart from the term “sustainability” the definitions below although inspired by literature (see references above) are formulated newly in this thesis.

Term	***Definition used in this thesis***
Digitization	Conversion of analog information and processes into digital format
Digitalization	A holistic view of all changes arising from the growing technical possibilities of software and data as well as the digital networking of people and machines
Sustainability	Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al., 1987).
Sustainability of digitalization	The ecological and social effects caused by the production and use of information and communication technologies (ICT)
Digitalization for Sustainability	The use of information and communication technologies (ICT) to reduce ecological and social problems in ICT and other sectors
Digital sustainability	Long-term availability of software and data (digital artifacts) for the entire society that provide positive ecological, social or economic effects

Table 2: Definitions of frequently used terms and concepts in this habilitation thesis

2. Substantiating the Concept of Digital Sustainability

Building on the terminology and concepts elaborated above this section formulates the thesis statement which encompasses the common goal of the publications of this habilitation. It then connects the thesis articles with the basic conditions of digital sustainability and discusses challenges of operationalization, terminology, and sustainable development.

2.1. Thesis statement

The research of this habilitation thesis assumes that digital sustainability is not limited to the technical characteristics of a digital artifact itself. For the long-term availability of digital knowledge the societal rules of its producing community are essential. And the software and data involved should also benefit society and environment to sustain its physical embedding.

Thus, the statement of this thesis is as follows:

> *For software and data to be available over time for the entire society, not only must sustainable digital artifacts meet the technical characteristics of quality, transparency, semantics and multiple locations. The associated ecosystem of businesses, governments, and individuals must also meet the legal and organizational characteristics of an open license, shared tacit knowledge, participation, good governance, and diversified funding. And the digital artifacts must lead to ecological, societal or economical benefits.*

2.2. Connecting the articles with the basic conditions

The following 13 peer-reviewed articles published in academic journals and conference proceedings (Table 3) substantiate the thesis statement above. These publications are grouped into five distinct perspectives on digital sustainability thus representing the body of this habilitation (see Appendix).

Perspective A) Digital Sustainability:				
#1	Matthias Stuermer	2014	*Characteristics of Digital Sustainability*	8th International Conference on Theory and Practice of Electronic Governance (ICEGOV 2014) in Guimarâes, Portugal
#2	Matthias Stuermer, Gabriel Abu-Tayeh	2016	*Digital preservation through digital sustainability*	13th International Conference on Digital Preservation (iPRES 2016) in Bern, Switzerland
#3	Matthias Stuermer, Gabriel Abu-Tayeh, Thomas Myrach	2017	*Digital sustainability: Basic conditions for sustainable digital artifacts and their ecosystems*	Sustainability Science, Special Feature "Sustainability and Digitalization" March 2017, Volume 12, Issue 2, pp 247–262
Perspective B) Open Source Software:				
#4	Lukas Heppler, Remo Eckert, Matthias Stuermer	2016	*Who cares about my feature request?*	12th International Conference on Open Source Systems 2016 (OSS 2016) in Gothenburg, Sweden
#5	Remo Eckert, Sathya Kay Meyer, Matthias Stuermer	2017	*How are Open Source Practices Possible within a Medical Diagnostics Company? Developing and Testing a Maturity Model of Inner Source Implementation*	OpenSym '17 Proceedings of the 13th International Symposium on Open Collaboration, Galway, Ireland
#6	Remo Eckert, Matthias Stuermer, Thomas Myrach	2019	*Alone or Together? Inter-organizational affiliations of open source communities*	Journal of Systems and Software 149, pp 250–262
Perspective C) Procurement of Information Technology (IT):				
#7	Matthias Stuermer, Oliver Krancher, Thomas Myrach	2017	*When the exception becomes the norm: Direct awards to IT vendors by the Swiss public sector*	10th International Conference on Theory and Practice of Electronic Governance (ICEGOV 2017) in New Dehli, India
#8	Oliver Krancher, Matthias Stuermer	2018	*A Knowledge-Based Perspective on Contract Choice in Application Outsourcing*	Multikonferenz Wirtschaftsinformatik 2018 (MKWI2018)
#9	Oliver Krancher, Matthias Stuermer	2018	*Multisourcing Decisions in Application Outsourcing: Test of a Multi-theoretical Model*	26th European Conference on Information Systems (ECIS 2018) in Portsmouth, UK
Perspective D) Open Data and Linked Data:				
#10	Matthias Stuermer, Marcus Dapp	2016	*Measuring the promise of open data: Development of the Impact Monitoring Framework*	International Conference for E-Democracy and Open Government 2016 (CeDEM16) at Danube University Krems, Austria
#11	Benedikt Hitz, Oliver Neumann, Matthias Stuermer	2019	*Balancing Control, Usability and Visibility of Linked Open Government Data to Create Public Value*	International Journal of Public Sector Management, 2019
Perspective E) Open Government:				
#12	Matthias Stuermer, Adrian Ritz	2014	*Public Governance durch Open Government: Zwei sich ergänzende Ansätze für die staatliche Aufgabenerfüllung der Zukunft*	SGVW Jahrbuch 2014 „Sustainable Public Governance – Nachhaltige Politik und Verwaltungsführung“
#13	Gabriel Abu-Tayeh, Oliver Neumann, Matthias Stuermer	2018	*Exploring the motives of citizen reporting engagement: self-concern and other-orientation*	Business & Information Systems Engineering, June 2018, Volume 60, Issue 3, pp 215–226

Table 3: List of the 13 publications of this habilitation grouped into five perspectives on digital sustainability

These publications include theoretical as well as data-driven contributions, focused on software development, data management and governmental services, inducing inter-generational and intra-generational perspectives on the subject. Aggregated in five groups (digital sustainability, open source software, procurement of IT, open data and linked data, as well as open government) they present five perspectives on digital sustainability.

Table 4 provides an overview of how the basic conditions of digital sustainability are covered by the five perspectives of this habilitation thesis. In the following, the relationships between the articles and the basic conditions of digital sustainability are elaborated.

		Perspectives:	A) Digital Sustainability			B) Open Source Software			C) Procurement of IT			D) Open Data & Linked Data		E) Open Govern-ment	
Basic Conditions of Digital Sustainability:			**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#11**	**#12**	**#13**
Digital artifact	**1**	**Elaborateness**	▒	■	■	■						■	■		■
	2	**Transparent structures**	▒	■	■	■	▒		■			■	■		■
	3	**Semantic information**	▒	■	■								■		
	4	**Distributed location**	▒	■	■								■		
Ecosystem	**5**	**Open licensing regime**	▒	■	■			■	■			■	■	■	
	6	**Shared tacit knowledge**	▒	■	■		■	■	■	■	■		■	■	■
	7	**Participatory culture**	▒	■	■	■	■	■					■	■	■
	8	**Good governance**	▒	■	■	■	■	■	■	■	■		■	■	■
	9	**Diversified funding**	▒	■	■	■		■					■		
World	**10**	**Contribution to sustainable development**	▒		■				■			■	■	■	■

Table 4: Connecting the concept of digital sustainability with the publications of this habilitation

Perspective A) elaborates the theoretical foundation of the concept of digital sustainability. The article *#1 "Characteristics of Digital Sustainability" (2014)* introduces the notion of digital sustainability but does not explicitly mention any of the ten basic conditions (thus the boxes are marked in light gray). The article *#2 "Digital Preservation through Digital Sustainability" (2016)* outlines nine of the ten basic conditions including the notion of a digital artifact and its associated ecosystem. Finally, article *#3 "Digital Sustainability: Basic Conditions for Sustainable Digital Artifacts and their Ecosystems" (2017)* describes the full concept of digital sustainability including the final condition that sustainable digital artifacts must contribute to the triple bottom line of sustainable development.

In **perspective B),** the case of open source software is studied in order to sharpen the conditions for digital sustainability regarding the digital artifact and the ecosystem. Article *#4 "Who Cares about my Feature Request?" (2016)* focuses on the quality of the digital artifact, in this case the open source software Eclipse. The transparency of the development process enables insights into the participatory culture and the governance mechanisms of open source communities, both elementary characteristics of ecosystems of sustainable digital artifacts. In addition, the research identifies the crucial role of funding by employing open source developers. Article *#5 "How are Open Source Practices Possible within a Medical Diagnostics Company? Developing and Testing a Maturity Model of Inner Source Implementation" (2017)* treats certain aspects of digital sustainability – tacit knowledge transfer, participatory culture, and good governance – in corporations applying Inner Source practices. Because it is not the goal of Inner Source to release digital artifacts to the public (transparent structures), this basic condition is only partly satisfied (thus marked in light gray). Article *#6 "Alone or Together? Inter-Organizational Affiliations of Open Source Communities" (2019)* explores the dynamics of different open source communities (the ecosystems of digital artifacts) by explaining the role of the open licensing regime, practices of tacit knowledge sharing, forms of participation, varying governance mechanisms and different funding models.

Perspective C) highlights issues of digital sustainability in the public IT procurement sector by analyzing a large dataset of procurement information. Article *#7 "When the Exception becomes the Norm: Direct Awards to IT Vendors by the Swiss Public Sector" (2017)* illustrates the consequences of vendor lock-in through proprietary systems. If the source code is not available (no "transparent structures"), the license forbids switching the IT provider (no "open licensing regime"), and if the tacit knowledge is located at only one company (no "shared tacit knowledge") then competition is eliminated resulting in higher fees and less flexibility (negative "contribution to sustainable development"). Article *#8 "A Knowledge-Based Perspective on Contract Choice in Application Outsourcing" (2018)* is connected with the concept of digital sustainability by analyzing the relationship between knowledge distribution and coordination. In outsourced IT projects, the role of tacit knowledge is pivotal to perform complex tasks thus controlling the system, which is an aspect of good governance. Moreover, article *#9 "Multisourcing Decisions in Application Outsourcing: Test of a Multi-theoretical Model" (2018)* provides in-depth insight into aspects of knowledge management and governance mechanisms of IT projects thus connecting with digital sustainability in these two areas.

The publications in **perspective D)** focus on the data as digital artifacts. On the one hand, article *#10 "Measuring the Promise of Open Data: Development of the Impact Monitoring Framework" (2016)* features the benefits of open data by developing an impact assessment framework. It explains how elaborate, transparent, and open-licensed data may contribute to sustainable development by triggering positive effects for the environment, the society, and the economy. On the other hand, article *#11 "Balancing Control, Usability and Visibility of Linked Open Government Data to Create Public Value" (2019)* introduces linked data, which are semantically connected datasets capable of providing high quality, transparent data possibly stored on different servers. As described e.g. Wikidata enables different stakeholders to share linked data under open data licenses within a participatory ecosystem therefore presenting an ideal example of digital sustainability.

In **perspective E),** the concept of digital sustainability is applied to the public sector. Article *#12 "Public Governance durch Open Government: Zwei sich ergänzende Ansätze für die staatliche Aufgabenerfüllung der Zukunft" (2014)* merges the notion of public governance with the concept of open government illustrating the effects of open data on transparency, participation and collaboration. Finally, article *#13 "Exploring the Motives of Citizen Reporting Engagement: Self-Concern and Other-orientation" (2018)* is an open government example based on open data gathered by citizens who participate in reporting infrastructure defects. The study thus touches various aspects of digital sustainability around motivational characteristics of contributors.

By elaborating the different perspectives of digital sustainability, these habilitation articles highlight the importance of all basic conditions defining a sustainable digital artifact and its ecosystem. Nevertheless, there are challenges related to the concept of digital sustainability, which will be discussed next.

2.3. Difficulty to measure and reach digital sustainability

Some of the basic conditions of digital sustainability described above represent goals that are easy to define and achieve, while others are very challenging if not impossible to reach. For example, condition 5, applying an open license regime, is clearly outlined by a list of open source, open content or open data licenses. Open source licenses are provided by the Open Source Initiative (Open Source Initiative, 2019), open content is mostly by Creative Commons licenses (Fitzgerald and Oi, 2004), and open data is ensured with a license that complies with the Open Knowledge Definition (Molloy, 2011). However, basic conditions such as elaborateness of the digital artifact or good governance of the community are difficult to define in a "one size fits all" way. Depending on the type of a digital artifact, we need to measure different properties and even if we agree upon certain characteristics they are usually vaguely operationalized.

But the same holds true for the Sustainable Development Goals: For example, "ending poverty" requires a clear definition of "living in poverty". Thus, the United Nations clarified that living on less than $1.25 a day means extreme poverty (UN General Assembly, 2015). Other requirements are defined a bit more vaguely, e.g.: *"By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance".* This indicator will be rather hard to reach, looking at the history of mankind.

Along the same lines, measuring and operationalizing the conditions of digital sustainability are key for assessing progress. But, as with the SDG, there will remain a certain blurriness of the goals. And in some cases, it is rather unlikely that they will be achieved. Therefore, the purpose of these basic conditions of digital sustainability is not to meet them all immediately but to provide a long-term agenda in which direction future investments in digital initiatives should happen. Thus, the concept of digital sustainability presents the foundation of a vision on where to go with digitalization.

2.4. Confusion with terminology

As mentioned in the introductory section, there is a need for clarification of the terminology involving digitalization and sustainability. In fact, there are some critical voices questioning the term "digital sustainability" since digitalization does not represent a scarce resource (Martens, 2013) or since the concept of digital sustainability does not sufficiently treat ecological issues (Schmidt and Wytzisk, 2019). Both include reasonable arguments, but they are beside the point because they ignore the definition of digital sustainability described above.

On the one hand, digital artifacts are in fact non-rival (capable of being consumed by many) but they are excludable (access can be refused): Owners of software or data providers may control who can use it or not. Therefore, to maximize societal benefit of digital artifacts, access to use and modify them should be available to everyone (Stuermer et al., 2017a). On the other hand, our concept of digital sustainability does recognize the importance of natural resources by including as a basic condition that the digital artifact needs to contribute to the triple bottom line definition of sustainability. Admittedly, in retrospect the example of Bitcoin in the article on the basic conditions of digital sustainability is an unfortunate one because of its high energy consumption today. It would have been better to choose a Blockchain technology without proof-of-work consensus algorithms, e.g. proof-of-stake which does not use mining approaches, thus not relying on significant amounts of electrical energy (Kiayias et al., 2017; Saleh, 2019).

2.5. Challenges of sustainability and digitalization

A more fundamental critique against the role of digitalization is voiced by proponents such as Kuntsman and Rattle (2019), who demand “abolishing digital solutionism” and van der Velden (2018) who carries out research into technological design connected to the SDG. These scholars take the view that digitalization basically has a negative impact on the environment by emphasizing the negative effects such as electronic waste, energy consumption etc.

It is correct to point out that producing smart phones and running servers uses scarce resources and causes greenhouse gas emissions no matter how it is done. Still, the best way of progress is to follow the strategy “doing one thing without abandoning the other.” While saving energy and reducing waste is important, further demand of hardware, software, and data to run governments, corporations, and even universities and NGOs will be unavoidable. Therefore, whenever digital artifacts are created, the goal should be to use and produce open source software, open data, open content etc. to let humanity receive the maximum benefit of this digital knowledge while at the same time contributing to sustainable development in the sense of the triple bottom line. In this regard, digital sustainability presents a conceptual framework aligned with sustainable development that includes specific basic conditions to assess the level of social value and digital preservation of digital initiatives.

Linux is a good example of a sustainable digital artifact with a large and diverse ecosystem of corporations, governments, researchers, and civic programmers. As described in the main publication on digital sustainability (Stuermer et al., 2017), the Linux kernel development meets all basic conditions very well. Particularly condition ten regarding the contribution to sustainable development is achieved because, on the one hand, old hardware can be used with Linux and other OSS much longer than with proprietary software (Kshetri, 2004; Faugel and Bobkov, 2013). On the other hand, developing countries are able to benefit from OSS since they do not need to purchase proprietary software licenses, thus lowering their IT costs substantially (Noronha, 1999; Kshetri, 2004). This “ICT for Development” (ICT4D) action empowers especially sub-Saharan African countries to benefit from the global digital transformation without the need of payments to software vendors from developed countries (May, 2006a, 2006b, 2008).

As such, Linux is an example where one individual, Linus Torvalds, had decided 1991 to hand over his intellectual property to the public by releasing the software under an open source license (Raymond, 2001). Thus, if governments and other public entities continue to use and contribute to Linux and other OSS, they can satisfy their needs while actually supporting others, thereby increasing intra-generational justice.

3. Summary of Habilitation Publications

The 13 peer-reviewed articles published in academic journals and conference proceedings are summarized in the following five sections, each representing a different perspective on the topic of digital sustainability.

3.1. Digital sustainability

This initial section comprises three publications on the overall concept of digital sustainability. They indicate how the term “digital sustainability” has developed from a rather fuzzy idea to a clearly defined concept embedded in current literature on information systems, knowledge management, digital goods theory, and innovation research.

#1 “Characteristics of Digital Sustainability” (2014)

In Stuermer (2014) the concept of digital sustainability was introduced by connecting it with the literature on digital preservation as well as research on OSS. This conceptual approach indicated that, on the one hand, digital sustainability addresses the cultural heritage of digital artifacts, leading to an inter-generational perspective on the subject: How should we store data today so that future generations are able to read and use them? On the other hand, digital sustainability is also about sharing digital knowledge among today’s social classes and cultural spaces entailing an intra-generational perspective. Therefore, this publication also connects digital sustainability with the openness movement, as documented by the abundant research about OSS. Releasing and using software under an open source license is a key example of satisfying several conditions of digital sustainability.

Following an existing framework of sustainable development, six characteristics of digital sustainability were initially proposed: 1) Inter-generational justice targets the long-term availability of data and software. 2) Regenerative capacity improves the digital artifact continuously. 3) Economic use of resources requires unrestricted access and reuse of data and software. 4) Risk reduction is facilitated through low vendor dependence. 5) Absorptive capacity is enabled by the use of structured data and elaborated documentation. And 6) ecological and economic added value are achieved through appropriate regulatory conditions. While these six characteristics describe well the notion of digital sustainability, they were not sufficiently specific to form an applicable concept in order to distinguish sustainable from non-sustainable digital artifacts.

#2 “Digital Preservation through Digital Sustainability” (2016)

Based on the previous lines of thought, the concept of digital sustainability was further elaborated in Stuermer and Abu-Tayeh (2016). In this publication, the number of basic conditions for digital sustainability was increased to nine illustrated with issues from the area of digital preservation. Linking these conditions with challenges from digital preservation research allowed a refinement of the definition of the concept of digital sustainability.

Those nine basic conditions are divided into a group of four addressing the digital artifact itself, while the other five target the ecosystem in which the digital artifact is embedded. Thus, the notion of a community was introduced as an important prerequisite for digital sustainability. Besides technical aspects, an ecosystem consisting of individuals and organizations using and improving the digital artifact was recognized as part of the concept of digital sustainability. The conditions regarding the digital artifact include elaborateness, transparent structures, semantic data, and distributed location, while the ecosystem must ensure an open licensing regime, shared tacit knowledge, participatory culture, good governance, and diversified funding. The final condition, the contribution to sustainable development, was still missing in this publication.

#3 "Digital Sustainability: Basic Conditions for Sustainable Digital Artifacts and their Ecosystems" (2017)

Aggregating all insights and feedback from previous publications and presentations, a mature model of digital sustainability was developed and published in Stuermer et al. (2017a) This study provides a thorough discussion of different streams of literature (digital information, knowledge management, digital goods, and innovation), connecting them with recent sustainability research. The current notion of the role of knowledge within sustainable development was challenged: While previous research had seen knowledge and in particular digital information as a means to an end to increase sustainability, our conceptual publication explained why digital artifacts themselves are important resources worth protecting.

The article elaborated the nine conditions mentioned in the previous publication and added a tenth criterion: All sustainable digital artifacts must contribute to the classical triple bottom line definition (see above in section 1.2) of sustainable development. With this final criterion, the concept of digital sustainability has been connected with the goals of sustainable digitalization. As an illustration, these basic conditions were applied to four specific projects: the Linux kernel development as an example of an open source project, Bitcoin as a blockchain-based cryptocurrency, Wikipedia as an example of an open content platform, and Linking Open Drug Data (LODD) representing a particular set of linked data in pharmaceutical research. These initiatives turned out to fulfill many but not all of the ten basic conditions. For example, Bitcoin has the deficiency of good governance structures due to its lack of an organizational body with sound governance mechanisms. In addition, Bitcoin is weak on contributing to sustainable development from an ecological or social angle since it uses much energy for the consensus algorithm and because it is often used for payments in illegal situations such as ransomware or drug deals. Wikipedia on the other hand mostly lacks semantic data. Thus, machines are not able to process most of the knowledge within the largest online encyclopedia.

3.2. Open Source Software

While the overall theoretical foundations of digital sustainability are elaborated in the above publications, an additional line of research further investigates the dynamics of one particular, rather technical perspective: open source software (OSS). OSS is probably the oldest example of sustainable digital artifacts. Since the 1980s, people have used and published Free Software and later OSS to share software tools and products thus contributing to the increasing amount of publicly available OSS. Each of the following research articles presents a different view on the subject of OSS.

#4 "Who Cares about my Feature Request?" (2016)

In this research project, the issue tracking system of the integrated development environment (IDE) of the Eclipse foundation was analyzed (Heppler et al., 2016). This publication addressed the first basic condition of digital sustainability, elaborateness of a digital artifact, predating the current concept of digital sustainability. In today's terminology this research contributed to the understanding of how to increase digital sustainability within OSS projects through implementing feature requests to improve the software.

Eclipse was initiated by IBM in the early 2000s. Therefore, enough data had been aggregated to analyze if core community members such as IBM employees had a higher influence on feature implementation than non-IBM employees. By applying a logistic regression to a sample of 11’479 feature requests, the significant variables predicting the successful implementation of such a request were identified. Among other results, it turned out that feature requests by IBM employees are twice as likely to be implemented than those from non-IBM contributors. This points to a weak spot within this specific and possibly also other OSS communities: requests by insiders are taken more seriously than those from outsiders. Viewing this finding from the perspective of digital sustainability also challenges basic condition seven, a participatory culture, showing that a prosperous community is not a matter of course.

#5 “How are Open Source Practices Possible within a Medical Diagnostics Company? Developing and Testing a Maturity Model of Inner Source Implementation” (2017)

“Inner Source” is a way to apply the OSS development model in an organization without releasing the source code. This contradicts the notion of digital sustainability because no open source license is applied. However, it demonstrates that certain aspects of the open source movement can still be adopted within corporate environments by practicing at least partly the way of efficient collaboration and knowledge sharing. This phenomenon was investigated in a medical diagnostics company (Eckert et al., 2017).

By studying previous literature on Inner Source, a “Capability Maturity Model of Integration for Development” was developed specifically for this topic. The maturity model included three dimensions (people, procedures and methods, as well as tools and equipment) on four implementation levels of increasing maturity (incomplete, performed, managed, and defined). Using a qualitative approach, this maturity model was tested by interviewing software engineers as well as senior management staff of the medical diagnostics company. In addition, organizational and legal documents regarding Inner Source practices within the corporation were analyzed. Eventually, this led to an assessment of the implementation level regarding Inner Source of this medical diagnostics company. The results showed that the organization achieves a high maturity level between “performed” and “managed”. Thus, this study connects basic conditions of digital sustainability – transparent structures, tacit knowledge sharing, participatory culture, and good governance – with internal proprietary software development.

#6 “Alone or Together? Inter-Organizational Affiliations of Open Source Communities” (2019)

As described above in articles #2 and #3, the ecosystem of a sustainable digital artifact is a key element of the concept of digital sustainability. It is therefore essential to understand the interrelations between the sub-structures of such communities. In order to explain why some OSS projects belong to an umbrella organization while others form communities on their own, different OSS governance structures were analyzed (Eckert et al., 2019).

A qualitative study of four mature OSS communities (GENIVI, PolarSys, LibreOffice and PostgreSQL) was conducted, analyzing their motives for building different forms of governance. One community (GENIVI) is completely independent while another one (PolarSys) strongly adheres to an umbrella structure (Eclipse Foundation). The other two communities (LibreOffice and PostgreSQL) pursue an intermediate way of affiliating loosely with a support organization. Applying resource dependence theory and transaction cost economics the advantages and disadvantages of the different strategies could be explained. It turned out that stakeholders of the autonomous community (GENIVI) appreciate being able to define their individual organizational processes and structures leading a strong identification with their community. On the other hand, community members of the integrated approach (PolarSys within the Eclipse Foundation) enjoy efficiency gains by reusing existing bylaws and other out-of-the-box principles, thus being able to spend more time on their core activities such as developing and promoting their open source project. The integrated open source community (PolarSys) also benefits from the visibility of its umbrella organization (Eclipse Foundation). The communities pursuing the intermediate way (LibreOffice and PostgreSQL) loosely affiliating with a support organization (Software in the Public Interest) enjoy the advantages of both approaches, thus possibly choosing the most efficient strategy.

3.3. Procurement of IT

On a practical level, public procurement of IT is confronted with the need to select the appropriate solutions and vendors for a certain requirement. In this respect, digital sustainability is relevant since the choice of a certain technology today has long-term consequences. For example, vendor lock-in strongly reduces the number of alternatives if the costs go up or the provider stops supporting the platform. Thus, the criteria for defining as well as evaluating possible choices of an IT system are key for achieving sustainable digital artifacts. Usually, operationalizing and measuring such selection processes is difficult since either the number of observations is low or the data is not available at all. By crawling and refining data from the Swiss public procurement platform Simap.ch ("Système d'information sur les marchés publics en Suisse"), a large database of tender and vendor information was created going back more than ten years. This set of data enabled the investigation of a range of important questions regarding IT procurement, shedding light on several aspects of digital sustainability.

#7 "When the Exception becomes the Norm: Direct Awards to IT Vendors by the Swiss Public Sector" (2017)

In this initial publication, the dataset on Swiss public procurement crawled from Simap.ch was introduced describing its context, methodology, and data structures. Descriptive statistics on the significantly high level of direct awards (contracts without a competitive public tendering process, also called "no-bid contracts") in IT procurement was provided (Stuermer et al., 2017b).

Between 1 January 2009 and 31 August 2016, 25'449 distinct procurement projects awarded to suppliers were found. Of these, 22'695 projects were not labeled IT-related while 2754 awards were IT-related. There was a share of 14.6% of direct awards in the non-IT sector while this share was more than 3 times higher at 47.2% with IT-related contracts although according to procurement law such direct awards should be the exception. Since procurement agencies had to declare why they had awarded no-bid contracts, it turned out that vendor lock-in or a lack of alternatives were the reasons. Obviously, the consequence of vendor dependence is a high level of direct awards excluding competition and therefore leading to monopoly rents and inflated prices. Consequently, in the light of digital sustainability there is a problem with governmental IT systems. The conclusions of the article propose the use of open source software in order to lower vendor lock-in and thus eventually decrease the number of no-bid contracts.

#8 "A Knowledge-Based Perspective on Contract Choice in Application Outsourcing" (2018)

Besides direct awards, the Simap.ch IT procurement dataset enabled the investigation of another research question. Krancher and Stuermer (2018a) examined if a knowledge-based view could explain contract choice in application outsourcing. To apply the knowledge-based view, the two independent variables "knowledge specificity" and "task scope" were defined. Custom-developed software has high knowledge-specificity, packaged software has low knowledge-specificity. The more an IT project includes a variety of services (application design, development, maintenance, hardware procurement etc.), the higher its task scope. The dependent variable “contract choice” describes the choice between a fixed-price and a time-and-materials contract by an application vendor. In the first case the company delivers the specified software for a defined amount of money, in the latter case the supplier provides the software based on the actual effort required.

Using the Simap.ch data, 1035 IT projects were analyzed including either fixed-price (188) or time-and-materials (847) contracts, an information stored in the dataset. Independent coders added semantic information about the IT projects to measure the independent variables. Additional control variables such as familiarity (if the client had previously awarded a contract to the vendor), project size (value of the contract), client size (sum of all contract values) and vendor size (sum of all contract values) were extracted automatically from the dataset. Applying a generalized linear mixed model (GLMM), it was found that the probability of a fixed-price contract decreased by 70% when knowledge specificity was high and increased up to 57% for each service type included in the contract (task scope). Thus, we were able to show the important role of knowledge for the decision which contract type to choose.

#9 “Multisourcing Decisions in Application Outsourcing: Test of a Multi-theoretical Model” (2018)

The third research project using the Simap.ch dataset investigated the reasons of organizations to choose a multisourcing contract as opposed to assigning a project to a single vendor (Krancher and Stuermer, 2018b). Other than contracting multiple vendors for independent tasks called “multi-vendor outsourcing”, the term “multisourcing” means the delegation of interdependent tasks to different companies. Thus, a client is able to induce post-contractual competition among the vendors lowering the dependence on a single vendor. Multisourcing also provides access to the knowledge and experience of best-of-breed vendors, as it enables highly qualified companies to be hired for specific tasks.

Based on transaction cost economics, property rights theory and the knowledge-based view eight hypotheses were developed to explain why in some IT projects, the clients contracted only one vendor and multiple vendors in others. Testing a Simap.ch dataset of 1093 application projects (972 single-sourcing and 121 multisourcing) by applying a logistic regression, six of the eight hypotheses were supported: On the one hand, a statistically significant relationship between the likelihood of multisourcing and client-specificity of the software was not found. However, in large IT projects, knowledge specificity augmented the likelihood of multisourcing. In addition, transaction cost economics theory and the knowledge-based view were supported: Clients chose multisourcing when opportunistic threats (e.g. delivering poor quality of software) were high and when they sought to access vendor knowledge through the outsourcing project. In general, the likelihood of multisourcing increased with project size. Interestingly, clients avoided multisourcing when projects relied on proprietary technology. But clients were more inclined to choose multisourcing when they were experienced in information systems outsourcing.

3.4. Open Data and Linked Data

Besides software, data is the other elementary digital artifact covered by the concept of digital sustainability. While software contains algorithms to conduct certain activities, data is created or processed by the software. They are both inherently connected to each other. As with software, opening up the data is a key requirement for digital sustainability, allowing society to benefit most from it. The impact of open data is the topic of publication #10. In addition to the open licensing regime, linking the data with semantic information represents another basic condition for digital sustainability. Semantic information enables individuals, organizations and eventually society to absorb previously created knowledge and advance that knowledge. This aspect was investigated in the 2019 publication #11 on linked open government data.

#10 “Measuring the Promise of Open Data: Development of the Impact Monitoring Framework” (2016)

Open data is publicly available data that is not subject to privacy or security-related concerns. Governments, corporations, and other organizations publish open data because they expect value generation for society and businesses by improving democratic processes, leading to higher administrative efficiency, and increasing innovative capabilities. In the context of digital sustainability, this means open data may contribute to sustainable development by exerting a positive ecological, social or economic impact. This promise of open data was investigated by developing an impact monitoring framework (Stuermer and Dapp, 2016).

To measure the impact of philanthropic investments the Social Return on Investment (SROI) approach was applied to the open data context. The SROI model distinguishes between the use of resources (input), directly controllable results (output), indirect activities (outcome), and value creating consequences (impact). These four levels were combined with the 14 high-value data categories from the G8 Open Data Charter. Those high-value data categories include datasets such as business registers, crime statistics, meteorological data, agricultural information, educational sector data, pollution levels, public spending data etc. To illustrate the applicability of the framework, a 4-by-14 matrix was created with illustrative scenarios showing how this approach could be applied in practice. Several examples indicate the potential of open data for contributing to sustainable development. For instance, linking data about average solar radiation of certain buildings and meteorological information (input) allows the calculation of potential solar energy on roofs (output). Aggregating this information in a web application of solar energy per neighborhood (outcome) could eventually lead to the founding of new energy cooperatives collecting and selling solar energy from the roofs of a town (impact). However, an empirical validation of this framework is still missing.

#11 “Balancing Control, Usability and Visibility of Linked Open Government Data to Create Public Value” (2019)

Open data meets the basic conditions for sustainable digital artifacts regarding transparency, licensing and potentially sustainable development. To additionally satisfy the requirement of semantic information we need linked open data (LOD). On a technical level, this means connecting Resource Description Framework (RDF) data with unique addresses (so-called Uniform Resource Identifier or URI) to make it machine-readable across different storage systems. Today the LOD data standard is used by thousands of organizations to share structured data on the web. However, there are different ways of where and how to store LOD. To evaluate their advantages and possible drawbacks, three distinct governance modes of managing LOD were elaborated carving out the peculiarities of each scenario (Hitz-Gamper et al., 2019).

The three governance modes represent different options for governments to store linked open government data (LOGD): Either they manage the data on their own storage system, a so-called dedicated triple store. Or they use a shared triple store together with other government agencies e.g. of the same country or the same region. Or they decide to save the LOGD on a crowd-sourced open knowledge base – thus complying also with the criterion for sustainable digital artifacts regarding participatory culture. Evaluating each approach leads to a practical guideline: If controlling the complete data stack on a technical and legal basis is important and cost and community are less so, a dedicated triple store is the best choice. If a government agency wants to benefit from shared resources of other organizations and does not care much about controlling the technical details, then a shared triple store or even an open knowledge base fit best. Three case studies illustrated each of the governance modes in practice: The dedicated triple store of the Swiss Federal Office of Topography swisstopo, the Linked Data Service LINDAS by the Swiss Federal Archive as a shared triple store, and the crowd-sourced open knowledge base Wikidata.

3.5. Open Government

The concept of open government is a notion aiming to advance transparency of, as well as participation and collaboration with government agencies. Open data represents a critical element that provides the technical foundation for achieving the goals of open government. As mentioned in the section above on open data and linked data, public agencies can facilitate participation of the civic society by releasing open government data. Sustainable digital artifacts such as open data thus enable open government to implement the concept of digital sustainability in practice.

#12 "Public Governance durch Open Government: Zwei sich ergänzende Ansätze für die staatliche Aufgabenerfüllung der Zukunft" (2014)

Although the notion of public governance has been discussed in academia for decades, it still lacks implementation in practice. On the other hand, having evolved from e-government research, "open government" as a practitioner-oriented trend has been coined 2009 by the Obama administration and since then spread over many countries in the world. This conceptual article (translated "Public Governance through Open Government: Two Complementary Approaches for the Future Execution of Governmental Tasks") connects these two approaches and describes the added-value of open government as an implementation strategy for public governance (Stuermer and Ritz, 2014).

Starting with a summary of the abstract goals of public governance an overview is provided of this concept which rejects strong hierarchies and promotes interactions through social self-orientation. The importance of collaboration in public governance is pointed out, showing how government interacts with civic organizations through horizontal, network-like structures. Similar to this traditional public management approach, the open government movement is defined through the three key activities transparency, participation and collaboration. First, extending the passive freedom of information laws, open government expects authorities to actively disclose every non-security-critical or personally identifiable information as open government data. On a second level, citizens are invited to participate in governmental activities such as reporting of infrastructure defects via mobile apps. As a third level of open government implementation, public administrations collaborate closely with their societies to improve public services, for example in the IT area. The article concludes with a 4-by-3 table connecting the four public governance premises (not only hierarchical structures, management of interdependence, cooperation, negotiation) with the three open government principles (transparency, participation, collaboration), posing relevant issues at each intersection. For example, the connection between management of interdependence in the public governance concept with the notion of participation of open government leads to the question: "To what extent can public participation bring added value to cross-policy, cross-organizational and cross-cutting issues?"

#13 "Exploring the Motives of Citizen Reporting Engagement: Self-Concern and Other-orientation" (2018)

Based on the theoretical insights from the previous article, an empirical investigation of the citizen reporting application mentioned above was started. Reports on infrastructure defects released as open data by the city of Zürich were analyzed and a survey was sent out to all users of the application. Linking the empirical findings with smart city, open government, citizen sourcing, and co-production literature permitted an in-depth understanding of the motivation of citizens using this civic tech application (Abu-Tayeh et al., 2018).

To identify the motivational drivers of reporting, participants were asked why they reported issues on the mobile app "Züri wie neu" ("Zurich as good as new"). In total, 650 app-users submitted the full questionnaire responding about their intention to solve a problem that affected them personally (self-concern) as well as to help other citizens (other-orientation). Using anonymized identifiers, these two independent variables were connected with the number of reports of each respondent, the dependent variable. This method permitted a test involving actual use data, a much more robust source than self-reported data. In addition, several control variables such as gender, age, education, and employment were included. A negative binomial regression showed that both types of motivation had a significant impact on the quantity of reports, although the effect of self-concern appeared to be stronger in comparison. In conclusion, self-concern as well as other-orientation are deemed important drivers for the success of such a citizen sourcing application. The socio-economic control variables indicated that employed persons and men contribute to the citizen reporting initiative significantly more frequently than unemployed persons or women. These findings contribute to a better understanding of what characterizes and motivates citizens to participate in citizen reporting platforms, which are a frequently cited example application in many smart cities.

4. Conclusions and Future Research

The publications of this habilitation provide a comprehensive overview of the topic of digital sustainability. They make clear that sustainable digital artifacts need to be of high quality (*elaborateness*), their technical elements have to be open (*transparent structures*), their content must be machine-readable (*semantic information*) and there has to be redundancy in physical copies (*distributed location*). As the thesis statement points out these technical characteristics are necessary, but not sufficient conditions for digital sustainability:

> *For software and data to be available over time for the entire society, not only must sustainable digital artifacts meet the technical characteristics of quality, transparency, semantics and multiple locations. The associated ecosystem of businesses, governments, and individuals must also meet the legal and organizational characteristics of an open license, shared tacit knowledge, participation, good governance, and diversified funding. And the digital artifacts must lead to ecological, societal or economical benefits.*

The various examples of investigated open source communities (Eclipse, GENIVI, LibreOffice, PolarSys etc. in articles #4 and #6) as well as the open data and linked data cases (weather data, Wikidata, swisstopo geo data etc. in articles #10 and #11) illustrate the need of additional preconditions of the ecosystem in order to create an ideal environment for sustainable digital artifacts: The open source licenses and the data in the public domain (*open licensing regime*) establish the legal framework under which software and data can be shared and reused.

The close exchange of knowledge and experience (*shared tacit knowledge*) for example within the Inner Source communities of the medical diagnostics company (article #5) highlights the importance of continuous knowledge transfer in teams of software developers. The case of “Züri wie neu” (articles #12 and #13) emphasizes the creative power of citizens engaging in a smart city platform who contribute their time for improving their neighborhood (*participatory culture*). The importance of controlling opportunistic behavior such as vendor lock-in (*good governance*) is illustrated in the analysis of public IT procurement where governments and other IT users depend on IT providers (articles #7, #8 and #9). And the challenging role of money within such ecosystems (*diversified funding*) is shown by the example of IBM-employed Eclipse developers whose feature requests are implemented faster than those of non-IBM developers (article #4).

The final requirement for digital sustainability (*contribution to sustainable development*) is a crucial element of the concept. The goal is not to play off the objectives of sustainable software and data (focused on digital artifacts and ecosystems) against sustainable development in the traditional sense (focused on ecological, social, and economical aspects). In order to ensure the long-term availability of digital knowledge, it is important that the natural environment, human rights and a functioning economy be maintained. The cases of open data leading to social or ecological benefits (article #10) and the cases of open government and citizen sourcing applications (articles #12 and #13) illustrate well the positive impact openly available data and software may exert.

By summarizing and connecting these publications the thesis demonstrates the current understanding of digital sustainability. It lays out that digital artifacts have to fulfill distinct properties, their ecosystems need to satisfy conditions as elaborated above, and the output has to be positive for sustainable development. Nevertheless many questions remain open. In this final section, some future research topics are highlighted.

Despite abundant studies already conducted in the area of open source software, the topic still continues to evolve and engender new questions and phenomena. For example, the growing corporate support of the open source development model (Shahrivar et al., 2018) generates new challenges of collaboration between users and producers of software and between companies, public institutions, and civic communities. And the growing demand for digital tools increases in-house development of software by governments and non-ICT companies leading towards new opportunities for releasing open source projects and collaboration across institutional boundaries.

Using the vast amount of procurement data from Simap.ch enables a better understanding the antecedents of direct awards within IT procurement and how they influence lock-in effects and other forms of vendor dependence. Eventually, the goal is to provide evidence-based empirical scientific insights and policy advice on IT procurement strategies in order to answer questions such as “Does open source software really lead to lower numbers of no-bid contracts and thus less dependence on single vendors?”

The same public procurement data is currently being used by the Swiss National Science Foundation (SNSF) National Research Programs “Sustainable Economy: resource-friendly, future-oriented, innovative” (NRP 73). Our research project on sustainability in public procurement intends to identify suitable ecological and social criteria for public tenders[1]. By using machine learning and natural language processing methods, currently more than 1000 gigabytes of public procurement documents using statistical models and machine-learning approaches based on natural language processing are analyzed.

1 http://www.nfp73.ch/en/projects/supply-chain/sustainable-public-procurement

Also in the area of open data and linked data, there are many open research questions. For instance, research is needed on the benefits of releasing open data by applying the impact monitoring framework in an empirical context. In addition, the growing number and size of linked open data repositories indicates further need for research, e.g. to respond to fears regarding privacy and data protection. Linking publicly available data will increase the threat of de-anonymization via big data techniques (Lubarsky, 2016; Su et al., 2017).

New trends in the ICT sector, such as artificial intelligence and the Internet of Things, are on the rise. So far, digital sustainability does not yet consider aspects of data privacy or ethics of algorithms, two topics of growing relevance with advances in machine learning and other areas of artificial intelligence. Researchers are investigating issues such as “machine ethics” (Anderson and Anderson, 2011) and other topics involving ethics in artificial intelligence (Bostrom and Yudkowsky, 2014). The concept of digital sustainability should be enhanced by connecting to these important issues of the digital transformation.

In addition, future research on digital sustainability needs to focus on how to apply the concept in fields other than ICT. For example, there is a growing threat of agricultural companies protecting their plant germplasm with intellectual proprietary rights, preventing farmers from using better cultivation techniques. Recently, an “Open Source Seed License” was released by European plant breeders, agricultural scientists, lawyers, and commons experts, and applied to the genotypes of a tomato they call Sunviva (Kotschi and Horneburg, 2018). This and other cases link to digital sustainability, possibly leading to an enhanced concept such as “sustainable digital knowledge” or “sustainable intellectual property”.

Furthermore, the role of public agencies regarding digital sustainability should be addressed. Public pressure on governments to release software and data is growing. For example, the Free Software Foundation Europe (FSFE) has launched a campaign “Public Money? Public Code!” in 2019, requesting governments to publish source code which was funded with public money (FSFE, 2019). Thus, empirical investigations on the impact of releasing open source software, open data, and other digital artifacts by governments could support or challenge the validity of this activist claim.

Finally, the application of open data in the public sector exposes research gaps in the open government area. How should governments collaborate with civic hackers and startups to increase the public value of digitalization? How do public hackathons stimulate innovation and produce valuable results? Why are some smart city applications beneficial for public service and others are not? These and more questions motivate to further investigate the topic of open government and eventually on how digitalization may benefit society the most.

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Appendix: Habilitation Publications