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Originally published at:
Hilty, Lorenz; Lohmann, Wolfgang (2013). An Annotated Bibliography of Conceptual Frameworks in ICT for Sustainability. In: ICT4S – First International Conference on Information and Communication Technologies for Sustainability, Zürich, 12 February 2013 - 14 February 2013. ETH E-Collection, 288-300.

An Annotated Bibliography of Conceptual Frameworks in ICT for Sustainability

Lorenz M. Hilty and Wolfgang Lohmann

This bibliography covers articles published in journals, conference proceedings or as book chapters that reflect on the role of Information and Communication Technology (ICT) in society's challenge of developing more sustainable patterns of production and consumption. The bibliography is focused on contributions presenting conceptual frameworks intended to structure this interdisciplinary field of research. Some sources not explicitly presenting a conceptual framework were included for their contribution to structuring the research field.

The earliest frameworks classify ICT applications designed to process environmental data or information. They could be called 'application-oriented' frameworks.

(1) Radermacher, Riekert et al. (1994) introduce five categories of ICT systems for environmental information processing: (a) specific monitoring and control systems that "interact very closely with environmental objects and processes", (b) applications of conventional information systems "for input, storage, structuring, integration, retrieval, and presentation of various kinds of environmental information", (c) specialized evaluation and analysis systems supporting "the processing of environmental data using complex mathematical-statistical analysis methods and modeling techniques", (d) planning and decision support systems to "support decision makers by offering criteria for the evaluation of alternatives or for justifying decisions", and (e) "integrated environmental information systems" combining some of the functions (a) – (d) (Radermacher, Riekert et al., 1994, 4-5).

(2) Hilty, Page et al. (1995) extend this approach by relating the five system types to seven computational methodologies, yielding a 5 x 7 matrix that can be used to discuss the relevance of each methodology for each system type. The methodologies are: modelling and simulation, knowledge-based systems, user interface design, computer graphics and visualization, artificial neural networks, and data integration. The paper cites examples for environmental applications of all methodologies and introduces the term "Environmental Informatics" for the systematic application of information processing methodologies in the environmental domain (Hilty, Page et al., 1995, 1). The development of Environmental Informatics is documented in the proceedings of the three main conference series of this community.[1]

[1] Conference series: Environmental Informatics (EnviroInfo, n.d.), International Symposium on Environmental Software Systems (ISESS, n.d.), International Conference on Information Technologies in Environmental Engineering (ITEE, n.d.). A part of this work can be accessed via the ICT-ENSURE literature information system (ICT-ENSURE, n.d.), a result of the European Commission's support action for building a European Research Area in the field of "ICT for Environmental Sustainability" 2008-2010.

Some approaches focus on impacts of ICT on the environment instead of environmental applications. These impacts (or effects) can be positive or negative with regard to sustainability goals. This type of framework could be called 'impact-oriented'.

(3) Berkhout and Hertin (2001) introduce in their OECD report the distinction among first-, second- and third-order effects of ICT, which has been widely used in later literature: (1) "direct environmental effects of the production and use of ICTs", (2) indirect environmental impacts through the change of "production processes, products, and distribution systems", and (3) indirect environmental impacts "through impacts on life styles and value systems" (Berkhout and Hertin, 2001, 2). This framework became seminal and has been re-used and re-interpreted many times.

(4) If we restrict our focus to the special case of impacts of telecommunications on transportation, even earlier frameworks should be mentioned, such as the typology introduced by Mokhtarian (1989) and its predecessors in the field. The basic idea is here that telecommunications can decrease the demand for transportation by substituting it, but also increase the demand by stimulating it (inducing new demand). Telecommunications have also an effect on the supply of transportation by optimizing the use of the existing networks. This can lead to rebound effects because the time saved for travel may be used for other trips, and "telecommunications infrastructure and services may lead to long-term changes in land-use patterns (e.g., more dispersed residential and employment locations) that may in turn result in longer trips or more travel in general." (Mokhtarian, 1989, 235)

(5) Spreng's Triangle (Spreng, 2001) is a framework in the same intellectual tradition. The approach is based on the idea of "substitutional relationships between time, energy, and information" (Spreng, 2001, 83). Spreng's main conclusion from theoretical considerations and case studies is: "Both, IT's potential to do things with less energy input, thus generally more sustainably, and IT's potential to do things faster, i.e. less sustainably, are enourmous. Unfortunately, so far, the latter potential has been extensively tapped while the former remains but potential." (Spreng, 2001, 89) The approach has been recapitulated by Aebischer (2009) and Spreng (2013).

(6) Hilty and Ruddy (2000) combine the distinction among substitution, induction and optimization effects (based on Mokhtarian, 1989) with the application-oriented approach. They structure the applications in public-sector applications ("Environmental Information Systems", EIS) and private-sector applications ("Environmental Management Information Systems", EMIS), where both application types are further classified by their objectives: EIS may have the objective of creating "public awareness about the condition of public goods", fulfilling "prerequisites for political decisions" or just "executing instruments of environmental policy". EMIS may have the objectives "legal compliance", "environmental reporting to stakeholders" or "eco-efficiency and material flow management" (Hilty and Ruddy, 2000, 3).

Several attempts have been made to extend the focus from environmental applications and effects to a broader concept of sustainability.

(7) Isenmann (2001) proposes to extend Environmental Informatics to "Sustainability Informatics" by adding an ethical dimension that addresses issues of acceptability of ICT solutions to human individuals, to the whole society, and to the global ecosystem. The aim of the ethical dimension is to avoid that "we become 'information giants' having huge data bases [...] but 'knowledge pygmies' who lack of ethical thinking about ends and guidance." (Isenmann, 2001, 131)

(8) The Working Group GIANI[2] of the German Informatics Society (GI) presents a roadmap to a "sustainable information society" (Dompke et al., 2004) basically combining the Isenmann (2001) with the Berkhout and Hertin (2001) approach. Sustainability is decomposed into three nested spheres along the line of Isenmann's acceptability criteria: the human individual, society, and nature.[3] Berkhout and Hertin's three orders of effect are re-interpreted as "effects of ICT supply" (first order), "effects of ICT use" (second order) and "systemic effects of ICT" (third order). Combining these two dimensions (sustainabiliy aspects and orders of effect) leads to a 3 x 3 matrix, or nine areas of opportunities and risks of ICT with regard to sustainability. The report identifies needs for action for each area and formulates recommendations to academia, politics, business and NGOs. The report concludes: "There is no doubt that ICT offer great potential for sustainable development that has hardly been tapped yet. However, unless the downsides and risks of ICT described above are assessed realistically and discussed openly, the opportunity to reorient our activities towards a sustainable Information Society may be lost." (Dompke et al., 2004, 11)

(9) Naumann (2008) makes another proposal to extend Environmental Informatics to Sustainability Informatics. He structures the research field into four focal areas: (i) "Analysing the Application Domain" by using ICT to observe, measure, model and simulate phenomena within environment, business, and society; (ii) "Analysing and Classifying the Impacts of ICT" using the framework introduced by Dompke and colleagues (2004) and related approaches; and (iii) "Design of Software Systems" following principles of sustainability, such as using "algorithms which reduce directly or indirectly power consumption and environmental pollution" (Naumann, 2008, 385f.). The last area is called "Sustainable Software Engineering", which addresses two main issues. The first one is "system-bounded sustainability", covering quality aspects of the software itself. The second one is "overall sustainablity" or "system-unbounded sustainability", covering the interaction between the software and "ecological, economical, and social systems" (Naumann, 2008, 386).

[2] GI-Arbeitsgruppe Nachhaltige Informationsgesellschaft. The report was published in German under the title "Memorandum Nachhaltige Informationsgesellschaft" ("Memorandum Sustainable Information Society") by the Fraunhofer Society, with a one-page summary in English (Dompke et al., 2004, 11).

[3] By decomposing sustainability into three nested spheres, the working group intentionally deviates from the frequently used "three pillars" or "three dimensions" approach to sustainability that puts environment, society, and economy on the same level.

Life-cycle assessment (LCA) is standard practice for detecting the overall environmental impact of providing a functional unit by following products from cradle to grave.[4] Life-cycle thinking and methodology can be applied to any function provided by any product, including ICT products or products affected by ICT.[5]

(10) Hilty (2008, Chapter 6) uses the distinction among substitution, induction and optimization inspired by Mokhtarian (1989) to link life cycles of ICT products with life cycles of other products. The links between life cycles thus consist of substitution effects, induction effects, and optimization effects. For example, a service provided by an ICT product can be used to optimize the design, the production, the use, or the end-of-life treatment (e.g., recycling) of another product. The production, use, and end-of-life treatment of the ICT product itself has to be balanced against the intended or actual positive effects of the optimization. The ICT life cycle can also increase or decrease demand for other products (induction or substitution, respectively). This framework (taken up by the OECD Working Party on the Information Economy, OECD, 2010), covers first-order effects (here: environmental impacts of the ICT product life-cycle) and second-order effects (here: environmental impacts of ICT applications), both assessed by an LCA approach. An extension of the framework includes third-order effects, defined here as "adaptive reactions of a society to the stable availability of ICT services". This includes structural changes of the economy, which assumed to be more sustainable if less material-intensive. In a dematerialized economy, "value-added would depend a lot more than it does today on the creation of structures and not on the churning of material and energy." (Hilty, 2008, 156)

(11) Naumann, Dick et al. (2011) propose the GREENSOFT reference model, which has a focus on the life-cycle of software products with the aim to improve it with regard to sustainablity. The model has four parts: "Life Cycle of Software Products", "Sustainability Criteria and Metrics", "Procedure Models", and "Recommendations and Tools" (Naumann, Dick et al., 2011, 296). The first two parts explicitly borrow from LCA, treating software similar to a material product that goes through a development (or production), a use and an end-of-life phase. The last two parts of the GREENSOFT model aim at improving the processes in each phase of the life-cycle in order to meet the sustainability criteria, which are intended to cover all types of ICT impacts (from first to third order).

(12) Balin, Berthoud et al. (2012) present an approach starting from LCA applied to ICT hardware, which is then extended by the introduction of four additional factors: innovation-related factors, such as software bloat and obsolescence;

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[4] This concept of product life-cycle (as used in the LCA context) should be distinguished from the product life-cycle concept in marketing, which refers to the rise and decline of product sales.

[5] The last stage of the ICT hardware life cycle, electronic waste (e-waste or WEEE, Waste Electrical and Electronic Equipment) and its world-wide impact has stimulated highly specialized activities and publications that would deserve their own bibliography. See Manhart (2011) or Schluep et al. (2013) for the "Best-of-Two-Worlds" approach and Streicher-Porte et al. (2009) for the sustainability assessment of reuse and refurbishing options in education.

behavioural factors such as the addiction of users; organizational factors such as the IT productivity paradox, and structural factors such as the acceleration of economic processes by ICT and the related rebound effects. (Balin, Berthoud et al., 2012, Chapter 4)

(13) Standards and guidelines developed for the assessment of the environmental impacts of ICT based on a life-cycle approach can only briefly be mentioned here because the sources are numerous; the interested reader is referred to the joint activities of the World Resources Institute (WRI), the World Business Council for Sustainable Development (WBCSD), the Carbon Trust and the Global e-Sustainability Initiative (GeSI), described by Stephens and Didden (2013), and the framework developed of the International Telecommunications Union (ITU) (ITU-T, 2012).

Another set of conceptual frameworks can be grouped under the heading of "Green IT", a term that became popular around 2008 and has later been complemented by "Green IS", "Green Software", "Green Software Engineering" and "Green Computing".

(14) Murugesan (2008) defines Green IT as "the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems [...] efficiently and effectively with minimal or no impact on the environment." He identifies the following focus areas: "design for environmental sustainability; energy-efficient computing; power management; data center design, layout, and location; server virtualization; responsible disposal and recycling; regulatory compliance; green metrics, assessment tools, and methodology; environment-related risk mitigation; use of renewable energy sources; and eco-labeling of IT products" (Murugesan, 2008, 26). Besides these focus areas (directed to a reduction of negative first-order effects), he mentions two additional aspects: "Using IT for Environmental Sustainability [...] by offering innovative modeling, simulation, and decision support tools" and "Using IT to Create Green Awareness" by "tools such as environmental Web portals, blogs, wikis, and interactive simulations of the environmental impact of an activity" (Murugesan, 2008, 32f.).

(15) Coroama and Hilty (2009) indicate that the umbrella terms "IT" or "ICT" are not clearly defined and possibly not useful in a "green" context. They suggest "decomposing the 'ICT monolith' and look at its (naturally heterogeneous) parts separately." Coroama and Hilty (2009, 353). They investigate more specific types of digital equipment with regard to the relation between their own energy consumption (first-order effect) and the energy efficiency they enable (second-order effect). The authors found substantial differences, e.g., TV sets and set-top boxes having a high consumption and a low enabling effect on energy efficiency, whereas telecom satellites have a low consumption and a higher enabling potential through the services they provide.

(16) The British Computer Society (BCS, 2010) defines a detailed "Green IT Syllabus" specifying what should be included in the key concepts and "best practice principles of 'Green IT'" (BCS, 2010, 2). The syllabus shows that Green IT is understood mainly as an approach to minimize the negative first-order effects

of IT (or ICT). In particular, the carbon footprint of an organization is to be minimized by “greening its IT” (BCS, 2010, 4).

(17) Noureddine, Bourdon et al. (2012) define Green IT from a software perspective as a “discipline concerned with the optimization of software solutions with regards to their energy consumption” (Noureddine et al., 2012, 21). Their focus is on the environmental impacts caused by software, mainly CO2 emissions related to power consumption; the approach is thus restricted to first-order effects. The approach conceptually includes energy models showing the energy use caused by software in hardware resources (in particular processors, working memory and hard disks), power monitoring at runtime, and the use of “power-aware information to adapt applications at runtime based on energy concerns” (Noureddine, Bourdon et al., 2012, 27).

(18) Gu, Lago et al. (2012) develop a “Green Strategy Model” in the IT context that aims to “provide decision makers with the information needed to decide on whether to take green strategies and eventually how to align them with their business strategies” (Gu, Lago et al., 2012, 62). This conceptual model distinguishes among green goals (which an organization decides to achieve), green actions (that should help achieving a green goal), action effects (the ecological effects of the action with regard to the green goal), and economic impacts of the action effects. Green actions are divided into two categories, “greening of IT” and “greening by IT” (Gu, Lago et al., 2012, 65), which can be interpreted as reducing negative first-order effects and increasing positive second-order effects, respectively. The model is explored in a case study with Dutch data centers.

(19) Loeser, Erek et al. (2012) conceptualize Green IS (Green Information Systems) strategies, where IS is differentiated from IT by including not only technical infrastructure, but also the human activities within an organization. The need for Green IS is justified by their higher transformation potential: Compared to Green IT, “Green IS […] promise a much greater, organization-wide potential to measure, monitor, report and reduce the firm’s environmental footprint, but the transformation of the business with the help of Green IS requires a holistic long-term strategy.” Green IS strategy is defined as “the organizational perspective on the investment in, deployment, use and management of information systems (IS) in order to minimize the negative environmental impacts of IS, IS-enabled products and services, and business operations.” (Loeser, Erek et al., 2012, 4)

(20) Erek, Loeser et al. (2012) present a two-dimensional reference model for “Sustainable Information Systems Management”, which is intended to integrate Green IT and Green IS approaches. One dimension is a re-interpretation of the widespread classification into first- to third-order effects from an organizational perspective: (1) “the fields of action that are associated with corporate sustainability within IT organizations”, (2) “the IT supported business process of a company” (also called “Green through IT”), and (3) “the end products and/or services offered in the market”. The second dimension covers the three levels known from traditional Business Engineering: “strategy (strategic goals), processes (planning tasks) and operational implementation” (Erik, Loeser et al., 2012, 5). This matrix is then used to address the fields of action for a company. For example,

at the operational implementaion level of (2) “Green through IT”, the application of Environmental Information Systems (EIS) to calculate, control and optimize resource usage and emissions of the business processes of the company is indicated.[6]

(21) Penzenstadler (2013) discusses concepts of sustainability and interprets them in a software engineering context. She introduces a distinction between “software (engineering) *for* sustainability”, which is aimed at global sustainability goals, and “sustainable software (or sustainability *in* software engineering)”, which is related to the sustainability of the systems that are developed (Penzenstadler, 2013, 1184). Along the software product life cycle, she identifies four aspects in software engineering that should be addressed when discussing sustainability aspects of software: the “Development Process Aspect”, the “Maintenance Process Aspect”, the “System Production Aspect”, and the “System Usage Aspect” (Penzenstadler, 2013, 1184f.).

(22) Malakuti, Lohmann et al. (2013) structure “Green Computing”, introducing the distinction between “Greening in software” and “Greening by software”, where the former “aims to reduce the environmental effect caused by the development, application and retirement of software” and the latter “aims at saving resources by the help of software such as substitution of processes by more efficient processes or by dematerialization.” (Malakuti, Lohmann et al., 2013, 1149)

Instead of focusing on technology first, a number of approaches are taking a user-oriented perspective, addressing sustainability in design, behaviour, or life styles.

(23) Blevis (2007) creates a perspective in Human-Computer Interaction (HCI) he calls “Sustainable Interaction Design” (SID), which includes two aspects: “how interactive technologies can be used to promote more sustainable behaviors” and “how sustainability can be applied as a critical lens to the design of interactive systems, themselves.” (Blevis, 2007, 503) He introduces principles that are directed to extending the useful life of embedded materials, either by linking design to end-of-life considerations, by promoting renewal and reuse, or by decoupling ownership and identity to enable sharing for maximal use.

(24) DiSalvo, Sengers et al. (2010) provide an empirical analysis of the emerging structure of Sustainable HCI research. They divide the field in six genres: “Persuasive technology” stimulating desired (sustainable) behaviour; “Ambient awareness” systems making users aware of some aspect of the sustainability of their behaviour, or qualities of the environment associated with issues of sustainability; “Sustainable interaction design”, “Formative user studies”, and “Pervasive and Participatory Sensing”. He identified emerging issues, such as that “we [the Sustainable HCI community] frequently address individual consumers, but now need to find ways to address collectives and regional and national contexts” (DiSalvo, Sengers et al., 2010, 1980).

[6] EIS for this purpose are usually called EMIS (with “M” for “Management”) in the Environmental Informatics community (e.g., DAAD, 2012; Teuteberg and Marx-Gomez, 2010; Hilty and Rautenstrauch, 1997).

(25) Huang (2011) describes an "initial wave of research" in Sustainable HCI, having shown that "HCI can contribute to solutions to sustainability challenges", but also that problems of sustainability cannot be "framed purely as problems for HCI or interaction design issues." (Huang, 2011, 16) Based on this she proposes to build bridges to other fields, namely existing bodies of environmental data (such as LCA data) and related theories, methods and models; to environmental psychology (e.g., when designing eco-feedback systems); and last but not least to real-world situations such as negotiating with a municipality.

(26) Zapico, Brandt et al. (2010) propose a renewed typology of indirect ICT impacts on the environment, namely "Optimization", "Dematerialization", and "Behavioural Change". Behind these proactive usages of ICT as a tool for mitigating environmental problems is the crosscutting issue of environmental metrics (measuring and accounting of data). Environmental metrics can be expected to improve by ICT as well: "As computers become more pervasive, metrics are getting more accurate, more extensive, and more important in the way the world is viewed and decisions are made." (Zapico, Brandt et al., 2010, 704)

(27) Kramers, Höjer et al. (2013) present an analytical framework to identify ICT-related opportunities for energy savings and other sustainability issues in private households. The framework is a two-dimensional matrix of household functions and ICT opportunities. The household functions are: personal functions, including "activities such as sleep, clothing, hygiene, recreation, entertainment, certain types of trips and holiday homes" and durable and semi-durable goods; housing, including "the residence and parts of its equipment such as residential service, heating and lighting; furnishings such as furniture, carpets and textiles; and domestic services such as cleaning, maintenance and repair"; food, including "energy use related to food items and the equipment required for storage, purchasing and preparation of food, as well as parts of the restaurant and café visits"; care, including "education, social security and healthcare; common, including "the basic needs of safety and security"; and support, including commuting to work. Each household function can be analysed with regard to the following opportunities provided by ICT: "dematerialization", "demobilization", "mass customization", "intelligent operation", and "soft transformation" (Kramers, Höjer et al., 2013, 186f.). The framework has been applied to the City of Stockholm.

Macro-economic developments are the result of interactions of large numbers of agents at the micro-level. Some studies address the problem of linking the two levels or make assumptions about such a link.

(28) Yi and Thomas (2007) found in their review of research on the "environmental impact of e-business and ICT" that "the currently dominant approach is either a micro-level case study approach or a macro-level statistical approach. It is concluded that a more predictive and empirical model [...] should be more beneficial in the long term." They address models that are able to simulate the development of a sector, making it possible to assess the potential impacts of changes. They also see a challenge in translating macro-level results back into action: "The challenge of any research is not to just recognise the problem, but to know what can be done, how it can be done, and to choose certain solutions.

It is not enough to know that ICT/e-business has been changing our daily life, economy, transport, air, water, forests, etc., it is not even to understand how it is changing everything, ultimately an approach which can influence the behaviour, say of a company, for example, is desirable." (Yi and Thomas, 2007, 848)

(29) Grant, Seager et al. (2010) provide a framework for the evaluation of ICT systems designed to support industrial symbiosis, namely the "Designing Industrial Ecosystems Toolkit (DIET)", the "Industrial Materials Exchange Tool (IME)", the "Industrial Ecology Planning Tool (IEPT)" and 10 more. Industrial symbiosis is defined as the "mutualistic interaction of different industries for beneficial reuse of waste flows or energy cascading that results in a more resource-efficient production system and fewer adverse environmental impacts." An industrial symbiosis can be analyzed as a material flow network and a knowledge network at the same time. The evaluation framework includes an industrial symbiosis development process model and a generic description of the functionality of industrial symbiosis ICT tools. The authors observed that "industrial symbioses, compared with traditional commodity exchanges, are characterized by more tacit knowledge flows and application. [...] Put simply, tacit knowledge or know-how cannot be transferred vertically through a hierarchy or to and from a central authority." (Grant, Seager et al., 2010, 740f.) The study concludes "perhaps the most critical challenge to the systems surveyed was their lack of sociability. This was best illustrated by their focus on connecting inputs and outputs rather than people." (Grant, Seager et al., 2010, 750)

(30) Laitner (2010) recapitulates studies about the relationship of ICT, energy productivity, and labour markets. He concludes that, in the U.S., "smart policies" could save energy, reduce greenhouse gas emissions and create jobs at the same time. In order to implement such a "semiconductor-enabled efficiency scenario", substantial investment would be necessary (Laitner, 2010, 694).

(31) Erdmann and Hilty (2010) review 10 studies providing quantiative future scenarios about the future impact of ICT on greenhouse gas emissions at the macro-economic level, analysing their underlying conceptual framework and methodology. A basic distinction is the approach taken, "bottom-up", "top-down", or "hybrid". The result shows that the methods, geographic scopes and time horizons used are diverse and lead to incomparable results. Roughly half of the studies don't address third-order (systemic) effects, such as rebound effects. Some of the studies are able to break down their results to the level of ICT application areas (such as transport, industrial production, buildings) and to demonstrate which changes to the scenarios imply which effects, making them potentially useful for policy support. The authors conclude that the next generation of ICT impact models should combine the scope of the existing global studies with a "methodology that is able to address effects on all three levels." They address the interaction between scenario modelling and decision support: "A process that adjusts the scenarios used in such assessments periodically to real-world developments and recalculates the implications could provide opportunities for mutual learning between researchers and decision makers." (Erdmann and Hilty, 2010, 841)

(32) The participants of ICT4S 2013, the First International Conference on Information and Communication Technologies for Sustainability, have endorsed a set of recommendations under the title “How to Improve the Contribution of ICT to Sustainability” (ICT4S, 2013). The recommendations are structured in three groups: “Sustainability in ICT”, in particular to use the power of software to reduce the energy consumption of hardware and to reduce hardware obsolescence and close material cycles at a global scale; “Sustainability by ICT”, in particular more intelligent energy management in buildings and planning urban structures taking into account the structural changes enabled by ICT, supporting a change towards a sustainable information society; and “Overarching aspects”, in particular ICT applications that create incentives for more sustainable behaviour and support people systematically in adopting more sustainable lifestyles. The detailed recommendations are published on the ICT4S website http://2013.ict4s.org and in the proceedings (ICT4S, 2013, this volume).

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Suggested citation: Hilty, Lorenz M. and Lohmann, Wolfgang 2013. An Annotated Bibliography of Conceptual Frameworks in ICT for Sustainability. In: ICT4S 2013: Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich, February 14-16, 2013, pp. 288-300 DOI 10.3929/ethz-a-007337628