DIGITAL SYSTEMS FOR SUSTAINABILITY

A CLASSIFICATION OF ICT4S AND SMART GREEN STARTUPS DISTINGUISHING AUTOMATION, SOCIAL COMPUTING & CLEANTECH PUSH

by

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ABSTRACT

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

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DIGITAL SYSTEMS FOR SUSTAINABILITY:

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Amongst the many innovations of the digital industry have been systems termed "smart green", "cleanweb" or "Sustainability by ICT" that enable more sustainable patterns of production and consumption. The field of ICT for Sustainability (ICT4S) has developed conceptualisations of these systems such as the LES Model that describes their "enabling impacts" upon production and consumption. However, initial action research amongst cleanweb startups suggested that important groups of smart green system are not distinguished by existing conceptualisations, notably the highly social systems with many interacting users, and the systems that support the adoption of more sustainable products.

To address these limitations with existing conceptualisations of ICT4S, a qualitative analysis was undertaken of cleanweb companies, mapping out the range of possibilities being explored by the industry. 500 company descriptions were analysed, primarily from the CrunchBase online database. A list of search terms was developed to identify the most relevant companies. Significant characteristics of the companies were coded, and the codes were then sorted and resorted to identify higher-level concepts and categories, refined by classifying new samples, and modelled by diagramming. The result, and main contribution, is a typology of the enabling impacts of smart green systems termed the "Smart Green Map" (SGM) that organises them along five dimensions.

Digital systems were found to decouple resource use either by "saving" resources directly through efficiency, or otherwise indirectly by "pushing cleantech" i.e. enhancing the adoption,

construction and operation of more sustainable products. This dichotomy forms a dimension of the SGM called “Decoupling Directness”. The contrasting mechanisms of “saving” and “pushing” were modelled with the LES Model’s resource-use hierarchy theory. The new “push” category of enabling impacts of DDS was not clearly distinguished by established conceptualisations of ICT4S. These push impacts work by actually increasing consumption of certain products such as solar panels, bicycles, or home insulation.

A fresh sample of cleanweb companies and ICT4S research papers was then classified with the SGM, to assess its utility for research. Classification by Decoupling Directness found that, as hypothesised, whilst “push systems” comprised half of the startups, they made up only 18% of research papers.

Digital systems were found to combine people and digital technology in four contrasting ways, termed the “Enablers”: “Automation” is purely technological with little human involvement; “Augmentation” supports and shapes the actions of one main user; “Coordination” supports the communication, interaction and collective action of many users; whilst “Autination” – a term proposed here for “automated coordination” – automates interactions between human actors. These four Enablers are the cells of a 2x2 matrix whose axes are “level of automation” and “level of social interaction”, two further dimensions of the SGM. A venture capital firm has used the Enablers as the basis for their investment framework, informing decisions and communicating policies to investors and the wider market, as described in a case study.

The processes of production and consumption by which resource use is decoupled were best described as part of the Circular Economy. These processes form a further dimension of the SGM that situates recycling, reuse and maintenance within ICT4S, and Sharing Economy systems such as tool-sharing and ride-sharing platforms. The remaining dimension of the SGM is the type of resource, such as heat energy, water or materials.

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ABBREVIATIONS AND TERMINOLOGY

Abbreviations and acronyms used in the thesis, and original terminology introduced.

AR	Action research
Autination	Autonomous actions and interactions of the digital devices of different human actors.
Automation	Autonomous actions of an individual human actor's digital device.
autoPush	Cleantech production and adoption improvements due to the actions of digital devices acting autonomously.
autoSave	Resource efficiencies due to the actions of digital devices acting autonomously
Augmentation	Actions of an individual employing digital devices.
Coordination	Actions of groups of human actors interacting via digital devices.
DDS	Digital Decoupling Systems. Those digital system that make resource use more sustainable, contributing to macro-scale dematerialisation (Section 1.2). Cleanweb systems. A subset of DSS.
DD	The Digital Decoupling dimension of the SGM, composed of Save and Push enabling impacts or systems.
Enablers	Four categories of enabling impact as different combinations of human actors and digital devices: Automation, Augmentation, Coordination and Autination.
Enabling impact	The ability of digital technology to mobilise, control and supplement the action and experience of individuals, groups and devices (Section 2.3.3).
DSS	Digital Sustainability Systems. Those digital system that are applied to sustainability challenges (Section1.2). The central phenomenon of Sustainability by ICT. A superset of DDS.
GT	Grounded theory
HCI	Human-Computer Interaction, a field of computer science about how people interact with computers, and to what extent computers are or are

	not developed for successful interaction with human beings (Dix, Finlay, & Abowd, 2003).
iPush	Cleantech production and adoption improvements due to the actions of an individual employing digital devices.
iSave	Resource efficiencies due to the actions of an individual using digital devices.
ICT	Information and communication technologies, digital hardware and software.
ICT4S	Information and communication technologies for sustainability, a young interdiscipline investigating the role of ICTs in sustainability (Hilty & Aebischer, 2014).
This investigation	This entire doctoral research project.
LES Model	The leading strategic theory of the field of ICT4S. It is an acronym referring to the three levels of impact of ICT that it identifies: Life-cycle impact, Enabling impact and Systemic impact (Hilty & Aebischer, 2014).
LCA	Life-cycle assessment
Push	Enhancing the production and adoption of other more sustainable products ("cleantech catalysis").
Save	Creating resource efficiencies more directly by controlling machines or influencing peoples' behaviour
SGM	The Smart Green Map, a five-dimensional classification of DDS and their enabling impacts. The SGM and its components are the central theoretical contribution of this thesis. It has three versions: SGM1, SGM2, SGM3. The term "smart green" follows its use by Ecosummit (Hess & Butter, 2016).
The study	The research of the particular chapter.
Social machine	Highly social digital systems based on ICTs e.g. ride-sharing sites. (O'Hara, 2012; N. Shadbolt et al., 2013; N. R. Shadbolt, Van Kleek, & Binns, 2016; Smart & Shadbolt, 2014; Ramine Tinati & Carr, 2012).

Sustainability by ICT Applying ICT as an enabler in order to reduce the footprint of production and consumption by society. One of two major pillars of ICT4S, and the focus of this thesis (Hilty & Aebischer, 2014).

SHCI Sustainable Human Computer Interaction, an area of HCI, itself an area of computer science. Hilty identifies sustainable human-computer interaction (HCI) as one of the major fields of ICT4S, focussing on the relationship between humans and technology in the context of sustainability.

wePush Cleantech production and adoption improvements due to the actions of groups of human actors interacting via digital devices (Coordination).

weSave Resource efficiencies due to the actions of groups of human actors interacting via digital devices (Coordination).

CHAPTER 1 INTRODUCTION

1.1 MOTIVATION

Over the last decade, looming environmental risks and the rapid development of Information and Communication Technologies (ICTs) have spurred interest in the topic of **Sustainability by ICT**, *"the transformational power of [ICT] to develop more sustainable patterns of production and consumption"* (Hilty & Aebischer, 2014). This topic has been investigated by **ICT for Sustainability (ICT4S)** and a number of related fields (Chapter 2).

The Web sector is noted for its vigorous entrepreneurship and innovation, and some Web startups - termed "**cleanweb**" or "**smart green**" - are developing a diverse range of Sustainability by ICT applications such as smart thermostats or tool-sharing platforms. The possible ways in which ICT can address environmental challenges are gradually being explored by these entrepreneurs (Carlota Perez, 2016; Eisenberger, 2015; Masero & Townsend, 2014; Paul & Allen, 2012). Cleanweb startups have attained significant success: Nest was bought for $3.2bn (BBC News, 2013), Climate Corporation for $1.1bn, Opower and Zipcar for $500m, and Solar City has a market capitalisation of $2bn.

Addressing the limits of central theories is an important process in the development of a field such as ICT4S. Such theories can have practical applications, such as frameworks for investment in cleanweb systems that address climate change (Chapter 7). Cleanweb companies are creating systems that are not fully accounted for by the leading conceptualisation of ICT4S, the **LES Model** (Hilty & Aebischer, 2014) (Section 2.3.3). These limitations in the model may restrict its practical applications.

The term "**cleantech**" is widely used within entrepreneurship to describe more sustainable products and technologies such as renewable energy (Cleantech Group, 2016) (Section 3.4.1). One limitation of existing conceptualisations of Sustainability by ICT is that they do not distinguish those systems that work by enhancing the adoption, construction or operation of some cleantech, such as solar panels.

In addition, the LES Model does not sufficiently describe the wide **social variation** between cleanweb systems. For instance, smart thermostats heat homes with little human attention required, saving fuel **automatically**. In contrast, ridesharing platforms are networks that connect passengers with millions of drivers with spare seats, thus saving fuel **socially**. Within the field of Web Science, highly social systems such as ridesharing platforms are conceptualised as “social machines” (T. Berners-Lee et al., 2006; Halford, Pope, & Carr, 2010). At the intersection of ICT4S and Web Science (Figure 1), questions remain about how Sustainability by ICT brings together people and digital technology to benefit sustainability, often by supporting cleantech.

To uncover and address these limitations with existing conceptualisations such as the LES Model, this investigation used a mixture of methods to map out the space of possible Sustainability by ICT systems revealed by cleanweb entrepreneurship and ICT4S scholarship.

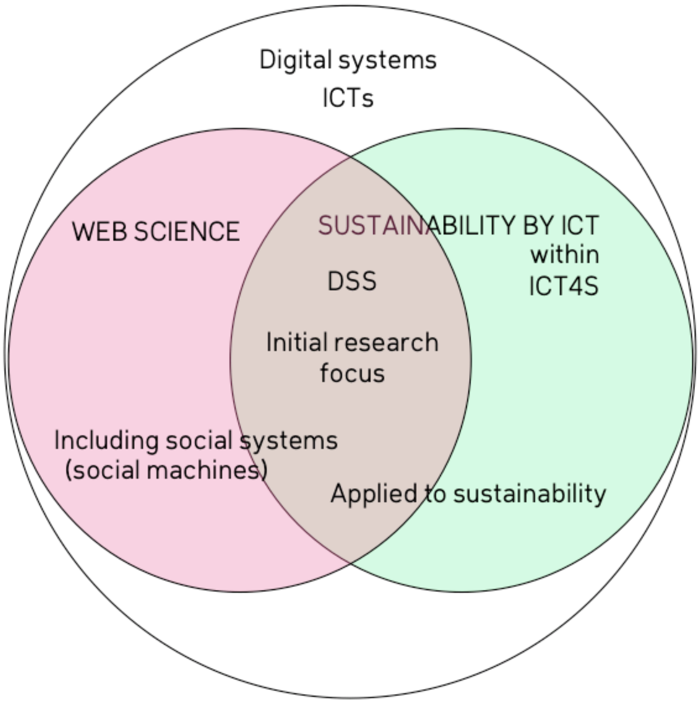

Figure 1 This investigation addresses questions at the intersection of Web Science and ICT4S, about how the interactions of people and digital technology can address sustainability challenges such as climate change.

1.2 AIMS AND METHODOLOGY

Tinati *et al.* argue that a mixture of methods is required to investigate the complex sociotechnical phenomena of the Web (R Tinati, Halford, Carr, & Pope, 2012). This investigation employed a range of methods that are mainly **qualitative and inductive**, but also include the deductive and quantitative. The investigation began with action research that engaged with relevant communities, learnt about their possible research requirements and formed hypotheses about the present distribution of activity. Based on these requirements, a qualitative classification development was undertaken and mechanistic models were developed to explain the observed variation. A simple quantitative comparison was then employed to test hypotheses about the distribution of ICT4S research and cleanweb entrepreneurial activity. Finally, a qualitative case study described the use of elements of the theory by a venture capital firm as a basis for investment decisions.

The primary aim of this investigation was to develop a new classification in order to describe the variation observed amongst the digital tools, products and social networks of Sustainability by ICT. These then became the "phenomena of study" of the investigation. However, no single concept was encountered that encapsulated all these phenomena together, so three novel concepts were defined: digital systems, DSS and DDS. These are nested categories: digital systems include all DSS, and DSS include all DDS.

This investigation is about the **possibility space of enabling impacts of digital systems**. **Enabling impacts** are described by the second level of the LES Model (Section 2.3.3) as any actions enabled by the application of ICT. This investigation focuses in on **DSS,** the set of digital systems that undertake **Sustainability by ICT** by applying their enabling effects to sustainability challenges. This investigation then focuses in further on **DDS,** those DSS that make **resource use more sustainable** by causing **decoupling or dematerialization** at the third level of the LES Model. The thesis does not address the life-cycle impacts of ICT use that make up the first level of the LES Model (i.e. Sustainability in ICT), nor quantitative methodologies for calculating the structural effects at the third level of the LES Model (Section 2.3.4 and 2.3.5).

- **Digital systems** are any ICT, ICT-based system, digital hardware, software or digitally mediated network of people (social machine). The concept of the digital system is developed in order to encompass all the systems that make up "the Web" or "the Internet", whether ICTs or social machines. By embracing this broad diversity, the "digital system" concept avoids the question of whether a social machine is an ICT or rather a sociotechnical phenomenon emergent from the interactions of ICTs and human beings. Chapter 4 will define the concept of the digital system more formally by developing a model of their structure (Figure 28).

- **Digital sustainability systems** or **digital systems for sustainability (DSS)** are those digital systems that are being effectively applied to progressing environmental sustainability. Therefore, DSS are all the systems of Sustainability by ICT, and include all social machines applied to sustainability challenges e.g. ridesharing platforms. DSS are the subject of Sustainability by ICT research as they are **applied** to progressing sustainability by employing the "transformational power of ICTs" (L. Hilty & Aebischer, 2014). However, DSS are not just digital hardware and software, but also the networks of people that make up social machines. Figure 1 visualises DSS at the intersection of Web Science and ICT4S. Within the LES Model, DSS can be identified as any digital system that is creating, enabling and encouraging sustainable patterns of production and consumption, including via **institutional change** to the "rules of the game" such as laws, policies, social norms (Section 2.3.3 & 2.3.6).

- **Digital decoupling systems (DDS)** are those digital systems that are being effectively applied to progressing sustainability by making **resource use more sustainable.** DDS are therefore a subset of DSS, excluding those primarily undertaking institutional change. Chapter 8 (Table 43) will show that most digital systems researched and built by the ICT4S and cleanweb communities are DDS. Within the LES Model, DDS can be identified as any digital system that is creating, enabling and encouraging sustainable patterns of production and consumption, specifically by contributing to macro-scale **dematerialisation** (Section 2.3.3 - 2.3.6). Section 6.3.2 will argue that a DDS is equivalent to a cleanweb system.

Research was undertaken in a progression of three overlapping phases, as summarised in Figure 2 and Figure 3.

Phase 1 explored the breadth of Sustainability by ICT practice, contributed to it, and identified research needs of practitioners. **Action research (AR)** was undertaken amongst cleanweb startups and other relevant communities, alongside **literature review** of strategic theories of ICT4S. As the investigation was early-stage and exploratory, an AR methodology was *"most likely to be appropriate when you do not know where to start… where you do not yet have a very precise research question"* (Dick, 1998). The AR sought to answer three initial questions:

- **What communities are addressing Sustainability by ICT and how do they compare?** Identifying communities is of course a prerequisite to engaging with them. For each community, leading conceptualisations of the domain were sought, as a basis for later analysis (Sections 3.3 and 3.4).
- **What further research might benefit Sustainability by ICT communities?** As action research, the investigation sought to work with members of a social setting to collaborate in the diagnosis of a problem and in the development of a solution based on diagnosis (Bryman, 2001). The interactions and observations identified the research aims for Phase 2 (Section 3.6 and 3.7).
- **How can the AR contribute to Sustainability by ICT communities?** As AR it sought to work within the communities to address practical challenges and have direct and practical outcomes (Reason & Bradbury, 2001) (Section 3.6).

Phase 2 sought to develop a new classification of Sustainability by ICT systems that described how they combine people and digital technology to progress sustainability. The method was qualitative analysis of descriptions of cleanweb startups. Phase 2 forms the core of the investigation, addressing the following questions:

- **How can Sustainability by ICT systems be classified effectively and usefully?** Phase 1 found that a new classification of DDS could address the needs of the cleanweb community by better describing the diversity of systems the community is developing. The central method of Phase 2 and of the entire investigation, was qualitative classification development from descriptions of cleanweb companies. In effect, this explored the possibility space by crowdsourcing the ingenuity of cleanweb entrepreneurs. The result of Phase 2 is the first version of the main theoretical contribution, a **classification of DDS** called the **Smart Green Map (SGM1)**, which initially has two dimensions: the **Enablers** (Chapter 5) that describes how digital systems combine people and digital technology and **Decoupling Directness (DD)** (Chapter 6) that describes whether or not they catalyse cleantech (see following questions specific to each).

- **What is the conceptual basis for the observed variation in DDS?** Phase 2 and 3 aimed to not just describe the observed variation, but to model the mechanism that causes it, just as the LES Model is based upon the underlying "resource-use hierarchy model" (Section 2.3.3).

- **How are DDS benefiting sustainability?** Phases 2 and 3 sought to understand how digital systems are able to contribute to dematerialisation, and thus sustainability, by developing a classification of DDS and modelling the observed variation.

- **How are DDS combining people and digital technology?** The cleanweb entrepreneurship and Sharing Economy systems observed in Phase 1 showed that there is a wide variation in how social DDS are. Phases 2 and 3 investigated these varying ways in which people and machines are brought together by DDS to benefit sustainability.

- **How are DDS "catalysing cleantech"?** Phase 1 showed that many DDS enhance the adoption, construction and operation of more sustainable products. Phases 2 and 3 investigated how this occurs, and how it relates to other forms of Sustainability by ICT.

Phase 3 applied a mix of methods to **employ, evaluate and develop** the SGM classification first formed in Phase 2, by addressing the following questions:

- **Is the Smart Green Map classification effective and useful?** To assess the utility of the classification to researchers, Phase 3 **compared** a recent sample of cleanweb startups with one of ICT4S research papers by categorising them with the SGM. To assess its usefulness to practitioners, a **case study** was undertaken of an implementation of the classification by a cleanweb venture capital firm.
- **Are social systems and cleantech catalysts more prevalent in cleanweb entrepreneurship than ICT4S research?** This hypothesis is an observation first made during the Phase 1 AR within Sustainability by ICT communities. The hypothesis was tested by comparing recent samples of cleanweb startups and ICT4S research papers.
- **How can leading conceptualisations of ICT4S better describe social systems, cleantech catalysts, the Circular Economy and the Sharing Economy?** Phase 3 undertook a synthesis of the SGM classification from Phase 2 with the leading conceptualisation of Sustainability by ICT, the LES Model. This synthesis was developed by integrating concepts from the Circular and Sharing Economies – two communities encountered in Phase 1.

This research is **descriptive**, but also considerably **normative**, as it investigates DSS, those systems for which "ICT is part of the solution" (Three-Levels model of ICT4S, Section 2.3.1). Similarly, Web Science research is motivated by the need to "ensure the Web benefits the human race" by understanding it better (Web Science Trust, 2010). Terms like "cleantech" or "cleanweb" are intrinsically normative, and without a normative distinction there is no basis for the Environmental, Social and Governance (ESG) investment industry in the case study of Chapter 7.

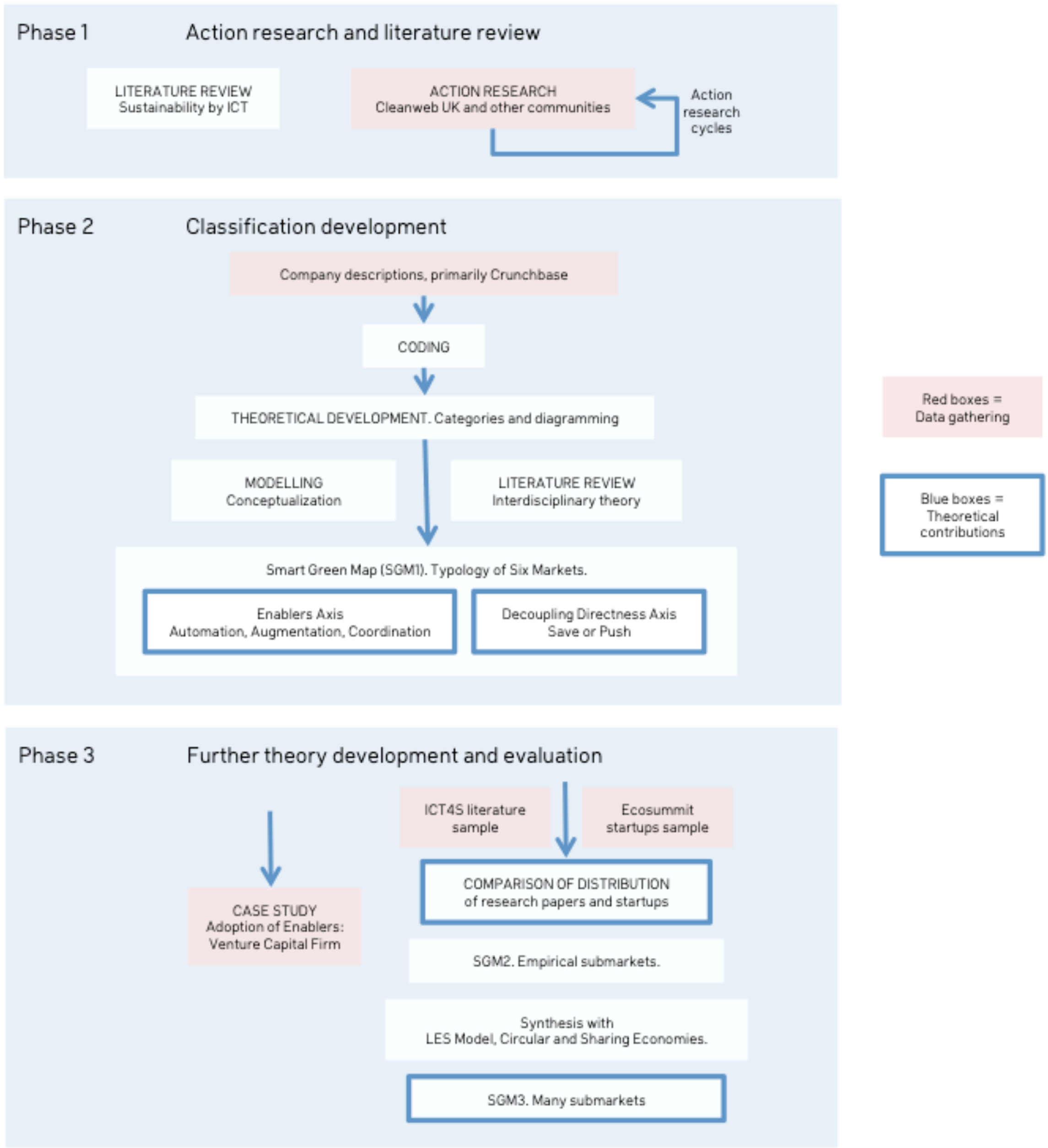

Figure 2   Diagram summarising the methodological structure of three research phases

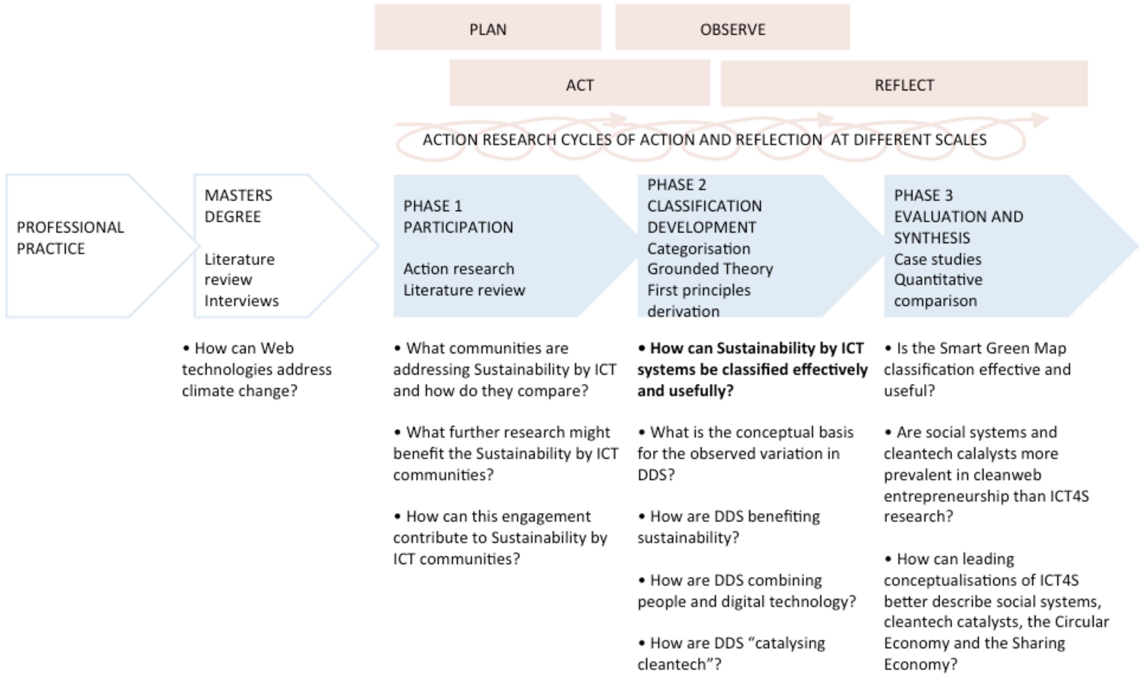

Figure 3 The research phases and research questions. They constituted action research cycles at different scales. This doctoral investigation took place in three phases, preceded by professional practice and a Master's degree.

1.3 CONTRIBUTIONS AND IMPACT

A number of contributions to the fields of ICT4S and Web Science were made by this investigation (Chapter 10):

- That digital systems that make resource use more sustainable (DDS or cleanweb systems) can usefully be organised along **five dimensions -** described below - forming a typology here termed the **Smart Green Map**[1] (SGM) (Table 60, Figure 61). Three versions were developed: the SGM1, SGM2, and SGM3 (Section 10.3).

- That digital systems can decouple resource use either directly by "saving resources" or indirectly by "pushing cleantech". This form a two-category dimension of the SGM called "**Decoupling Directness" (Chapter 6)**.
    - When **saving resources**, DDS contribute to resource efficiencies more directly by monitoring and optimising resource use, or by media substitution. Examples of such save systems are smart thermostats and ridesharing apps.
    - In contrast, when **pushing cleantech**, DDS enhance the adoption, construction and operation of more sustainable products. Examples include

[1] smartgreenmap.com

manufacturing robots and crowdfunding platforms for solar panels. The concept of such a push system is the greater contribution as it had not been clearly distinguished by existing conceptualisations of ICT4S (Section 10.2). Push systems were modelled as resource-use hierarchies as described in the LES model (Figure 54, Section 9.3.1).

- That cleantech push systems have been a lot more prevalent amongst cleanweb startups than ICT4S research papers (Section 10.4).
- That four contrasting processes distinguish how digital systems **combine people and digital technology**. These four "**Enablers**" are the cells of 2x2 matrix of two dimensions of the SGM, "level of automation" and "level of social interaction".
    - "**Automation"** is purely technological with little human involvement, such as in smart thermostats or solar panel manufacturing robots[2].
    - "**Augmentation"** supports and shapes the actions of one main user, such as in behaviour change apps or travel planning and navigation tools.
    - "**Coordination"** supports the communication, interaction and group action of many users, such as in teleconferencing or sharing economy systems.
    - **"Autination"** automates social interaction, such as when autonomous agents control distributed supply and demand of energy in the smart grid. The term "autination" is coined here.
- That DDS always work via economic processes of production and consumption identified by the Circular Economy model. This forms a further dimension of the SGM (Section 9.2). This connects ICT4S theory with leading concepts of sustainability as circularity by recycling, reuse, maintenance and sharing of resources. The role of save systems is to reduce resource use within production and consumption processes and circularise flow of resources. In contrast, the role of push systems is to increase production and consumption of cleantech.
- That Sharing Economy systems such as tool-sharing and ridesharing platforms are a significant form of DDS is also recognised by the Circular Economy model of economic processes of production and consumption.
- That DDS can also be usefully classified by the type of resource they decouple, such as heat energy, electrical energy, water, materials or space. It is this resource type

[2] E.g. Google Nest https://nest.com/uk/thermostat/meet-nest-thermostat/

dimension that is the basis of most classifications of industrial activity, including those of the cleantech industry and the Sharing Economy (Section 3.4). It forms the final dimension of the SGM.

This investigation has produced the following peer-reviewed publications.

Townsend, J. H. (2015). **Digital Taxonomy for Sustainability.** Proceedings of ICT for Sustainability 2015.[3] Part of the series *Advances in Computer Science Research*. doi:10.2991/ict4s-env-15.2015.33

Townsend, J. H. (2014). **Web for Sustainability: Tackling Environmental Complexity with Scale.** Proceedings of ICT for Sustainability 2014.[4] Part of the series *Advances in Computer Science Research*. [Best paper nomination] doi:10.2991/ict4s-14.2014.8

Townsend, J. H., et al. (2013). **Creating an Open Data Application for Sustainability Education: Globe-Town.** Proceedings of the LinkedUp Veni Open Education Competition.[5] CEUR Workshop Proceeding. Vol-1124 urn:nbn:de:0074-1124-4

Townsend, J. (2012). **Digital Research for Sustainability: Conveying Global Change via the Web.** Poster at Digital Research 2012, Oxford.

A number of other publications and communications were also produced:

Townsend, J. H. (2016). **Cleanweb Taxonomy - Mapping the Cleanweb Sector.** Meetup Presentation. Cleanweb UK Youtube Channel.

Masero, S., & Townsend, J. H. (2014). **Cleanweb in the UK: How British Companies are using the Web for Economic Growth & Environmental Impact.** Industry report for Nesta.[6]

Townsend, J. H. (2014). **Cleanweb entrepreneurship.** Lecture to business students at University of East London.

Townsend, J. H. (2013). **Open Sustainability: Securing the Natural Commons with the Knowledge Commons***.* Plenary presentation at OKCon 2013, Geneva. Article published in the Open Knowledge Open Book .

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[3] eprints.soton.ac.uk/378266/
[4] eprints.soton.ac.uk/364783/
[5] http://ceur-ws.org/Vol-1124/linkedup_veni2013_02.pdf
[6] http://www.nesta.org.uk/publications/cleanweb-uk-how-british-companies-are-using-web-economic-growth-and-environmental-impact

Townsend, J. (2013). **Open Sustainability and Environmental Regulation.** Presentation at ICT for Environmental Regulation workshop, Galway.[7]

Townsend, J. (2013). **The Promise and the Perils of Efficiency.** Blog for Cleanweb UK.[8]

Gardiner, B. (2013). **Harnessing the Net to Power a Green Revolution.** Interview by the New York Times.[9]

Townsend, J. (2012). **Open Sustainability.** Presentation at TEDxSouthamptonUniversity[10].

Townsend, J. (2012). **Globe-Town.** Presentation at World Bank Headquarters, Washington DC.

Townsend, J., Zapico, J. L., & Booth, J. (2012). **Green IT and Cleanweb.** Lectures to Undergraduate Computer Science Students (INFO1010).

Townsend, J. (2012). **Connecting the global with the local: using open data to explore the risks, responsibilities & opportunities of climate change.** Presentation at CODATA 2012 conference: Open Data for a Changing Planet.

Dimitrova, V., Zapico, J., Ebner, H., & Townsend, J. (2012).[11] **Recap of the Sustainability Stream of the Open Knowledge Festival.** Blog post for Open Knowledge Foundation.

Townsend, J. (2012). **How might open knowledge help develop a sustainable open society?** Presentation at OKFestival, Open Knowledge Festival, Helsinki.

Townsend, J., Taylor, G., & Noble, J. (2011). **The Significance of the Web and Related Technologies to the Challenge of Climate Change**. Dissertation Web Science MSc, University of Southampton.

This investigation has had a number of impacts beyond the theoretical contributions, primarily during the action research of Phase 1 (Section 3.6). These include:

- Leadership of the **London Cleanweb community**, where cleanweb entrepreneurs and specialists present their work each month, generating a resource of over 70 videos ("Cleanweb UK Youtube Channel," 2012). A number of cleanweb startups have emerged from these events, including Open Utility, Mastodon C and IYWTO.[12]

7 http://ict4er.org/wp-content/uploads/2013/08/Townsend.pdf
8 http://www.cleanweb.org.uk/blog/2013/02/28/the-promise-and-the-perils-of-efficiency/
9 http://www.nytimes.com/2013/06/19/business/energy-environment/harnessing-the-net-to-power-a-green-revolution.html?_r=0
10 http://www.youtube.com/watch?v=0a_3-lxbeGY&feature=youtu.be
11 http://openeconomics.net/2012/10/06/okfestival-sustainability-stream-recap/
12 https://www.openutility.com/ http://www.mastodonc.com/ https://iywto.com/

- Creating the **Globe-Town application** (Townsend et al., 2013) which was a winner of the **LinkedUp Open Data in Education competition** and **World Bank Apps for Climate competition** (World Bank Development Data Group, 2012).
- The Enablers model has been adopted within the investment policy of a **venture capital firm** focussed on resource efficient cleanweb companies. This is described in the case study (Chapter 7).
- Contributing to the Nesta report on the **UK Cleanweb sector** (Masero & Townsend, 2014), which incorporated a very early version of this research.
- A **TEDx talk** (Townsend, 2012) and interviews with the New York Times (Gardiner, 2013) and environmental magazine Grist (Suzanne Jacobs, 2015).
- Organising the sustainability stream of the **2013 Open Knowledge Festival** (Dimitrova et al., 2012) in Helsinki, and subsequent founding of the **Open Sustainability working group** (Dimitrova & Zapico, 2012).

1.4 THESIS STRUCTURE

The thesis is organised as follows. The research questions are highlighted in **bold** throughout.

Chapter 2 and Chapter 3 describe Phase 1, which employed action research and literature review to explore the context of research and praxis of Sustainability by ICT, and thus determine the aims and methodology for Phases 2 and 3. **Chapter 2** reviews the literature of conceptualisations of Sustainability by ICT, and particularly the leading LES Model. **Chapter 3** describes the action research engagement with a number of relevant communities. The entrepreneurial cleanweb community was prioritised for analysis and its research needs identified. It was observed that both social systems and those that "catalyze cleantech" appear more prevalent in cleanweb entrepreneurship than Sustainability by ICT research, a hypothesis that is tested in Chapter 8. Chapter 3 concludes by identifying a research problem of theoretical and practical value i.e. developing a classification of cleanweb companies. This forms the central methodology for Phase 2 and the whole investigation.

Chapter 4, Chapter 5 and Chapter 6 describe Phase 2, which develops the first version of the classification of Sustainability by ICT systems called the Smart Green Map (SGM)**.** **Chapter 4** describes the sourcing of data - qualitative descriptions of cleanweb companies - and the methods by which the classification was developed. **Chapter 5** employs the methods of Chapter 4 to identify three of the Enablers, describing the social variation in digital systems. A model of the function of digital systems is then developed from which the Enablers can be defined, allowing their properties to be analysed. Chapter 5 then explores the disciplinary context of each Enabler and their role within ICT4S. **Chapter 6** also employs the methodology of Chapter 4 to develop the Decoupling Directness dimension (DD) of Save and Push systems. Chapter 6 then combines the Enablers and DD axes to create the first version of the Smart Green Map, the SGM1.

Chapter 7, Chapter 8, Chapter 9 describe Phase 3, which employs, evaluates and develops the Smart Green Map, determining if it is an effective and useful classification of DDS. **Chapter 7** is a case study of the use of the Enablers by a venture capital firm, demonstrating their utility. The firm integrated the Enablers into their investment framework to inform investment decisions and communicate investment policies to existing and potential investors. **Chapter 8** compares the distribution of ICT4S literature with that of cleanweb startups by classifying them with the six SGM1 "markets", allowing it to be evaluating through use. This comparison also allows hypotheses from Phase 1 to be tested about the relative distribution of research and entrepreneurial activity. Furthermore, a more granular classification of "submarkets" is identified, which form the basis for the SGM2. **Chapter 9** discusses the results, comparing them with leading conceptualisations of ICT4S and then synthesising the SGM2 submarkets with the leading LES model of ICT4S to form the final SGM3. **Chapter 10** concludes the thesis by discussing the basis for each contribution and how they address the research questions, whilst identifying limitations and areas for future work.

CHAPTER 2 SUSTAINABILITY BY ICT LITERATURE

2.1 INTRODUCTION

The Introduction Chapter argued that many groups are applying the "transformational power of ICT" (Hilty & Aebischer, 2014) to the challenges of sustainability, and that there has been some consolidation around the label of "ICT4S" in research, and "cleanweb" or "smart green" in entrepreneurship. However, at the outset of the investigation neither the terms "ICT4S" or "cleanweb" had yet been coined. Moreover, one impactful form of ICT – the social systems frequent in the Web industry – has not been clearly acknowledged by ICT4S research and theory. This led to an early research question on how the application of ICTs to sustainability relates to the wide variation in how social they are.

This Chapter and the one that follows describe Phase 1, a journey of action research and literature review that explored the context of research and praxis to identify **what further research might benefit the communities of Sustainability by ICT.** Phase 1 constituted much of the research effort. The conclusions of Phase 1 – combining this literature review and the action research – will be presented in the next chapter, identifying the research issues that then motivate the aims and methods of Phase 2, the core of the investigation leading to the main theoretical contribution, a classification of cleanweb systems (DDS). Therefore, the conclusions of this chapter are combined with those of the next in Sections 3.7 and 3.6.

This chapter begins by identifying the major **academic communities addressing Sustainability by ICT** in Section 2.2, including ICT4S, Green IT, Sustainable HCI, Environmental Informatics, and Computational Sustainability. These fields have generated a considerable history of conceptualisations that describe the variety of Sustainability by ICT systems and the enabling impacts through which they work.

Section 2.3 then discusses **conceptual theories of Sustainability by ICT**, which are partial **classifications** of Sustainability by ICT. Section 3.7 will identify potential gaps in these conceptualisations and classifications for further analysis. The conceptual framework for this thesis is the state-of-the-art conceptualisation of the whole of ICT4S, the LES model, although it only emerged whilst the investigation was in its later stages. Section 2.3 describes the LES Model in some detail and the various elements of theory upon which it is based. Section 2.3 reviews how the core mechanisms of Sustainability by ICT identified by the LES Model, the **enabling** and **structural effects,** have been modelled and quantified.

The literature review in this chapter complements more systematic literature analysis in Chapter 8 and Chapter 9 employing the SGM classification developed in Phase 2. Chapter 9 will compare the conceptualisations of ICT4S from this chapter with the SGM classification in Table 58, and classify a sample of recent ICT4S and Sustainable HCI (SHCI) research papers in Table 52. Methodological background is addressed throughout the thesis in the methods sections. Other sources for the literature in this chapter include the publication *ICT Innovations for Sustainability*, the *ICT4S* conferences, and the Hilty & Lohmann's annotated bibliography of ICT4S (L. Hilty & Aebischer, 2015; L. Hilty & Lohmann, 2013).

2.2 FIELDS ADDRESSING SUSTAINABILITY BY ICT

As both ICTs and environmental sustainability are complex global phenomena relevant to many fields - from engineering to the humanities - research into their interrelationship has arisen in many academic communities (L. Hilty & Lohmann, 2013). In particular, a number of overlapping interdisciplinary fields and research fields have arisen whose scope relates directly to Sustainability by ICT. Hilty & Aebischer identify the following such fields, which are described in the remainder of this section: ICT for Sustainability (ICT4S), Sustainable HCI (SHCI), Green IT, Computational Sustainability (CompSust) and Environmental Informatics (EI) (L. Hilty & Aebischer, 2014).

The new interdisciplinary field of **ICT for Sustainability (ICT4S)** arose in 2012 to bring together diverse research into the environmental impacts of ICTs and the "transformational power of ICT" to address sustainability (L. Hilty & Aebischer, 2014). ICT4S was described in recommendations made by attendees at the first international ICT4S conference, which is now in its fourth year[13]: *"The transformational power of ICT can be used to make our patterns of production and consumption more sustainable."* However, the recommendations continue to state that *"the history of technology has shown that increased energy efficiency does not automatically contribute to sustainable development. Only with targeted efforts on the part of politics, industry and consumers will it be possible to unleash the true potential of ICT to create a more sustainable society"* ("Conference Recommendations: How to Improve the Contribution of ICT to Sustainability," 2013).

Hilty identifies two ways in which ICTs impact sustainability, which make up two distinct areas of ICT4S research[14]: *Sustainability by ICT* that focuses on "creating, enabling, and encouraging sustainable patterns of production and consumption by means of ICT"; and

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[13] http://2016.ict4s.org/ http://2013.ict4s.org/the-conference/about/
[14] Discussed much further in Chapter 2

Sustainability in ICT which makes ICT goods and services more sustainable over their whole life-cycle, mainly by reducing the energy and material flows they invoke.

Sustainable HCI (SHCI) is a sub-field of Human-Computer Interaction (HCI) (Dix et al., 2003) that focuses on the relationship between humans and technology in the context of sustainability, and the design of more sustainable digital artefacts. SHCI addresses both Sustainability **by** and **in** ICT.

Sustainable HCI emerged from proposals that sustainability should be a major criterion in the design process, as important as usability or robustness (Blevis, 2007). Mankoff *et al.* propose a similar distinction within SHCI between Sustainability *in* ICT and *by* ICT: "Sustainability in design" and "Sustainability through design" (JC Mankoff, Blevis, & Borning, 2007). DiSalvo *et al.* organised the field into six "genres": "Persuasive technology" stimulating sustainable behaviours; "Ambient awareness" systems which make 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" (Disalvo, Sengers, & Brynjarsdóttir, 2010).

The term **Green IT** became popular after the publication of a report by Gartner (Mingay & Gartner, 2007). The Google Trends data in Figure 4 shows that the term is used much more commonly than all other ICT4S terms in this thesis. Murugesan defined 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."* (Murugesan, 2008). Similarly Herzog et al. equate "Green IT" with Sustainability in ICT (Herzog, Lefevre, Pierson, & Paul, 2015), showing how Green IT is commonly used in used by a variety of commercial, and also academic contexts.

The field of **Computational Sustainability** (CompSust) has been defined as *"an interdisciplinary field that aims to apply techniques from computer science, information science, operations research, applied mathematics, and statistics for balancing environmental, economic, and societal needs for sustainable development"* (Gomes, 2009; J Mankoff, 2013). It is closely connected with the Institute for Computational Sustainability (ICS).

Environmental Informatics (EI) focuses on the challenges of environmental science and management, combining methods from computer science and information systems. (Avouris & Page, 2013; L. M. Hilty, Page, Radermacher, & Riekert, 1995; L. Hilty, Page, & Hřebíček, 2006). Similar to Health Informatics or Bioinformatics, EI emerged from the need to systematically meet domain-specific requirements to information processing.

Other related fields include ICT for international development (ICT4D) (Ospina & Heeks, 2010; Unwin, 2009), ICT for Energy Efficiency (ICT4EE) (J. A. S. Laitner, 2015), and Energy Informatics (Watson, Boudreau, & Chen, 2010). More broadly, a sustainability perspective can be applied to any field relating to ICT, and a digital perspective can be applied to any field relating to sustainability, so the number of relevant fields and topics is very large, as illustrated in Figure 14.

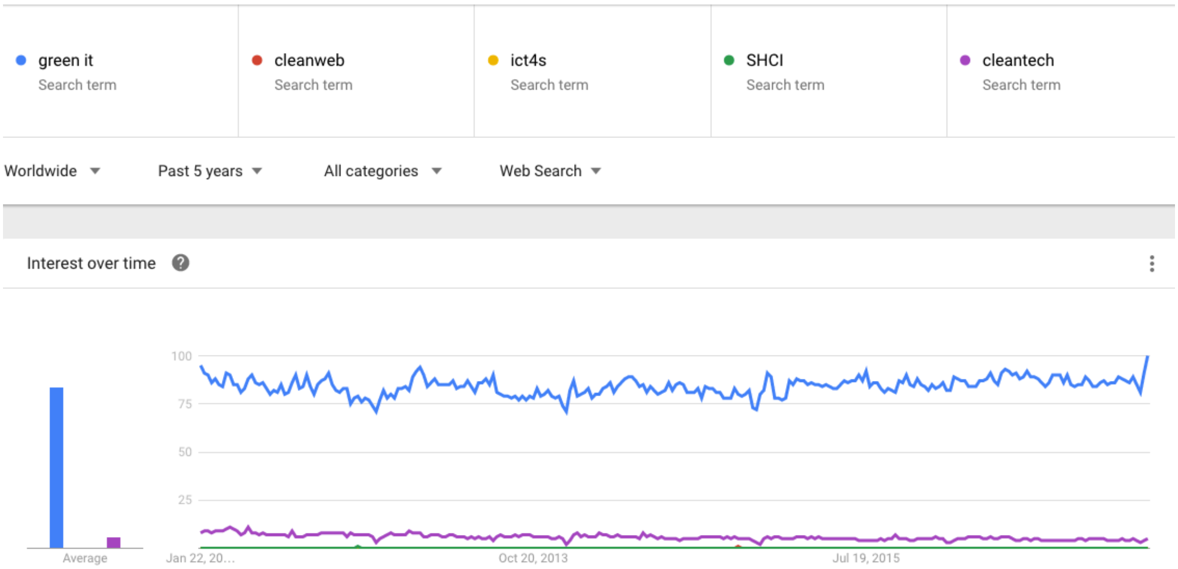

Figure 4 Comparing the popularity of key terminology used in this thesis, as search terms on Google. "Green IT" is by far the most popular term, followed by "cleantech", whilst the terms "ICT4S", "SHCI" and "cleanweb" are much less popular. © Google Trends

2.3 SUSTAINABILITY BY ICT CONCEPTUALISATIONS

This section presents strategic conceptualisations and classifications of Sustainability by ICT from the last two decades, concluding with the state-of-the-art framework LES model and the theory upon which it is based: resource-use hierarchies, and the mutual substitutability of energy, time and information (L. Hilty & Aebischer, 2014). This section also reviews the methods of quantifying the enabling impacts of ICTs.

Berkhout and Hertin first introduced the seminal distinction between first-, second- and third-order effects of ICT, in a 2001 OECD report (Berkhout & Hertin, 2001). This distinction has been widely used in later literature, and forms the basis for the subsequent LES Model. The three orders of effects of ICT are:

- **Direct environmental effects** of the production and use of ICTs. Addressing these "first-order" effects is the aim of **Sustainability in ICT.**

- **Indirect environmental impacts** through the change of production processes, products, and distribution systems.
- **Indirect environmental impacts** through impacts on life styles and value systems.

The 2008 WWF Report focussed on Sustainability by ICT, outlining a global IT strategy for CO2 reductions through *"Ten IT solutions that will reduce one billion tonnes of CO2 and begin the transformation towards a low-carbon society"* (Pamlin & Pahlman, 2008). Most are familiar elements of ICT4S discourse: **smart city planning, smart buildings, smart appliances**, **dematerialisation services**, **i-optimisation** (of production processes), **smart industry** (design tools), **smart grid** (demand response), **integrated renewable solutions** (smart grid for renewable energy), **smart work** (teleworking), and **intelligent transport**.

In 2010, Zapico, Brandt et al. identified three main topics of Sustainability by ICT research, distinguishing **"Optimization", "Dematerialization", and "Behavioural Change".** They identify environmental metrics (the measuring and accounting of data) as a cross-cutting issue which will improve along with the ICT. (Jorge L. Zapico, Brandt, & Turpeinen, 2010; Jorge Luis Zapico, 2013)

Mitchell identified five principles for creating "e-topias", "lean green cities that work smarter not harder" (W. Mitchell, 1999). Kramers *et al.* apply these principles to a list of household functions to create a two-dimensional matrix that identifies ICT related opportunities for energy savings and other sustainability issues in private households (Kramers, Höjer, & Lövehagen, 2013). The five principles are:

- **Dematerialisation** - replacement of big, physical things by miniaturised equivalents accomplishing similar results.
- **Demobilisation** – moving bits instead of moving people and goods e.g. telework
- **Mass customisation** – delivering just what is needed in particular context and no more
- **Intelligent operation** – optimisation of resource use and dynamic pricing to manage demand
- **Soft transformation** – adapting existing building stock, public spaces and transportation infrastructure to meet new requirements

The MSc research undertaken prior to this doctorate employed semi-structured interviews and literature review to identify five means by which the Web can address climate change: (Townsend et al., 2011)

- **Direct mitigation or exacerbation**, such as resource use efficiency, energy generation and carbon capture technology.
- **Innovation & coordination,** such as e-Science, using the crowd, emissions trading & carbon taxes.
- **Public engagement,** changing public opinion about climate change and mobilizing conscious behaviour change.
- **Global development,** addressing macroscopic issues such as economic growth, international development & technology transfer and land use.
- **Adaptation to climate change.**

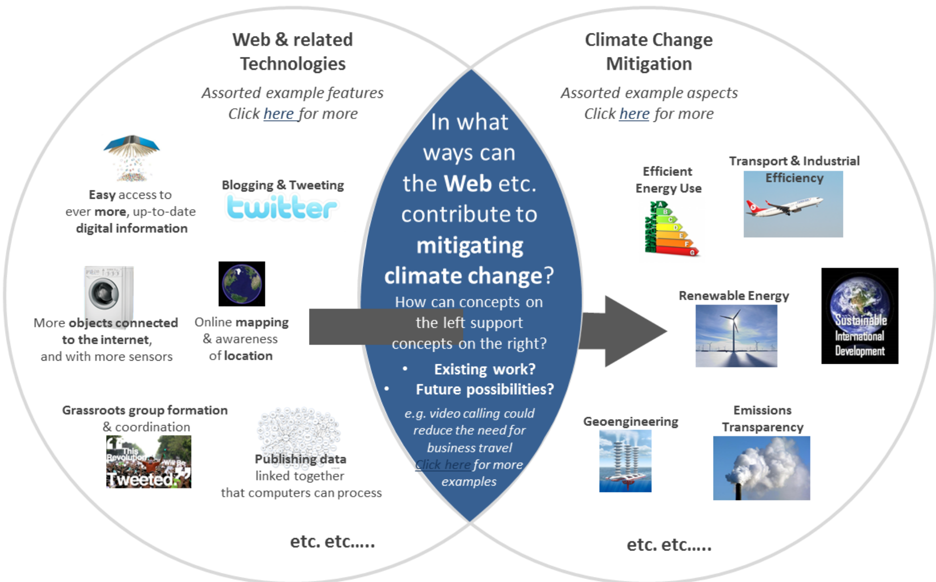

Figure 5 Diagram of the scope of the MSc research project, based on a Venn diagram that was used to gather input from research participants.

The high profile GeSI *Smart 2020* report, and its successor *Smarter 2020*, set out to analyse the impact of pervasive ICT on global warming. The resulting report detailed numerous form of DDS, organised under four "change-levers" by which ICT could enable sustainability, applied to different end-use sectors of the economy such as power, transportation, manufacturing, agriculture or buildings (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012):

- **Digitalisation and dematerialisation** – substituting or eliminating the need for an emission–intensive product, material, process or service. Also the reuse/multiple use of information sources, media, etc. by ICT.

- **Data collection and communication** – providing real-time data and analysis that allows for better decision-making identifies the need for change or encourages more efficient behaviours.

- **System integration** – managing the use of resources and integrating lower–emissions intensive processes

- **Process, activity & functional optimisation** – intelligent simulation, automation, redesign, or control to optimise process, activity, function or service.

2.3.1 THREE LEVELS–MODEL

Hilty's **Three-Levels Model** was also published in 2008. It combines the three orders of effect introduced by Berkhout and Hertin with a normative second axis that distinguishes whether ICT is part of the problem or part of the solution (Figure 6). Level two refers to be **enabling effects** of ICT services i.e. Sustainability by ICT, and identifies two type of "solution" effects:

- **Substitution effect:** the use of ICT replaces the use of another resource (e.g. an e–book reader can replace printed books, which is positive if it avoids the printing of a sufficiently large number of books).
- **Optimisation effect:** the use of ICT reduces the use of another resource (e.g. a smart home is able to use less energy if less people are home or if certain weather is forecast).

Two enabling effects are also identified on the "problem" side:

- **Induction effect:** ICT stimulates the consumption of another resource (E.g. a printer stimulates the consumption of paper as it uses it faster than a typewriter).
- **Obsolescence effect:** ICT can shorten the useful life of another resource due to incompatibility (E.g. a device that is no longer supported by software updates is rendered obsolete).

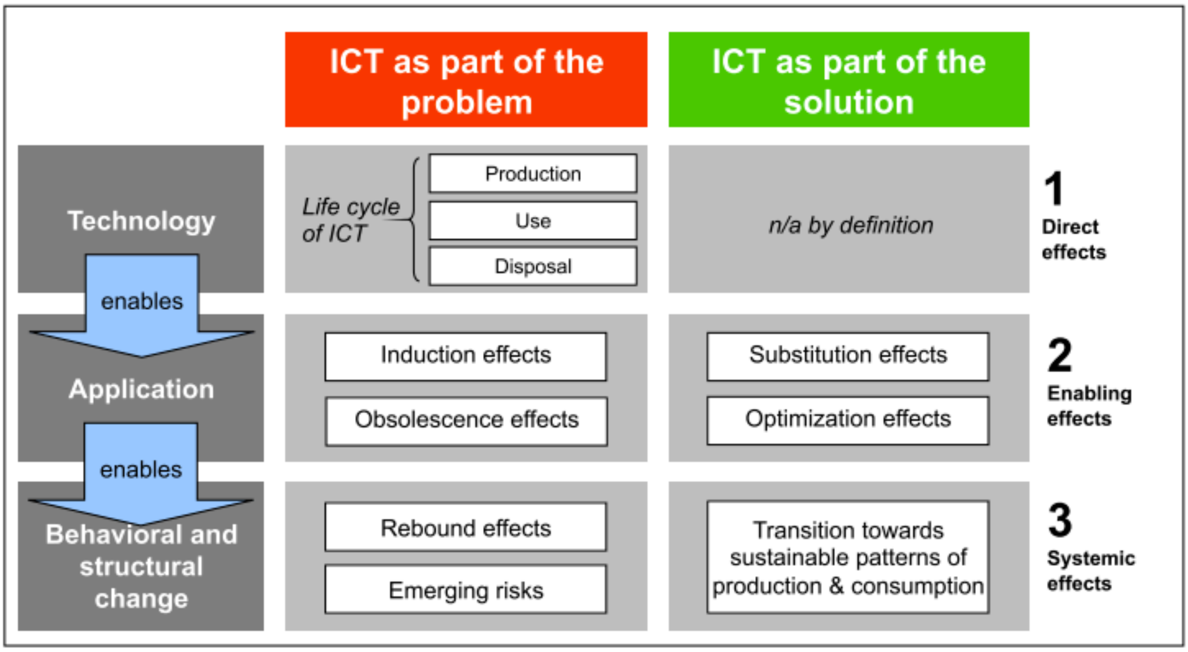

Figure 6 Hilty's Three-Level Model of ICT4S

To assess the sustainability impacts of a particular form of DDS, Sonnenschein *et al.* integrate the Three-Levels Model with three compatibilities of sustainability from the integrated sustainability model of Isenmann: ecological, social and human compatibility. Whilst the LES model is primarily focused on delivering the ecological goal of dematerialisation, this matrix allows it to be expanded to explicitly consider the benefits and harms of the system on society and individual people. However, this matrix is just a high-level typology, and is not quantitative. (Isenmann, 2007; Sonnenschein, Hinrichs, Niesse, & Vogel, 2015)

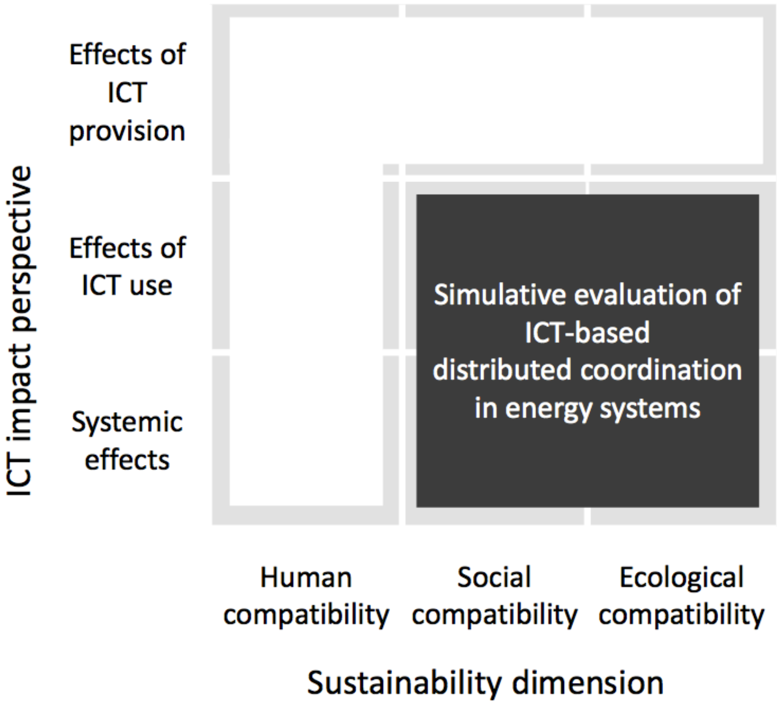

Figure 7 Sustainability assessment for ICT–based distributed coordination in energy systems following the conceptual framework from Isenmann (2007) and Sonnenschein (2015).

2.3.2 SUBSTITUTABILITY OF RESOURCE-USE HIERACHIES

Spreng has argued for the mutual substitutability of energy, time and information (D Spreng, 2013), evidenced with case studies from industrial production processes. The inputs required to produce a good or service are characterised by the three quantities energy, time and information, and the substitutability is represented graphically as a triangle (Figure 8). The ways in which a task can be performed are then represented as points in the triangle, with the distance to the sides measure the amounts of the three inputs applied. Any application of ICT (i.e. information) to a process allows either the time or energy to be saved. However, the profit imperative tends to favour the acceleration of production i.e. the reduction of time: *"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 enormous. Unfortunately, so far, the latter potential has been extensively tapped while the former remains but potential."* (D Spreng, 2001).

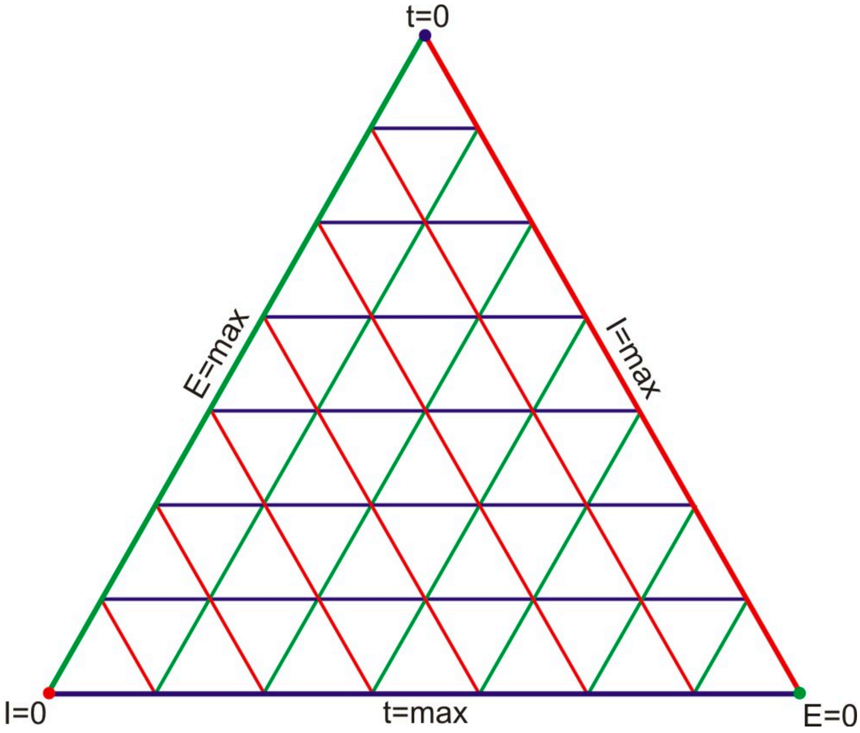

Figure 8 Spreng's triangle representing the mutual substitutability of time, energy and information. [15]

In line with a seminal UNEP report, Hilty *et al.* places decoupling at the centre of the challenge of sustainable development (UNEP, 2011). Decoupling is a process that increases the ratio of a well-being-orientated sustainability indicator with a resource-orientated sustainability indicator. (L. Hilty & Aebischer, 2014). For any given service consumed within the economy, a resource-use hierarchy is the tree of resources that provide the service, each node of which is a production process whose input is resources provided by other processes. Decoupling can then take place through substitution of these resources. The concept of the resource-use hierarchy is similar to a company's supply chain (Bonanni, 2011; Simchi-Levi D., 2003), or the value chain (Kaplinsky & Morris, 2001). Figure 9 is an example of the resource–use hierarchy of an intercontinental meeting, showing how each level offers opportunities for substitution with more sustainable alternatives.

[15] Reproduced from http://backreaction.blogspot.co.uk/2011/11/sprengs-triangle.html

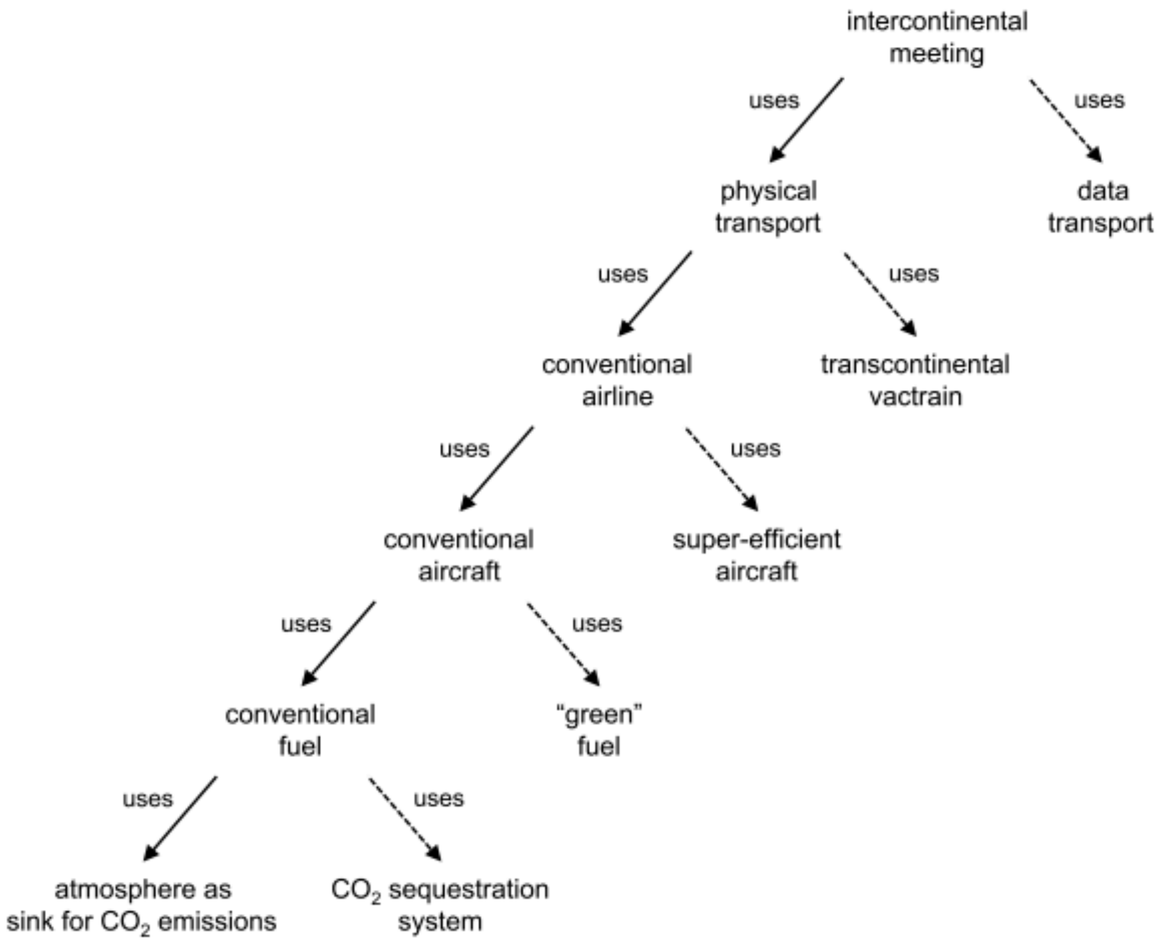

Figure 9 A single branch of a resource–use hierarchy with potential substitutes at each level, indicated by dotted arrows. Reproduced from Hilty & Aebischer (2014).

UNEP divide all resources into either material resources such as wood, minerals and machines, and immaterial resources such as genetic information, literature, algorithms and the shine of a star. Immaterial resources are distinguished as those whose use has no effect on the qualities that make them useful (UNEP, 2011). Material resources are natural assets deliberately extracted and modified by human activity for their utility to create economic value. They can be measured both in physical units (such as tons, joules or area), and in monetary terms expressing their economic value. All immaterial resources require a substrate or medium (L. Hilty & Aebischer, 2014). Dematerialisation is the special case of decoupling through the substitution of a material resource with an immaterial resource such as digital information.

2.3.3 THE LES MODEL

The Three-Levels Model has implicit normative assumptions, dividing the enabling "impacts" or "effects" of ICT into what is good and bad for sustainability. To remove this normativity and to allow future extension of the model, Hilty introduced the LES model (Figure 10). Whilst the Three-Levels model was encountered towards the middle of the investigation process, the LES Model was published very late in the investigation in 2015. It has three levels with similar meanings to the Three-Levels Model:

- **Life-cycle impact** *"refers to effects caused by the physical actions needed to produce the raw materials for ICT hardware, to manufacture ICT hardware, to provide electricity for using ICT systems (including electricity from non-ICT infrastructures, such as cooling), to recycle ICT hardware, and finally to dispose of non-recycled waste"[16]. This* is therefore equivalent to Sustainability in ICT.

- **Enabling impact** (micro-level) *"refers to actions that are enabled by the application of ICT. In the context of sustainability, it is important to understand the effects of these actions on resource use. We therefore view all actions as processes of production or consumption."*

- **Structural impact** (macro-level) *"refers to ICT impacts that lead to persistent changes observable at the macro-level."*

In the LES Model, all enabling impacts of ICT are viewed as special types of ICT-enabled resource substitution, based on Spreng's theory of the mutual substitutability of time, energy and information. The LES Model enabling impacts identify three mechanisms of ICT-enabled resource substitution. Figure 11 defines these three processes as forms of ICT-enabled substitution of resource-use hierarchies: process optimisation, media substitution and externalisation of control.

16 Quotations from (L. Hilty & Aebischer, 2014).

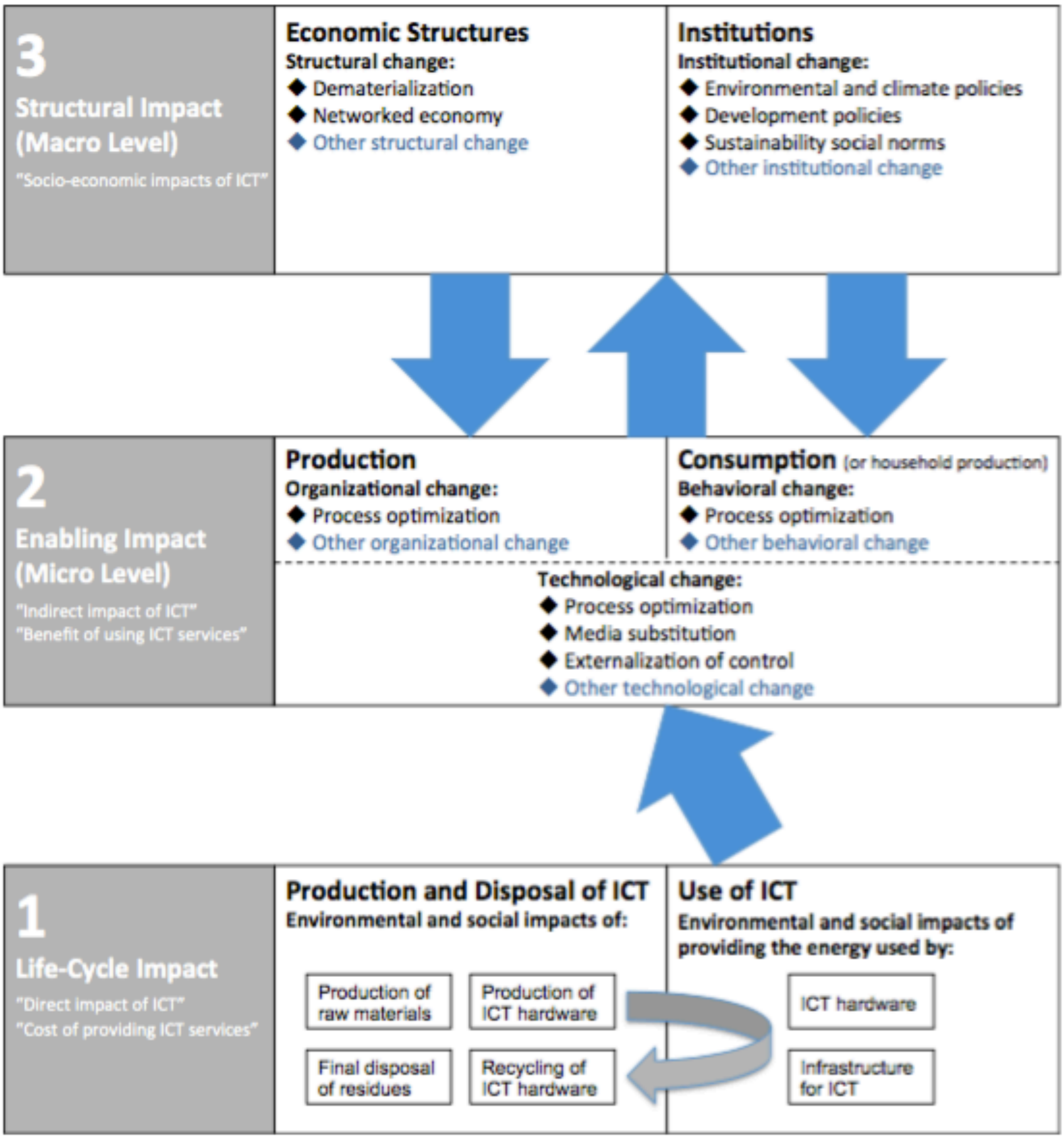

Figure 10 The LES Model of ICT4S (L. Hilty & Aebischer, 2014).

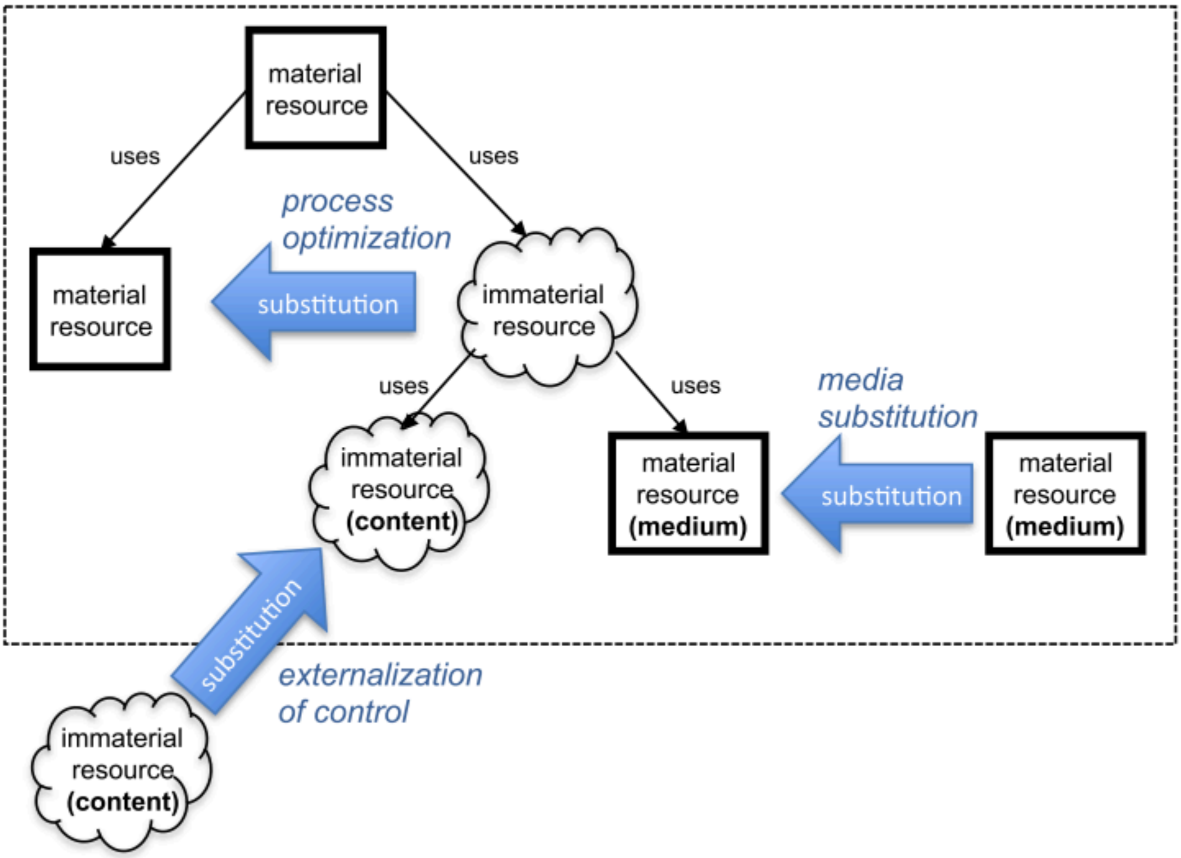

Figure 11 Process optimisation, media substitution, and externalisation of control, explained as resource substitution: the material resource can be partially replaced by an immaterial resource (process optimisation); the medium of an immaterial resource can be replaced by another medium (media substitution); and the content of an immaterial resource can be replaced by content provided from an external source (externalisation of control). Reproduced from Hilty & Aebischer (2014).

Hilty states that **process optimisation** is the use of information to control any process that has a purpose in order to minimise its use of resources. Process optimisation is equivalent to optimisation in the Three-Levels model. Two dichotomies distinguish different process optimisation effects (L. Hilty & Aebischer, 2014): 5

- Between lower-level technological change and higher-level change based on interaction with human beings.
- Between processes of the production and consumption of resources: *"In the context of sustainability it is important to understand the effects of these actions of resource use. We therefore view all actions as processes of production or consumption"* (L. Hilty & Aebischer, 2014). Hilty & Aebischer equate this distinction with that between organisational change (production) and behavioural change (consumption).

Zapico recognises an “optimization” category of ICT4S research that is similar to **organisational process optimisation** through production, which argues that ICT can improve and tune existing systems, reduce emissions and resource consumption whilst maintaining or increasing utility. Terms like smart cities, smart grids, smart appliances, intelligent transport systems and smart logistics are often used. (Jorge Luis Zapico, 2013).

Behavioural process optimisation is similar to Zapico’s “behaviour change” and to the concept of “Persuasive technology” which uses psychology theories and design rules such as those of Fogg to help users monitor and reduce their consumption of resources (Fogg, 2003). Di Salvo *et al* found that 70% of research papers within SHCI are on persuasive and ambient awareness. (Disalvo et al., 2010).

Media substitution is the replacement of the material medium of an immaterial resource with a digital electronic medium e.g. replacing a paper book with an e-book. This has often been called “dematerialisation” (Berkhout & Hertin, 2004; Fuchs, 2008), or the moving of “bits instead of atoms” (Negroponte, 1996). However, it is different from Hilty & Aebischer’s definition of the term – and equates to **substitution** in the Three-Levels model and to Zapico’s **dematerialisation of culture and knowledge artefacts** such as music, books, magazines and journals, which can now be downloaded online in purely digital formats. Claims that these modes of delivery of immaterial resources are more efficient require analyses such as Webber *et al,* who found that digital delivery of music can be up to 80% more efficient. (Weber, Koomey, & Matthews, 2010)

Zapico identifies a second area of dematerialisation, that of **human presence** such as teleconferencing, and services such as e-banking or e-government. For instance, Coroama *et al.* have found that a virtual conference can reduce overall energetic costs of participation per participant by a factor of 3.5 (Coroama, Moberg, Hilty, & Huber, 2015).

Hilty & Aebischer identify one other type of resource substitution, *externalisation of control,* which replaces or complements information that previously came from an internal source (i.e., from within the organization or household), with information from an external source. . Typically, this is enabled by a prior media substitution. Such externalisation opens the door to possible misuse of data. (L. Hilty & Aebischer, 2014)

2.3.4 MACRO SCALE STRUCTURAL IMPACTS AND REBOUND EFFECTS

Sustainable development is defined on a global level, which implies that any analysis or assessment must ultimately take a **macro-level perspective**. Hilty & Aebischer state that, for a sustainability claim to be validated, a procedure must in place to attempt to quantify the impact at the macro-scale of structural impacts. **Structural impact** is the third level of the LES model, which *"refers to ICT impacts that lead to persistent changes observable at the macro level. Structures emerge from the entirety of actions at the micro level and, in turn, influence these actions"* Two forms of structural impact are identified: **structural change** to economic structures that emerge through the accumulation of capital; and **institutional change**, which includes anything immaterial that shapes action, that is to say law, policies, social norms, and anything that can be regarded as the "rules of the game."

Dematerialization is a form of structural change, the economic form of structural impact. Hilty & Aebischer state that dematerialization is decoupling through the substitution of immaterial resources for material resources, the aggregate result of many process optimizations and media substitutions, moderated by rebound effects, which is a necessary but insufficient condition for sustainable development. Börjesson Rivera *et al.* (2015) emphasize the importance of including rebound effects in analyses of the environmental impacts of ICT.

Rebound effects are the difference between predicted resource consumption at the macro-scale and the actual amount of consumption following some micro-scale improvement in resource efficiency. There are three forms of rebound effect that are generally recognised (Gossart, 2015):

- Direct rebound effects, when lowering resource costs induce price reductions, triggering an increase in the demand for the cheaper good.
- Indirect rebound effects, when a resource is used more efficiently and its price goes down, inducing consumption of related goods.
- Economy-wide rebound effects, when declining resource prices induce a reduction in the prices of intermediate and final goods throughout the economy, causing structural changes in production patterns and consumption habits.

Due to the intrinsic complexity of calculating rebound effects, prominent analyses of Sustainability by ICT such as the Smarter 2020 report have not avoided taken rebound into account (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012).

2.3.5 METHODS OF QUANTIFYING ENABLING IMPACTS

This section briefly considers some of the methods by which the enabling impacts of ICT are measured.

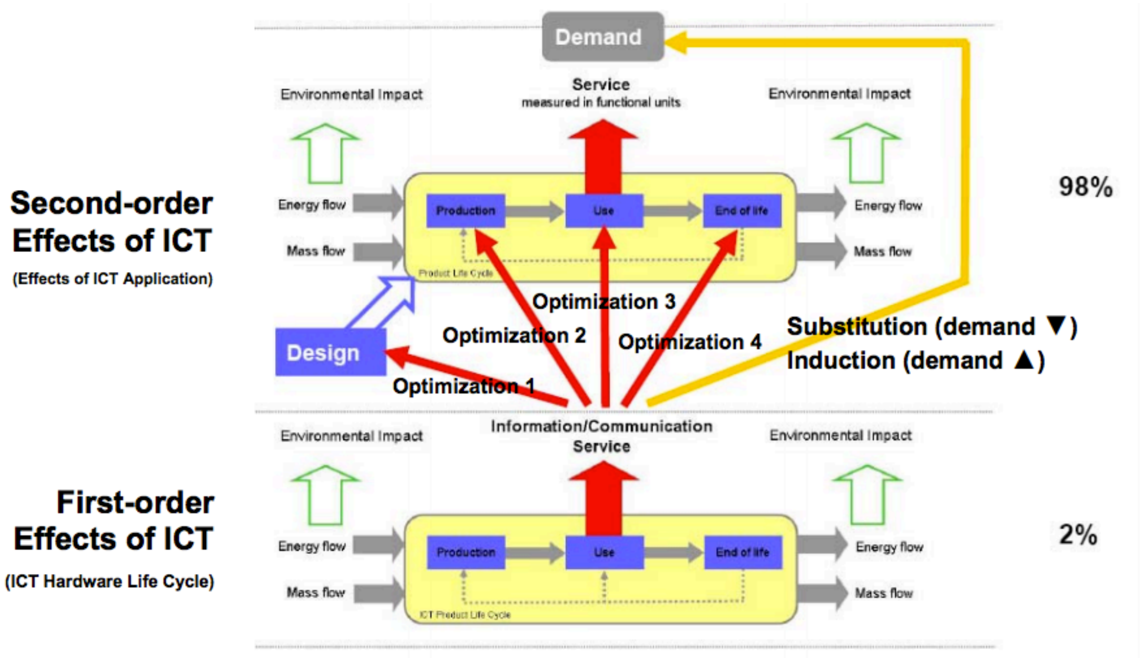

Figure 12 Hilty's linked life cycle framework relating to the Three-Levels model. "Both ICT products and non-ICT products that are influenced by the availability of ICT services are assessed by applying Life Cycle Assessment (LCA) methodology, yielding the first-order effects of each product. By estimating the second-order effects (1- 5) and accounting for them, the net environmental impact of the system can be assessed" (L. Hilty, 2008).

Life cycle assessment (LCA) is a methodology originally developed in the late 1960s that is used to assess the potential environmental impacts and resources consumed throughout a product's life cycle, from raw material extraction, through production and use phases, to waste management. LCA is an iterative process that takes place in four phases: definition of goal and scope, life-cycle inventory (LCI) analysis, impact assessment and interpretation (M. A. Achachlouei, 2015). Hilty developed the Linked Life Cycle model as a basis for the Three-Levels Model to measure the first and second order effects (L. Hilty, 2008). An alternative approach to LCA, that can address the complexities of rebound effects is **computer-based model and simulation of complex and dynamic systems,** which encompasses a range of techniques such as System Dynamics, agent-based modeling, discrete-event simulation, Monte Carlo simulation, and gaming modeling and simulation. Such modelling starts with the recognition of a problem situation, builds a conceptual model in an iterative process and then continues with coding, data collection, experimentation and interpretation of simulation results, and informing decision-making processes. (M. A. Achachlouei, 2015). Figure 13 is a simplified representation of the abstract causal structure of the first-, second- , and third-order effects of ICT, from Erdmann and Hilty (2010). Such a structure can form the basis for a systems dynamics model. The dynamic impacts of ICT originate from the feedback of third-order effects to first- and second-order effects, as modelled by Achachlouei & Hilty (2015).

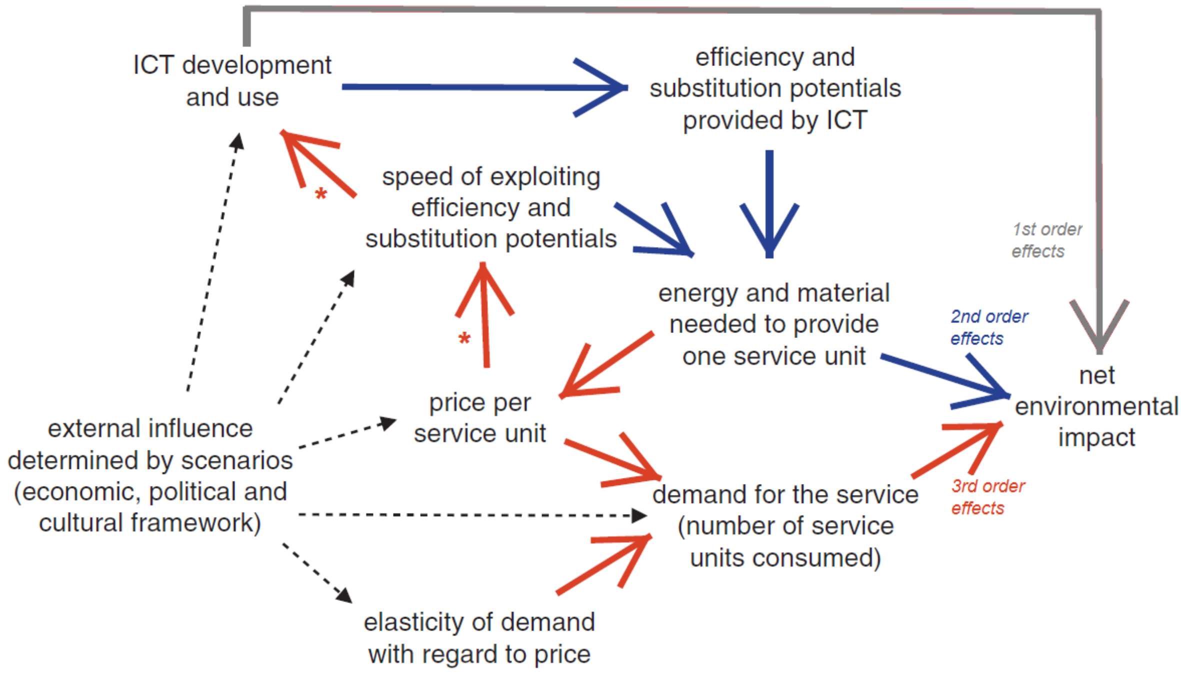

Figure 13 Abstract causal structure of the relationship between three types of ICT effects. First order effects are grey, second-order effects are blue, and third order effects are red. Starred arrows indicate that the dynamic impact of ICT originate from the feedback of third order effects to first and second order effects. (M. A. Achachlouei, 2015; Erdmann & Hilty, 2010)

2.3.6 INSTITUTIONAL AND DESIGN CHALLENGES

This thesis will focus on DDS, which in the language of the LES Model are digital systems whose enabling impacts lead to dematerialisation. There are significant areas of research within ICT4S and particularly SHCI that do not address particular types of DDS, such as those that address the process itself.

Huang argues that Sustainable HCI has contributed solutions to sustainability challenges, but that problems of sustainability cannot be framed purely as problems for HCI or interaction design issues (Huang, 2011). In an analysis of persuasive sustainability research from 2009-2011, Brynjarsdottir *et al.* critiqued its narrow modernist perspective which attempts to optmise narrow criteria, but lacks evidence of efficacy and does not address the complexities of sustainability. They suggest a number of measures including moving beyond the individual, including the user in design, and shifting from behaviours to practices (Brynjarsdottir et al., 2012). Similarly Foth *et al.* argue for the need to design for other scales from a single building up to the nation-state (Foth, Paulos, Satchell, & Dourish, 2009). Knowles critiques the field for employing the triple-bottom line perspective of “ecological modernization”, and argues for more radical and holistic perspectives (Knowles, 2014).

Given the wickedness of sustainability problems such as climate change, Tomlinson *et al.* have proposed a new field of "collapse informatics…the study, design, and development of sociotechnical systems in the abundant present for use in a future of scarcity." (Tomlinson, Silberman, Patterson, Pan, & Blevis, 2012). Knowles *et al*. argue that though preventing climate change through incremental reductions in energy consumption is unlikely to succeed, sustainable HCI can target alternative indirect causes of climate change as a route to affecting more significant and impactful research. They identify five routes to impact for SHCI: Addressing Values: Toward Caring; Addressing Material Insecurity: Toward Caring Enough; Addressing Survival Anxiety: Toward Desire for Change; Addressing Disavowal: Toward Empowerment; and Addressing Helplessness: Toward Activism. (Knowles, Blair, Coulton, & Lochrie, 2014). Silverman et al. identify a number of next steps for the field of SHCI, including addressing the full diversity of sustainability issues; moving beyond simple models to grapple with the full multi-scalar complexity of "wicked" sustainability problems; and doing research that considers longer time scales; (Silberman et al., 2014). Many of the systems created would be lead to **institutional change** i.e. DSS but not DDS.

CHAPTER 3 ACTION RESEARCH INTO CLEANWEB

3.1 INTRODUCTION

The chapter concludes Phase 1 with action research (AR) that explores the context of Sustainability by ICT praxis. At the outset, researching both the Web and sustainability appeared daunting as both were difficult to define clearly, and both operate at such a scale and complexity that they overflow all disciplinary boundaries. The application of the Web to sustainability appeared vast, opaque and amorphous. The novelty of the area and its rapid development meant a great deal was unknown, undecided or simply did not yet exist; key terminology such as “ICT4S”, “Sustainability by ICT” and “cleanweb” had yet to be coined.

Nevertheless, a methodological and theoretical basis for further investigation did slowly emerge from the AR and literature review of Phase 1, which sought to **identify the communities addressing Sustainability by ICT** and become familiar with them in order to **contribute to those communities directly** whilst identifying **what further research might be of benefit to those communities** during Phase 2 of the investigation.

Section 3.2 begins the chapter by introducing the methodology of AR that was employed. Section 3.3 then details the AR journey of engagement with, and exploration of, relevant communities of practitioners working on Sustainability by ICT. In line with AR methods, the first person is used. This chapter’s cataloguing of relevant communities is not exhaustive as there are so many perspectives on Sustainability by ICT, such as the academic communities identified in Section 2.2.

The community with whom I worked most was Cleanweb UK, organising monthly meetup[17] events in London with many people from startup companies. Three other topics encountered that were highly relevant to Sustainability by ICT were cleantech, and the Sharing and Circular Economies. Each topic has its own specialist communities who have developed conceptualisations of each topic. These conceptualisations are described in Section 3.4, as an extension of the literature review of the previous chapter, and as basis for developing a new conceptualisation of Sustainability by ICT in the remainder of the investigation. These observations are compared to the leading conceptualisation of ICT4S, the LES Model.

In particular, Section 3.4 documents the pivotal conversation with key figures in the international cleanweb network about the meaning of “cleanweb” and **how cleanweb**

[17] https://www.meetup.com/

companies can be classified effectively and usefully. Based on the experiences in these communities, a specific hypothesis for later testing was also developed about the relative distribution of entrepreneurship and research activity.

Section 3.5 considers the **impacts of the AR within the Sustainability by ICT communities** themselves, identifying what more could be done by practitioners, and for them, in order to develop the field and industry. Section 3.6 then considers the personal impact of my research, discussing areas in which I appeared most effective, and other ways in which my research and practice could improve.

Section 3.6 concludes the chapter by identifying **further research of potential benefit to the Sustainability by ICT communities.** The need for a new classification of cleanweb systems (DDS) is identified, which will form the methodology for Phase 2, and the main contribution of this investigation.

3.2 ACTION RESEARCH METHODOLOGY

Phase 1 initially adopted AR to explore a complex landscape of theory and practice, and reduce the unknowns in order to define a research question and method for the remainder of the investigation. Dick states that: "*Action research methods are most likely to be appropriate when you do not know where to start… It is useful for exploratory research, where you do not yet have a very precise research question*" (Dick, 1998). Bryman describes AR as "*an approach in which the action research and members of a social setting collaborate in the diagnosis of the problem and in the development of a solution based on diagnosis"* (Bryman, 2001). Action research is a rich and diverse family of ideas and practices, and an orientation towards research and practice in which engagement, curiosity and questioning are brought to bear on significant issues to achieve social progress (Marshall, Coleman, & Reason, 2011).

Reason and Bradbury describe five interlinking dimensions of action research: **practical challenges**, working towards practical outcomes and creating new forms of understanding; **worthwhile purposes,** paying attention to issues that the researcher deeply cares about; **participation and democracy,** aiming to engage those involved in issues at hand as co-researchers and partners; **many ways of knowing,** including the experiential and intuitive, the aesthetic and presentational; and **emergent form,** as projects cannot be predefined in detail because of the messiness of everyday life (Reason & Bradbury, 2001).

AR emphasises the integration of action and reflection through research cycling, bringing discipline to people's natural learning (Marshall et al., 2011). Cycles of experimental action follow phases of reflection and sense-making. The world of experience is explored, ideas and intentions are assessed, and researchers work towards more effective and appropriate action.

I became a central participant in a number of communities with contrasting perspectives on the topic. These were both established and new communities, global and local, online and offline. Participating within them helped understand their aims, methods, and achievements, in order to identify research problems of potential value to them and shaping the rest of the investigation. A wide variety of actors were engaged including entrepreneurs, developers, designers, digital activists, civil servants, startup accelerators, journalists, consultants, undergraduates and researchers. I participated actively, following opportunities as they arose, organising communities, sharing research insights and creating software (DSS).

Notes were captured with Evernote software[18], including hyperlinks to many online resources. Online content was created, such as 50 talks given by leading practitioners have been uploaded to the Cleanweb UK Youtube channel ("Cleanweb UK Youtube Channel," 2012).

Observation and reflection was undertaken in a series of action-reflection cycles at different scales (Figure 3). The largest cycle of the AR extends beyond Phase 1 to encompass the whole investigation, which developed a new theory to respond to the needs of practitioners in Phase 2, and then evaluates it in Phase 3.

3.3 COMMUNITY EXPLORATION

This section is a personal AR journey, observing communities and themes of Sustainability by ICT, contributing to them and sometimes leading them. For context, it is traced from before the AR itself began, from my professional practice as a digital innovation specialist in an energy corporation, through a Master's degree in Web Science, and into the doctoral AR research itself. As AR, the section is presented in the first person, unlike the rest of the thesis. The AR itself begins by describing my early participation in hackathons, competitive software-building events.

The entrepreneurial Cleanweb community was prioritised for analysis, as it works specifically on Sustainability by ICT and had received little academic attention. I facilitated an international conservation on how the cleanweb industry could be organised and defined, identifying research needs that shaped Phase 2.

[18] Evernote note-taking software http://evernote.com/

This journey began in the trading arm of a large energy corporation in London, where I had founded a team with responsibility for digital innovation. We developed a number of web-based applications that increased understanding of the fast-moving financial context using novel data flows. I was struck by the growing power of digital systems, their ability to make action more effective, and give informational advantage. Coming up with new ideas for systems seemed relatively easy because there was an ever-growing range of technological approaches to choose from and so many business problems to apply them to.

The enterprise IT practiced by the company's IT department through a waterfall methodology was focussed on reliability and risk avoidance. In contrast, our innovations were inspired by the emerging US Web industry, whose corporations and startups were using agile methods to create forms of digital system that were more social and focussed on the needs of the user.

On the BBC radio program Digital Planet[19] I first heard about research into Sustainability in ICT and the new field of Web Science (T. Berners-Lee et al., 2006; Preist & Shabajee, 2010). Web Science seemed an excellent context in which to try to understand what gave Web systems their evident power, and how that power could be applied beneficially, so I decided to undertake a Master's degree in Web Science at the University of Southampton.

The taught courses on the Master's degree offered new perspectives on the Web: as a global technical infrastructure; the largest ever information construct; as new media where we perform socially; and as an industry with its own culture (Castells, 2001; Halford et al., 2010). I began to understand what differentiates the Web from traditional IT. One enigmatic new concept was the "social machine" (N. Shadbolt et al., 2013), complex sociotechnical systems such as social networks, e-marketplaces, collaborative working, collaborative consumption, or crowdfunding (R Botsman & Rogers, 2010). Lectures in Complex Systems also helped me conceptualise the complexity of the Web and other forms of network. The course introduced interdisciplinary research methods, and digital openness, such as open source software, open data, open access to the scientific literature, linked open data and the Semantic Web.

I was interested in how digital technologies can address major societal and environmental challenges - what has since been termed "tech for good"[20] – but was unsure whether to focus on international development or on the environment. I read about ICT for International Development (ICT4D) and attended the second international ICT4D conference (Unwin,

[19] http://www.bbc.co.uk/programmes/p002w6r2
[20] Tech for Good e.g. http://www.huffingtonpost.co.uk/paul-miller1/london-tech-for-good-capital-of-the-world_b_10046178.html

2009). However, the environmental applications of ICTs seemed relatively less developed, and held more opportunities for less sociological approaches.

I proposed a Masters research project on "The Significance of the Web and Related Technologies to the Challenge of Climate Change" (Townsend et al., 2011). The Masters project reviewed the academic literature and other online content, and interviewed academics whose work broached the subject.

To express the scope of the research, I formulated the Venn-like diagram Figure 14 (lower diagram), showing how large and complex the topic is. There are numerous perspectives on both the Web and on environmental sustainability: both are global; both involve the whole range of human enquiry from the natural sciences to the humanities; both can be viewed at different levels of specificity, framing increasingly philosophical questions: "Is the Web a domain of ICT, or does its vast size and social nature make it something different?" "Is sustainability ultimately about the environment or is the environmental just one aspect of sustainability?" "And how does climate change relate to the rest of environmental sustainability?" Answers to these underlying questions became clearer over the course of the investigation.

I was seeking a "Web for Climate Change" that would organise the many combinations of concepts from the two domains; it would need to map the complex landscape of their intersection. I encountered relevant literature from many sources, and diverse examples of relevant systems, but did not encounter the full body of research that would evolve into ICT4S, perhaps because the concept of "the Web" appeared so different from that of "ICT". Even given the great complexity, the dissertation was able to identify five means by which the Web can address climate change (Section 2.3).

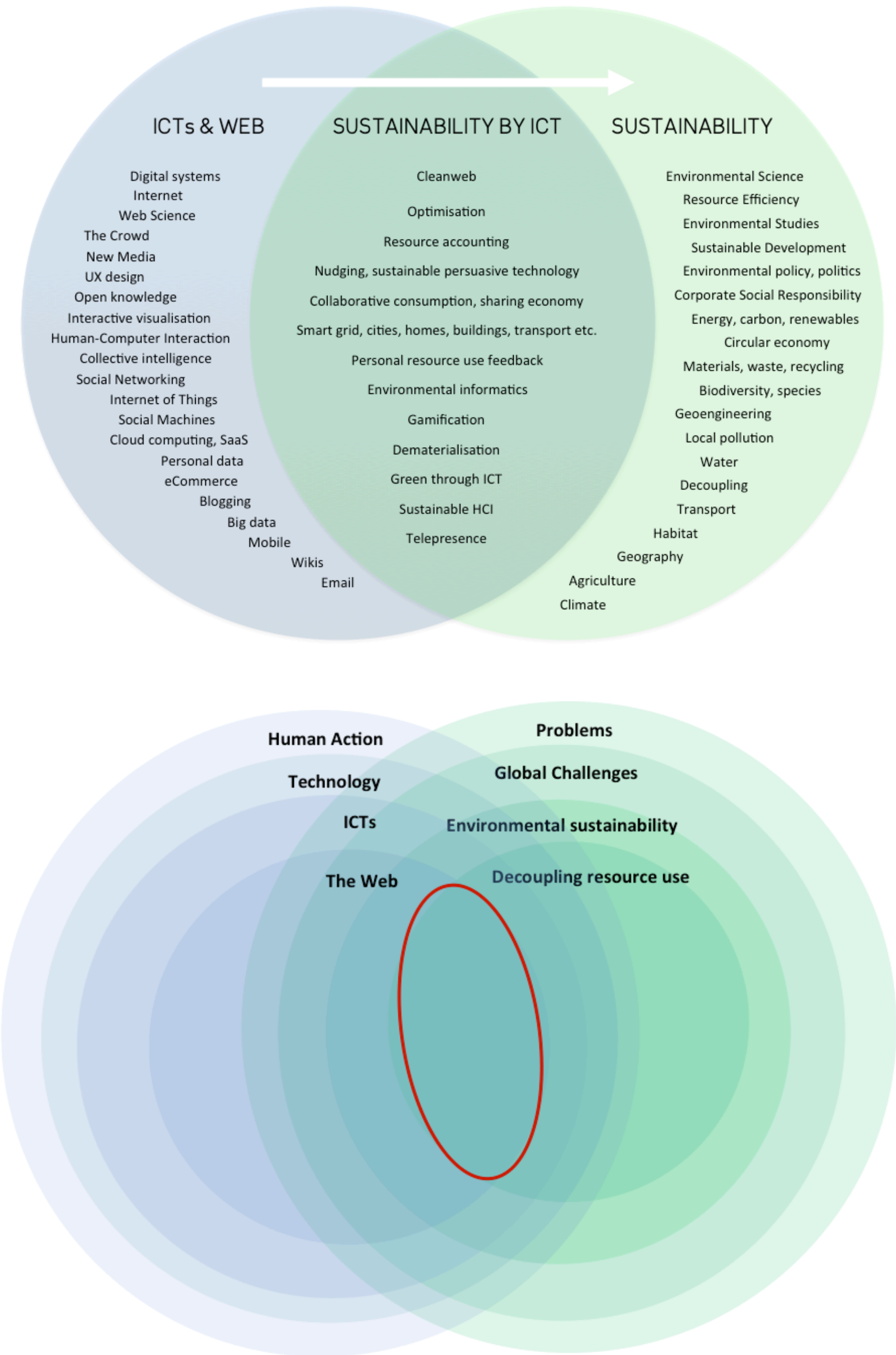

Figure 14 Venn diagrams illustrating the scope of Sustainability by ICT and of this thesis. The top diagram shows the application of ICTs and the Web (left circle) to the topics and challenges of environmental sustainability (right circle). The diversity of fields, technologies, trends and industries within each section is illustrated with examples. The lower diagram was created to help me conceptualise the novel space I was researching. It has been updated retrospectively so that the terminology is more aligned with the rest of thesis.

I then began this doctorate in Web Science, continuing the enquiry into what I conceptualised as "Web for Sustainability". The range of subjects at the intersection of these two vast topics continued to present a great challenge (Figure 14, upper diagram). I sought to learn more about key topics of both the Web and sustainability, attending a range of other courses on sustainability at geography department lectures, and on artificial intelligence in the computer science department. I began to share what I was learning on Twitter, and soon gained a body of followers with shared interests[21]. Through social media I discovered relevant ideas, people and events, and eventually connected with the nascent cleanweb and ICT4S communities.

In 2011, I participated in Random Hacks of Kindness in Oxford, my first "**hackathon**"[22], a competitive software creation event staged over a weekend (Briscoe & Mulligan, 2014). I joined a team working with the UK Met Office to build a web-based flood-warning tool called "FloodSource"[23]. In early 2012, I joined my first hackathon with a fully environmental theme, the London Green Hackathon. This was a pivotal moment in the consolidation of the London cleanweb community, and my first opportunity to meet the leading individuals with whom I would cooperate extensively. The Green Hackathon[24] is an international series of hack events to address environmental sustainability challenges, developed by Zapico (Jorge Luis Zapico, 2013).

Environmentally-themed hack events now take place regularly in London and elsewhere, on diverse themes from cycling[25] to fish conservation[26]. Environmentally-themed hack events have been held in cities around the world under the label "Cleanweb" including Berlin, New York, San Francisco and Barcelona[27]. Similar forms of events have emerged including data science datadives[28], design jams[29] and entrepreneurship challenges. I participated in many such events, as competitor, mentor or judge[30]. Above all, these proved excellent opportunities

21 Jack Townsend on Twitter https://twitter.com/jacktownsend_

22 The word "hack" has positive connotations of playful creativity for software developers, not just the negative connotations of malicious breaches of digital security.

23 FloodSource App http://floodsourcerhok.appspot.com/

24 London Green Hackathon webpage http://london.greenhackathon.com/

25 CycleHack http://www.cyclehack.com/

26 Fish Hackathon http://www.fishackathon.co/

27 Data Science for Sustainability meetup event, San Francisco http://www.meetup.com/Data-Science-for-Sustainability/

28 http://www.datakind.org/datadives

29 https://servicejamlondon.wordpress.com/

30 The events included: judging the Environmental Data Exchange Hackathon[http://www.digitalcatapultcentre.org.uk/event/environmental-exchange-hack-weekend/] and the Envirohack[http://www.digitalcatapultcentre.org.uk/event/envirohack-2015/], environmental hack weekend, Digital Catapult, London, 2015; supporting Climathon 2015, and #HackforGood 2014, global multi-city hack weekend events to address climate change; competing in the finals of the Energy and Environment Open Data Challenge[http://www.nesta.org.uk/project/open-data-challenge-series/energy-environment], organised by Nesta and the Open Data Institute, 2014; judging the Rich Internet Apps Module, ECS University of Southampton 2013 and 2014[http://www.ecs.soton.ac.uk/module/INFO6005]; mentoring a team of finalists at the global CleanTech challenge 2013[http://www.cleantechinvestor.com/portal/mainmenucomp/companiese/3210-edas/11476-cleantech-challenge-2013-bootcamp-entrant-edas.html], at London Business School, presenting a driving behaviour change app; taking part in the #Floodhack hackathon in 2013 and the release of Environment Agency flood data (Arthur, 2014); helping host a workshop at Mozfest 2013 with some of the pioneers of hackthons in the UK; mentoring at the Netherland's first Cleanweb Hackathon, 2013; and winning the Southampton Random Hacks of Kindness Hackathon 2012 with the EnergySource app [https://www.youtube.com/watch?v=TCvgFCwfdEM] to facilitate solar energy adoption in Africa.

to meet key actors coming to the topic from different origins. They also helped me understand the range of digital systems being employed, which I was seeking to encapsulate. These observations are discussed in the following sections.

It was through social media that I heard of the World Bank's Apps for Climate competition, which challenged teams to submit a Web application that used World Bank open data to address climate change. This was an opportunity to gain practical experience of building Sustainability by ICT systems and connecting with communities around the globe doing the same. I brought together a team of researchers over a three-week period in early 2012 to create **Globe-Town.org**[31], a web application and interactive information visualisation using open data, designed to convey the connections between economics, society and the environment in a globalising world.

Globe-Town.org (Townsend et al., 2013; Townsend & Prieto, 2012) (Figure 15) was research-through-design into Sustainability by ICT (Jorge Luis Zapico, 2013)(Zimmerman, Forlizzi, & Evenson, 2007). Globe-Town informs and engages users with the challenges of climate change in order to disseminate sustainable knowledge and beliefs. It builds up a multi-faceted picture of the environmental, economic and social pillars of sustainable development for all the countries of the world. Globe-Town shows a user how their home country and the topics that they care about are connected to global sustainability issues through an intensifying network of linkages, helping them find narrative threads of sustainability. The user can bridge the divide of scale between the global and local level, to help bring home what their discoveries mean to them personally.

Globe-Town came third in the *Apps for Climate* competition, and I presented the results at the World Bank headquarters. This was one of my first opportunities to meet people from around the World working on Sustainability by ICT. These experiences confirmed how diverse Sustainability by ICT practice is, and how little consolidation there had been around a single term such as "cleanweb". Even the other winners had little conception of Sustainability by ICT as a community of practice, an industry or a research area. Globe-Town also came second in the *Linked Up Open Education* competition in Geneva (Townsend et al., 2013).

31 http://www.globe-town.org

Figure 15 Globe-Town.org[32] *is a web-based interactive information visualisation using World Bank open data, created in the course of this investigation as action research and research-through-design into Sustainability by ICT* (Townsend et al., 2013; Townsend & Prieto, 2012).

The success of Globe-Town helped make new connections, particularly within the nascent **Cleanweb UK** community in London[33] ("Cleanweb UK," 2013). Cleanweb UK host regular events that attract developers and entrepreneurs from the London tech industry, as well as designers, consultants, academics and environmentalists. Events are run by volunteers and are free to attend. Cleanweb UK first formed in late 2011 as a monthly meetup in a pub in Shoreditch, a leading cluster of the digital industry. Many of the key figures in Cleanweb UK had met at AMEE[34], a digital startup formed in 2008 to use digital data to tackle climate change. AMEE stands for "Avoiding Mass Extinctions Engine". AMEE sponsored the Green Hackathon[35] (Jorge Luis Zapico, 2013), which increased awareness of the new Cleanweb UK meetup.

A "Cleanweb Ignite" event of five-minute lightning talks was planned as a hard launch for Cleanweb UK, at which I presented Globe-Town ("Cleanweb UK," 2013). Following this event, I joined the organiser team, and we then hosted an event each month on a different topic relating to ICT4S.

32 http://www.globe-town.org

33 Meetup webpage http://www.meetup.com/Cleanweb-London Website http://www.cleanweb.org.uk/

34 https://www.amee.com/

35 London Green Hackathon webpage http://london.greenhackathon.com/

3.4 LEARNINGS ABOUT ICT4S CONCEPTUALISATIONS

This section catalogues conceptualisations of four of the most relevant topics encountered: cleantech, cleanweb and the Sharing and Circular Economies. These conceptualisations will support the development of a classification of DDS in the following chapters. This section also documents the pivotal conversation with key figures in the international cleanweb network about the meaning of "cleanweb" and **how cleanweb companies can be classified effectively and usefully**. A number of further observations are made based on the experiences, including a specific hypothesis for later testing about the relative distribution of entrepreneurship and research activity. These observations are placed within the context of the LES Model of ICT4S.

3.4.1 CLEANTECH, A SUPERSET OF CLEANWEB

The Clean Technology Trade Alliance defines cleantech[36] as: *"a broad base of processes, practices and tools, in any industry that supports a sustainable business approach, including but not limited to: pollution control, resource reduction and management, end of life strategy, waste reduction, energy efficiency, carbon mitigation and profitability."*[37] Examples of cleantech include renewable energy and home insulation. This thesis will use "cleantech" for any product, system, resource or technology that makes resource use more sustainable i.e. that contributes to decoupling as defined by Hilty & Aebischer (2014).

The term "cleantech" was itself only coined in 2002 but was quickly adopted as the name of a new sector, with specialist investors and industry events. However, the existence of cleantech as an industry is still not universally accepted (Crosstaff Solutions, n.d.).

Classifications of cleantech are generally organised by type of resource. For instance, the Kachan Taxonomy identifies eight categories of cleantech, organised around different resources (Figure 16), and so does the Cleantech Group i3 database (Cleantech Group, 2013).

36 Investopedia definition of cleantech http://www.investopedia.com/terms/c/cleantech.asp
37 http://www.cleantechalliancewa.org/?page=Whatiscleantech

Figure 16. Kachan eight categories, a typical taxonomy of cleantech. ©Kachan (Kachan & Co., 2012)

I engaged with the cleantech sector whilst volunteering at Ecosummit, a conference for cleantech startups, investors and corporates of all forms, but with a particular focus on cleanweb, termed "smart green startups" (Hess & Butter, 2016). At Ecosummit I was able to meet leading cleanweb and cleantech entrepreneurs and investors from across Europe[38]. Ecosummit draws its participants from the cleantech sector more than the digital industry, and I found participants had a limited awareness of the role of ICT, and little awareness of research into Sustainability by ICT.

It was notable that many of the startups at Ecosummit use ICTs to support a traditional clean technology such as a solar panel. This observation lead to Decoupling Directness dimension, derived in Chapter 6. The distribution of cleanweb startups at Ecosummit will be analysed further in Chapter 8.

3.4.2 CLEANWEB, DISCUSSING A NEW CLASSIFICATION

Cleanweb is a similar concept to Sustainability by ICT. It has been particularly used to describe startup companies addressing resource and sustainability challenges (Eisenberger, 2015; Masero & Townsend, 2014). The term was coined in 2011 by Californian entrepreneur Sunil Paul as a portmanteau of "web" and "cleantech" (Paul & Fehrenbacher, 2011).

38 Ecosummit 2014 London http://ecosummit.net/london

The term “cleanweb” has appeared in European Union funding calls (European Commission, 2015), White House communiqués (Chopra & Sinai, 2012), newspaper articles (Gardiner, 2013) and World Bank blog posts (Ostman & Lerner, 2015); it has been adopted by national and international community groups (“Cleanweb UK,” 2013), and software-creation “hack” events around the world (“The Cleanweb Initiative,” 2013).

I first learnt of the term cleanweb through social media, allowing me to connect with cleanweb specialists around the World. This was greatly facilitated by the Cleanweb Initiative (TCI), a group from Texas who were working to develop a network of practitioners and spread the concept of cleanweb internationally. Through TCI I was interviewed for the New York Times article *Harnessing the Net to Power a Green Revolution*, 2013 (Gardiner, 2013), first visited the Rockstart Smart Energy Accelerator in Amsterdam[39] and spoke at the Cleantech Tuesday entrepreneurs event in Hong Kong in 2012[40].

I became the main organiser of Cleanweb UK for a period, helping organise regular meetings in London. The Cleanweb UK community aims to connect people and to spread ideas in order to progress sustainability by means of the Web. Cleanweb UK grew to be one of the largest regular events on the practice of Sustainability by ICT[41].

I was already considering developing a new classification of Sustainability by ICT systems, when I noticed a Twitter conversation with TCI about creating such a classification and better defining the term “cleanweb”. This interchange developed into a regular international teleconference with a number of individuals in the USA, Spain, Belgium and the UK. They were entrepreneurs and consultants who worked with investors, corporations and regulators with a need to understand the nascent cleanweb industry. We worked towards a definition and discussed the challenges and constraints of such a classification. We also discussed the potential benefits:

- A classification could **raise awareness** of the sector to all the stakeholders who might have an interest - such as startups, investors, corporates regulators and researchers – and help them coordinate better. Cleanweb companies use many labels to describe themselves, including cleantech, smart energy, tech for good, smart cities, smart buildings, Sharing Economy, ICT for Sustainability, Internet of Things, Green IT, digital, cleantech, fintech, foodtech, and ag-analytics. Of the 68 respondents to the Nesta Cleanweb UK report question (p25), no single label was used by more than half

39 Rockstart Accelerator Smart Energy Programme http://www.rockstart.com/accelerator/smart-energy/
40 My talk at Clean Tuesday Hong Kong http://cleantuesday.asia/slides-pictures-cleanweb-cleantuesday-hong-kong
41 http://www.meetup.com/Data-Science-for-Sustainability/

the sample of companies, suggesting limited consolidation around a single term to describe what they had in common (Masero & Townsend, 2014).

- A classification could **generate insights** into each defined category such as the nature of the technology used. The Nesta Cleanweb UK Report recommends understanding how "*common technologies can be applied for different environmental goals. Facilitate the exchange of best practice models from one economic system to another, i.e. from energy to transport to food*" (Masero & Townsend, 2014).
- A classification could also help clarify the **definition of cleanweb**, by showing what the sector is made up of.

One of the participants in the conversation was New York consultants Pure Energy Partners / SuperCollider (SuperCollider, 2015). In their earlier analysis of the cleanweb sector, they had identified four high-level themes: **catalyzing cleantech, resource cloud, big data, and new frontiers. These are** described in the Figure 17, and are compared with other strategic Sustainability by ICT literature in Section 9.4.

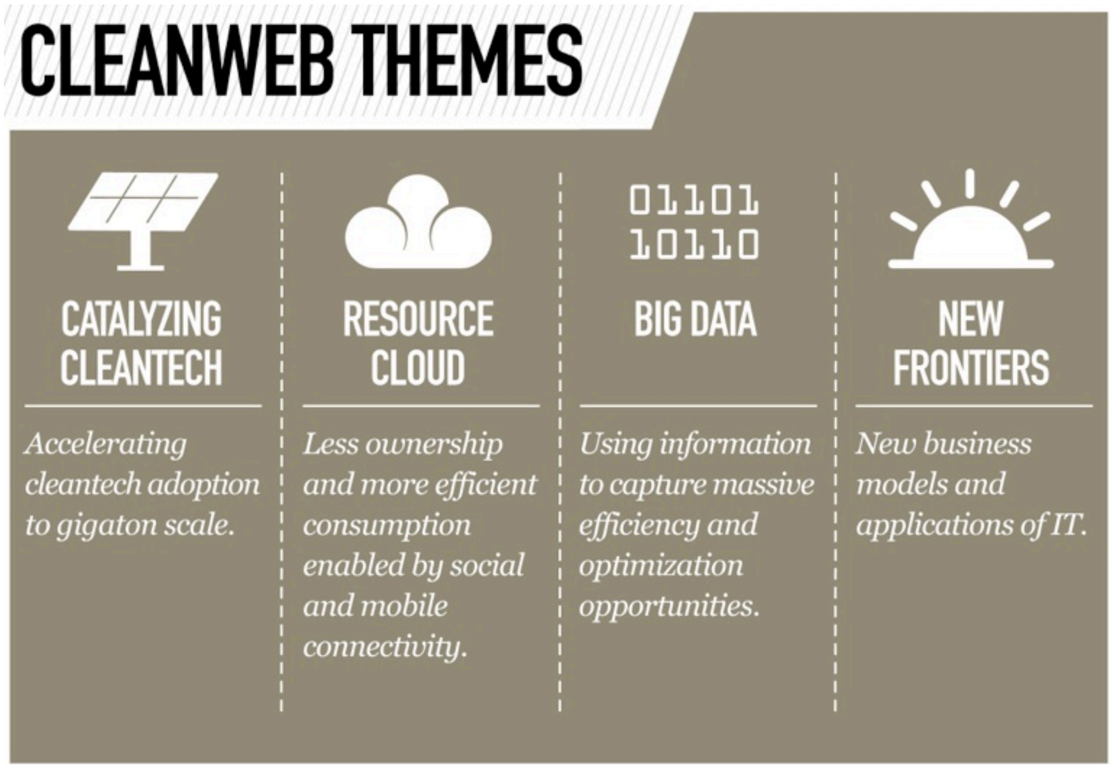

Figure 17. Classification of Cleanweb Companies by Pure Energy Partners, also based on company data sourced from Crunchbase (Pure Energy Partners, personal communication, 2013 © Pure Energy Partners / The Cleanweb Initiative).

Oriol Pascual was another participant in the conversation, who has visualised cleanweb at the intersection of cleantech, the Internet of Things and the Sharing Economy (collaborative consumption) (Figure 18) (Pascual, 2013, 2014).

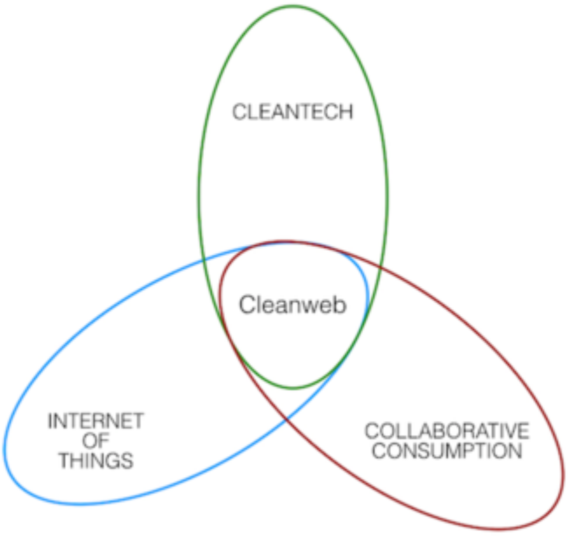

Figure 18 Pascual's diagram placing cleanweb at the intersection of cleantech, the Internet of Things and collaborative consumption © Oriol Pascual

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The following definition of the term cleanweb was agreed after a number of meetings:

Connected information technology solutions that address resource and sustainability challenges.

This definition is still used to introduce each Cleanweb UK meetup event ("Cleanweb UK," 2013). The key points of discussion were:

- Whether cleanweb refers only to technologies that address resource use, or to sustainability challenges in the broadest sense. This is a similar distinction to that between dematerialisation and institutional change in the LES Model (Section 2.3.3). The agreed compromise was "resource and sustainability challenges", which is somewhat ambiguous.

- Rebound effects were a similar point of discussion. One company that was a particular talking point was Stratajet, which allows private jet owners to rent out their underused aeroplanes to others. Is Stratajet "clean" because it makes private jet travel more resource efficient, or is it not "clean", because it promotes unsustainable private jet travel? The Decoupling Directness distinction developed in Chapter 6 helps explain this dilemma, which will be clarified in Section 9.3.2.

- Must a cleanweb system be connected to a digital network, or specifically to the Internet? The agreed term was "Connected" as it implies systems that transmit digital data but not necessarily over the Internet. “Connected” also includes systems that transmit data but via closed systems such as CCTV. “Connected” can imply both the human connectivity of social machines and the networked devices of the Internet of Things (Atzori, Iera, and Morabito 2010). This social variation is explored in Chapter 5.

- Does cleanweb refer just to the technology or to the full commercial and sociotechnical package? The term “Information Technology Solutions” implies the whole package of services that the customer receives that are enabled by ICT. This package is more than just the technology itself. “Information Technology Solutions” is somewhat similar to the concept of a “digital system” that will be defined in Section 5.3, although it is more explicitly commercial.
- The term “address….” was selected to have a similar meaning to “enabling impact” i.e. “actions that are enabled by the application of ICT” as used by Hilty & Aebischer in Section 2.3.3 and aligning with the definition of enabling impact in Section 5.3.

Masero created a even more pithy slogan for cleanweb (Masero & Townsend, 2014):

Smart, social, sustainable.

This international conversation did not reach any conclusion on classifying the cleanweb sector, but it provided valuable input into my own classification research in Phase 2.

3.4.3 THE SHARING AND CIRCULAR ECONOMIES ARE RELEVANT TO CLEANWEB

Botsman defines the **Sharing Economy** as “*an economic system based on sharing underused assets or services, for free or for a fee, directly from individuals*” (Rachel Botsman, 2015). The Sharing Economy has become a major theme within the digital sector, and many of the cleanweb companies that I came across in the course of this investigation are Sharing Economy platforms, such as ridesharing platform BlaBlaCar[42] (Casprini, Paraboschi, & Di Minin, 2015; Farajallah, Hammond, & Penard, 2016). Pascual identifies the Sharing Economy as one of three main components of the Cleanweb industry (Figure 18).

‘Many terms are being used to describe a broad swath of startups and models that in some way use digital technologies to directly match service and goods providers with customers, bypassing traditional middlemen. The terms "sharing economy," "peer economy," "collaborative economy," "on-demand economy," "collaborative consumption" are often being used interchangeably, though they mean very different things, as are the ideas they go hand-in-hand with, like

42 https://www.blablacar.co.uk/

"crowdfunding," "crowdsourcing", and "co-creation."' (Rachel Botsman, 2015; R Botsman & Rogers, 2010).

A closely related concept to the Sharing Economy that has emerged from academia is the product service system (PSS), *"a market proposition [in which the] customer pays for using an asset, rather than its purchase, and so benefits from a restructuring of the risks, responsibilities, and costs traditionally associated with ownership"* (Baines & Lightfoot, 2007).

Commercially these business models are often referred to as "C2C", as they facilitate "*an environment, usually online, where customers can trade with each other…C2C marketing has soared in popularity with the arrival of the internet, as companies such as eBay and Craigslist have fostered greater interaction between customers"*[43]. Three major groups of Sharing Economy system can arguably be distinguished within Sustainability by ICT:

- *Peer-to-peer borrowing* that allows individuals to offer short term access to assets such as real estate, cars or tools (Baines & Lightfoot, 2007). The potential sustainability benefit is that underused assets can be used more efficiently, producing more value whilst reducing the need for production and ownership. Examples include ridesharing platform BlaBlaCar[44] and tool-sharing system StreetBank[45].
- *Redistribution markets* allow individuals to sell, swap and barter items they no longer need. The potential sustainability benefit is prevention of waste and the reduction in production. Examples include eBay[46] or FreeCycle[47].
- *Crowdfunding* allows individuals to invest or donate to projects. This can provide the financial resources required for many different sustainability efforts. Examples include crowdfunding domestic solar panels with Mosaic[48], or sustainability innovation with Kickstarter[49].

Owyang's collaborative economy honeycomb is a classification of the sharing economy; it is organised by the type of resource: goods, food, services, transportation, space and money.

43 http://www.investopedia.com/terms/c/ctoc.asp
[44] https://www.blablacar.co.uk/
[45] http://www.streetbank.com/
[46] http://www.ebay.co.uk/
[47] https://www.freecycle.org/
[48] https://joinmosaic.com/
[49] https://www.kickstarter.com/

Figure 19. Owyang collaborative economy honeycomb: a taxonomy of the sharing economy. ©Jeremiah Owyang (Owyang, Tran, & Silva, 2013)

The **Circular Economy** *"is an alternative to a traditional linear (make, use, dispose) [economy] in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life"* (P. Mitchell & James, 2015).

My interest in the Circular Economy was heightened by Blumendorf's best-paper presentation at the first ICT4S conference (Blumendorf, 2013), which emphasised the cyclic nature of sustainability. This is based on The Natural Step Framework, which targets *"a minimal human intervention in natural processes (which is almost impossible given the rising human population) or the application of cyclic processes, which eventually give back what has been extracted"* (Blumendorf, 2013).

In 2014, a number of cleanweb specialists met in Barcelona, and we attended the FAB10 conference[50] on makerism and 3D printing. The Ellen MacArthur Foundation spoke at the conference on the role of the Circular Economy. I was intrigued by the relationship between the concept of cleanweb and the Circular Economy. Later that year I organised a Cleanweb meetup on the topic[51] as part of the first international #ThinkDif festival organised by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2014). The event explored the

50 https://www.fab10.org/en/home
51 https://www.youtube.com/watch?v=CrK6lmcJRso&t=17s

role of digital technology and big data in connecting industries to share, reuse, and recycle better. I later attended the international Open Source Circular Economy Day[52] .

Figure 20 shows two leading conceptualisations of the processes that make up a Circular Economy. Notably, the lower figure includes sharing. The Sharing Economy can therefore be considered a component of the Circular Economy.

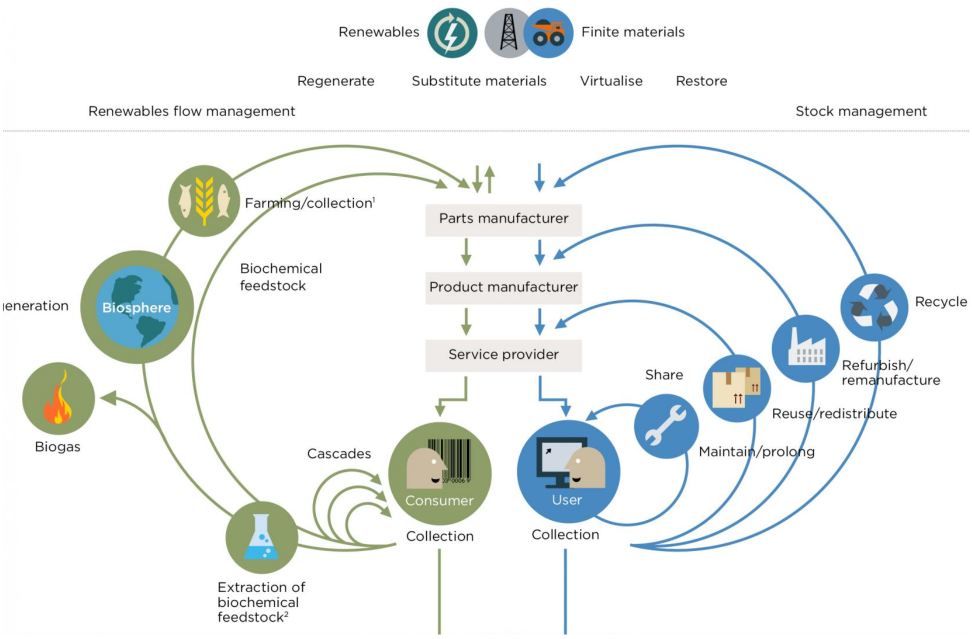

Figure 20 Models of the Circular Economy from ©WRAP[53] (upper diagram) and the ©Ellen MacArthur Foundation (lower diagram)[54].

52 https://oscedays.org/
53 http://www.wrap.org.uk/about-us/about/wrap-and-circular-economy
54 http://www.ellenmacarthurfoundation.org/

3.4.4 ORGANISING BY RESOURCE IS A USEFUL DESCRIPTION OF CLEANWEB SYSTEMS BUT NOT A SUFFICIENT ONE

The most common way to divide up the economy is by resource type into energy, water and food industries, as reflected in industrial taxonomies (Office of National Statistics, 2009). Owyang's map of the collaborative economy (Figure 19), and the taxonomies of the cleantech sector by Kachan and Cleantech Group are also organised by resource (Figure 16).

Resource use is central to the LES Model, which describes the decoupling of resource use through the enabling impacts of ICT on production and consumption. However, the LES Model does not specify the identity of that resource, be it heat, power or metal. Resource type is undoubtedly a useful way of organising Sustainability by ICT systems, just as it is for cleantech, the Sharing Economy and the whole economy. Therefore, organising by resource is also a useful way of organising Sustainability by ICT systems. This observation was made both in the AR and also emerged from the classification development of Phase 2. Resource type is therefore one of the five axes of the full SGM3 classification in Table 60 (Section 10.3).

Nonetheless, organising by resource is not a sufficient description of Sustainability by ICT systems such as those of the cleanweb industry. Resource type does not distinguish two qualities that distinguish cleanweb from cleantech as a whole: that they are digital and often social.

3.4.5 SOCIAL SYSTEMS AND CLEANTECH CATALYSTS APPEAR MORE PREVALENT IN ENTREPRENEURSHIP THAN RESEARCH

The Sharing Economy demonstrates how ICTs can link very large numbers of people to form social systems or "social machines" (N. Shadbolt et al., 2013). Examples include social networks, e-marketplaces, collaborative working, collaborative consumption, or crowdfunding (R Botsman & Rogers, 2010). The Web industry produces many highly social systems, and many were observed in the nascent cleanweb industry, that subset of the Web industry that "addresses resource and sustainability challenges" (Section 3.4.2).

Pure Energy Partners note that many cleanweb systems "catalyze cleantech… accelerating cleantech adoption to gigaton scale" (Pure Energy Partners, personal communication, 2013) (Figure 17). ICTs can help design, manufacture, maintain and sell environmentally beneficial technologies such as domestic solar energy. It was noted during this AR that catalyzing cleantech[55] appears to enhance some stage of the product life cycle to ultimately drive greater adoption.

Many social systems and cleantech catalysts were encountered amongst the cleanweb startups during the AR. Many startups that presented at Cleanweb UK meetups have systems that are highly social, and many catalyze cleantech. Examples that are both social and cleantech catalysts include train ticket marketplace Loco2, renewable energy crowdfunding platform Trillion Fund, and peer-to-peer energy provider Open Utility ("Cleanweb UK Youtube Channel," 2012).

However, social systems and cleantech catalysts did not appear to be nearly as frequent in the literature reviewed, nor are they clearly distinguished by the LES Model. There appeared to be significant differences between the focus of academics and entrepreneurs within the shared scope of Sustainability by ICT. This observation lead to the following hypothesis:

Social systems and those that catalyze cleantech are more prominent in entrepreneurship than ICT4S research.

Chapter 8 will test this hypothesis during Phase 3 with a quantitative comparison of research papers at the ICT4S conferences and of startups at the Ecosummit conferences. If confirmed, these observations suggest opportunities for new interdisciplinary research to investigate underrepresented forms of Sustainability by ICT (Section 8.4.2).

3.4.6 THE LES MODEL ENABLING IMPACTS DO NOT SUFFICIENTLY DESCRIBE SOCIAL SYSTEMS, CLEANTECH CATALYSIS, THE SHARING AND CIRCULAR ECONOMIES

Within the LES Model all actions are processes of production or consumption, and any service is produced by a causal tree of resources called a "hierarchy". The enabling impacts of ICTs are viewed as substitutions within the hierarchy for more sustainable resources such as information. However, the LES Model (Figure 10) does not clearly distinguish the role of ICTs as catalysts of cleantech. A robot on a production line may 1) manufacture a clean technology more effectively, making it more competitive with less clean technologies, or 2) simply use less resources in the manufacture of the product (whether or not the product itself is clean). These are different routes to progressing sustainability. Section 9.4 will show that the only conceptualisation of Sustainability by ICT encountered that clearly distinguishes such cleantech catalysts is Pure Energy Partners "Cleanweb Themes".

[55] This thesis uses "cleantech" in a broad sense for any product that can make resource use more sustainable i.e. any product that enables decoupling as defined by Hilty and Aebischer (2014).

At the time that the AR was taking place, the state-of-the-art of strategic ICT4S theory was arguably the Three-Levels Model (Section 2.1), which does not address the social nature of ICTs in any way. Its successor, the LES Model, has acknowledged limited **social variation,** with the distinction between the technological level that doesn't involve people, and the higher level that does (Figure 10). The LES Model enabling impacts also conflate the social variation between ICTs[56] with the distinction between production and consumption: production is seen as relating to organisational change (presumably involving many people), whilst consumption is relating to behavioural change (presumably primarily individuals). However, this assumption breaks down with the rise of the Sharing Economy, in which production increasingly takes place outside organisations, and consumption is collaborative. The LES Model enabling impacts do not account for social systems such as those from the Sharing Economy e.g. tool-sharing site StreetBank[57].

Section 9.2.1 will identify the LES Model's "processes of production and consumption" with those of the Circular Economy (Figure 20). However, the LES Model appears linear, rather than circular.

3.5 COMMUNITY LEARNINGS

This section considers what more could be done to develop the field and industry by the Sustainability by ICT practitioners encountered in this AR, and for them. The following suggestions for developing the community are based on these AR experiences, during which I worked on many of them. All could be undertaken by Sustainability by ICT bodies themselves. Some suggestions are discussed in more detail in the following sections. The list includes many of the recommendations of Masero *et al.* (2014).

- Develop Sustainability by ICT bodies such as trade organisations, conferences or accelerators (Section 3.5.2).
- Build internal relationships to help the field and industry consolidate. Develop online and offline forums (Sections 3.5.1 and 3.6.1).
- Represent and promote the concept of Sustainability by ICT. Build external relationships (Section 3.6.2).
- Identify and promote a single term for the area (Section 3.5.1).
- Identify useful regulatory changes and persuade policy makers.

56 The unwieldy expressions "how social it is" or "social variation" are used because the term "sociality" has a different, sociological meaning within social machines research (De Roure, Hooper, Page, & Willcox, 2015).
57 StreetBank http://www.streetbank.com

- Promote innovation by offering funding, running competitions or acceleration programmes (Section 3.6.4), and by identifying real sustainability problems from industry and consumers (Section 3.5.3).
- Similarly, identify opportunities for research and communicate them to academics.
- Support collective action on behalf of the community.
- Collect and disseminate useful data (Section 3.5.4).
- Develop a knowledge base of research results and methods.

3.5.1 SMART GREEN IDENTITY AND INTEGRATION

This action research suggests that only limited consolidation has taken place into a single community of Sustainability by ICT with a shared identity. This follows from observations of various communities made early in the AR:

- **No single term** has been widely adopted to describe Sustainability by ICT. Myriad terms exist such as **cleanweb, ICT4S, smart and green, digital cleantech, Green IT, smart energy, smart water, green computing, computational sustainability, smartups** and many more. Most of the hack events I attended invented a new term just to describe the event. Whilst no term has stuck for Sustainability by ICT, related concepts have seen much greater adoption such as cleantech, green tech, Circular Economy, Sharing Economy, fintech, smart homes, smart cities, and the Internet of Things.
- Many Sustainability by ICT practitioners, such as startups, **do not identify with the concept of Sustainability by ICT or any of the labels** above. After several years working on this topic, I still meet a lot of these “detached” companies, some very successful. Participants in the many hack events I attended had little awareness of the concept of Sustainability by ICT and how they could contribute.
- Without a shared identify or label, Sustainability by ICT practitioners are having **difficultly integrating with each other** for mutual benefit, such as investment, partnership, mutual learning or promoting the shared interests of the sector. The hack events I attended were organised by different groups with little awareness of each other or wider Sustainability by ICT efforts, such as the cleanweb network or ICT4S research community.
- **Awareness of the Sustainability by ICT concept** or any of the terms above is limited amongst digital and sustainability actors more broadly, such as the Web and cleantech sectors.

- Sustainability by ICT **communities have had limited awareness of each other**, particular cleanweb startups and ICT4S researchers. There is also a notable geographical division between Europe and North America, both for practitioners and researchers.
- **Companies may not identify with the sustainability benefits of their products**. They often identify with the resource they address i.e. the traditional sector they are in e.g. domestic heating, power generation or car transport. They also often identify with their digital-ness, using words such as "smart", "Internet" or "digital". However, they may not prioritise their sustainability benefits, or even be aware of them. Nevertheless, substantial numbers of consumers are motivated by sustainability, as are many investors, such as those at the Ecosummit event. And such efforts are not mutually exclusive, a company can participate in sustainability events as well as resource-specific and technology-specific ones.
- Sustainability by ICT systems and companies are **very diverse**, which may reduce the value of coordination between them. Many of the most important constraints for a company depend upon the traditional sector it is in, which follows from the resource that it addresses, varying greatly between companies. For instance, a transport-focussed startup such as car-sharing app ZipCar shares a regulatory context with the transport industry, which is where it is likely to seek investors, corporate partners or eventual buyers.

It would be surprising if all these difficulties were not impeding the growth of the smart green sector. However, quantitative evidence was not encountered to confirm this. Nevertheless the remainder of this investigation provides plentiful evidence that progress is still being made albeit somewhat disconnectedly. Addressing these challenges may help grow the body of Sustainability by ICT practice faster by increasing interest from investors, entrepreneurs, employees and policy-makers. This AR itself attempted to address these challenges in the following ways, which are detailed and evaluated in Section 3.6.1.

- **Promoting the concept of Sustainability by ICT through traditional media and new media**.
- **Connecting Sustainability by ICT practitioners** with each other and attracting people from the broader context of digital and sustainability practice by developing the **Cleanweb London community**.
- **Sharing ideas** amongst and beyond practitioners through the **Cleanweb Meetups and YouTube channel**.
- **Increasing mutual awareness** between different communities of Sustainability by ICT practitioners.

Efforts to address these challenges have also been made by many prominent actors within the various communities. Notable examples include:

- The leaders of the ICT4S research community who have brought together relevant research from many disciplines into a single conference.
- The Cleanweb Initiative (TCI) who worked to spread the concept of cleanweb around the world through hack events and developing a network of practitioners and experts.
- The Ecosummit conferences that bring together smart green startups, investors and corporate partners.
- The Green Hackathon international series of hack events developed by Zapico (2013).

Hopefully these efforts will continue and strengthen in order to consolidate the area further by addressing the challenges above. Further measures could include the following. Policy interventions could support all these goals, as well as continued effort from the bottom up, as discussed in the following subsection.

- Growing the events such as Ecosummit and ICT4S that help Sustainability by ICT practitioners network. Also, networking at hack events. The AR experiences suggest that the primary benefit of hack events is actually the networking that takes place rather than the software produced. This was also my experience with creating and celebrating Globe-Town.
- Developing bodies that represent, promote and integrate the industry and field. This is explored in the following subsection.
- Developing links between academic ICT4S community and the entrepreneurial sector. The researchers already have connections with some established corporates, mainly utilities or IT. Two forms of entrepreneurial organisation with the potential to undertake such systematic engagement with the academy are:
    - Sustainability by ICT focussed accelerators and incubators, such as Sustainable Accelerator[58] (London), Rockstart[59] (Amsterdam) or GreenStart (San Francisco)[60].
    - The new venturing arms of utilities and other resource-focussed companies that have emerged to address the challenges and opportunities of disruption due to digital and clean technologies. Examples include Innogy Venture Capital[61] or Centrica Innovations[62].

58 https://www.sustainableaccelerator.co.uk/
59 https://www.rockstart.com/
60 http://www.greenstart.com/
61 http://www.innogy-ventures.com/
62 https://www.centrica.com/innovation

- Investors such as venture capitalists. For instance, Zouk undertook such an engagement with ICT4S research, as detailed in Chapter 7.
- Developing virtual communities of ICT4S enthusiasts over social media.

3.5.2 SUSTAINABILITY BY ICT BODIES

One means to consolidate and grow Sustainability by ICT is through strategic bodies such as trade associations. There are a number of ways in which such bodies could originate:

- They can form top-down from the creation or repurposing of existing international bodies such as the International Telecommunication Union (ITU) or from within the United Nations or European Union.
- They could form top-down from efforts within each country to establish a national body (Masero *et al.* 2014).
- International bodies could also form bottom-up from a not-for-profit or commercial enterprise. This was attempted by The Cleanweb Initiative, so lessons could be drawn about what worked and what did not. Another example is Energy Unlocked[63], which aims to change the regulatory context for smart energy and incentivise specific innovations.
- Similarly national bodies could form bottom-up, such as by developing the Cleanweb UK community (Masero *et al.* (2014). The main challenge for Cleanweb UK is identifying a business model to support its growth and development (Section 3.6.4).

Such bodies could undertake the suggestions identified at the beginning of this section. Much of this work can also be undertaken by more localised bodies such as accelerators.

3.5.3 OPENING UP SUSTAINABILITY CHALLENGES

Another observation from the hackathons is how difficult it is to engage with practitioners with sufficient experience of the everyday challenges of sustainability, such as how to find and fix an underground water pipe, or how rural Africans would want to pay for solar energy. Sustainability problems are remarkably diverse, and the role of ICT is often to address critical but mundane difficulties that require deep subject matter expertise, rarely found amongst digital innovators themselves.

Sustainability by ICT innovators such as entrepreneurs, accelerators and researchers can address this challenge by working more closely with employees and consumers to discover

[63] http://www.energyunlocked.org/

the often-mundane reality of sustainability problems. Some of the hack events I attended attempted to integrate such subject matter expertise, but none were really successful.

An alternative digital approach is open innovation platforms that create a digital marketplace to connect sustainability problem holders with innovators.

3.5.4 OPENING UP DATA

One difficulty for startups can be access to the data they need. One way to mitigate this is providing open data, particularly from government or scientists. Open data can be a valuable resource for digital innovators, particularly those addressing sustainability, as interdisciplinary problems can require many different data sets.

Significant steps were taken during the action research to promote the concept of Open Sustainability, the application of open data to sustainability, as well as other forms of open knowledge such as open access to the scientific literature. I also helped organise the sustainability stream of the 2013 Open Knowledge Festival in Helsinki (Dimitrova et al., 2012).

The climax of this effort was a TEDx talk on Open Sustainability, which asked if our growing knowledge commons can help our endangered natural commons (Townsend, 2012). The TEDx talk argued that open knowledge can benefit sustainability by supporting **innovation**, **resource efficiency** and bringing **transparency to our impacts on the environment** ("making the invisible visible"). However, not all open data is beneficial sustainability. For instance, data on the locations of endangered species is often kept secret to prevent poaching. Such species require their own form of privacy.

3.6 PERSONAL IMPACT AND LEARNINGS

Many of the suggestions to develop Sustainability by ICT communities (made at the beginning of Section 3.5) were undertaken as part of the AR. This section discusses some of areas in which I appeared most impactful, and others where future action could be more effective.

The primary output of this AR is the contribution to knowledge made by the Smart Green Map classification. This makes up the largest AR cycle, detailed in the remainder of the thesis. In particular, Chapter 7 demonstrates an impact on the cleanweb industry, when the Enablers model was adopted by a venture capital firm as a component of their investment policy.

3.6.1 CONNECTING PRACTITIONERS AND COMMUNITIES

Efforts to connect Sustainability by ICT practitioners appear quite effective. An effective offline has been the **Cleanweb London** community, which also aims to attract people from the broader context of digital and sustainability practice. I lead the organisation and hosted events closest to my research interests, on topics including design, smart cities and the Circular Economy (Section 3.4.3).

To encourage people to connect, each Cleanweb London meetup has long intervals, free refreshments and then a continuation to the pub for further conversation and relationship building. A number of other measures were implemented to support recruitment to cleanweb startups, including community announcements, "give/get" cards upon which attendees could log requests for collaboration[64], and a website for posting cleanweb jobs[65].

54 cleanweb London meetups have now been held, generally attended by 30 to 100 people, and a community of regular attendees has developed. Assuming that each attendee meets two new people per meetup, then it can be estimated that 5000 new connections have been made between attendees. Although the ultimate impact of these many connections is unknowable, the clearest evidence of positive impact is the founding of startups after meeting at the events, including peer-to-peer energy platform Open Utility[66], urban data science provider Mastodon C[67], and cleanweb startup showcase IYWTO[68]. These companies now employ around 20 people.

I also helped connect many practitioners by volunteering at Ecosummit (Section 3.4.1).

The least successful method employed to connect Sustainability by ICT practitioners was creating online forums. A number were formed, but none have endured. These include attempts to connect the Cleanweb UK community nationally, cleanweb enthusiasts globally, and the Open Sustainability community. Future work on this would seek best practice to achieve self-sustaining virtual communities. This challenge overlaps with the subsection below, making software that lasts.

Whilst participating in the major communities of Sustainability by ICT practitioners, I was able to help make them more aware of each other. I presented a paper on cleanweb startups to the ICT4S community, presented ICT4S theory at startup events and hack days, and invited ICT4S research from Southampton and Stockholm to speak at Cleanweb UK meetups.

64 http://giveget.cleanweb.org.uk/
65 https://cleanwebjobs.com/
66 https://www.openutility.com/
67 http://www.mastodonc.com/
68 https://iywto.com/

3.6.2 PUBLIC COMMUNICATION

One irony of doctoral research is that there is more time to communicate early in the process when you know less. Nevertheless, I took every opportunity I encountered to speak about what I had learned so far. Despite the limited insights I could offer, this may have raised awareness of cleanweb and of my work, leading to many further connections and insights that informed the classification development of the following chapters.

Much effort was made to promote the concept of Sustainability by ICT through traditional media and new media. The term that appeared to have most momentum during the early part of this research was "cleanweb", so this was the main term that I used. I was interviewed about cleanweb for the New York Times (Gardiner, 2013) and the environmental magazine Grist (Suzanne Jacobs, 2015). An early version of this research was also included in a report on the UK Cleanweb sector for Nesta (Masero & Townsend, 2014).

Ideas were also shared amongst and beyond practitioners through the Cleanweb Meetups and YouTube channel. Many topics identified by the research process then became themes for Cleanweb London events including: the Internet of Things, transport, energy, mapping, environmental activism, food, gamification and biodiversity conservation (Figure 14). I spoke at the Cleanweb London event on open data and sustainability (Townsend, 2013) and at another event on mapping the cleanweb sector (Townsend, 2015a). The monthly meetings have generated a legacy of over 70 videos of presentations by cleanweb entrepreneurs and specialists, including three of my own ("Cleanweb UK Youtube Channel," 2012) [69]. These videos form a corpus of narratives from Sustainability by ICT practitioners, recording the emergence of an industry.

3.6.3 FOCUSSING SCOPE

The hardest challenge in the doctorate was defining a succinct central research problem and method. This challenge motivated the adoption of AR, but it also reduced its efficiency, dissipating time and energy, but allowing for a rich set of experiences and conversations. Limiting the scope was hampered by the following factors:

- The novelty of the field, making it harder to identify the body of literature, research problems and established methods.
- Finding supervision that was relevant enough to both the topic and the methods.

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69 Videos of past Cleanweb UK speakers on Youtube channel https://www.youtube.com/user/CleanwebUK

- The many possibilities opened up by interdisciplinarity, leading to a consistent worry that other important domains of knowledge were not being sufficiently considered, such as the management theory of entrepreneurship.

3.6.4 SUSTAINABLE DEVELOPMENT I.E. SOFTWARE THAT LASTS

This experience of creating Globe-Town reaffirmed that software applications generally require extensive work to find user acceptance, and on-going attention to maintain it. The application was initially impactful, receiving significant attention after winning the World Bank Apps for Climate competition and the LinkedUp Open Data in Education competition (Townsend et al., 2013). Usage of the application spiked with the publicity received, but then reduced again. Whilst the application has generated significant enthusiasm, it has not been adopted for regular use, and as other priorities arose, it was not possible to develop and publicise it further. As it is an original contribution to visualising the relationships between countries, and the impacts of sustainability, there may still be an opportunity for future development. At present, perhaps the greatest impact of Globe-Town has been the personal connections it helped develop.

My other contributions to software creation have been through participation in hackathons, participating in teams, advising them and judging them. However, despite going to many such events, I am skeptical whether they lead to “sustainable development” in the alternative sense of software projects that last! To address this challenge, some of these events take a multi-week approach that may lead to more project sustainability e.g. the Open Data Challenge[70]. My assessment is that the primary benefit of an environmentally-themed hackathon is the relationships that form between the participants, who may then go on to cooperate further. This was certainly my experience. The London Green Hackathon was where I first met many of the people with whom I would develop the Cleanweb UK community, and it also lead to the formation of the startup Mastodon C.

Problems of longer-term viability also effect many of the collaborations and communities I encountered, which rely on enthusiasts and doctoral researchers to keep them functioning. This leads to intermittency or ephemerality, as individual’s interest and commitments wax and wane. This can be addressed with external funding, or by developing a business model that generates revenue.

70 http://www.nesta.org.uk/project/open-data-challenge-series

3.7 PHASE 1 CONCLUSION: THE OPPORTUNITY FOR A NEW CLASSIFICATION OF SUSTAINABILITY BY ICT SYSTEMS

These AR observations of Phase 1 suggest that there is significant variation between Sustainability by ICT systems that is not sufficiently described by the enabling impacts of the LES Model. The conceptualisation of variation is the process of **classification** (K. D. K. Bailey, 1994). Phase 2 will therefore ask **how can Sustainability by ICT systems be classified effectively and usefully?** This is the central research question of the investigation, which will generate the main contribution, the Smart Green Map classification. Bailey states that:

"*Classification is arguably one of the most central and generic of all our conceptual exercises. It is the foundation not only for conceptualization, language, and speech, but also for mathematics, statistics, and data analysis in general. Without classification, there could be no advanced conceptualization, reasoning, language, data analysis or, for that matter, social science research… In its simplest form, classification is merely defined as the ordering of entities into groups or classes on the basis of their similarity… we arrange a set of entities into groups, so that each group is as different as possible from all other groups, but each group is internally as homogeneous as possible*" (K. D. K. Bailey, 1994).

Based on the observations of Phase 1, it is hypothesised above that **social systems and cleantech catalysts are more prevalent in cleanweb entrepreneurship than ICT4S research**. To test such a hypothesis requires a new classification of Sustainability by ICT systems that distinguishes their wide **social variation**, and those systems that **catalyse cleantech** from those that do not. To better describe the social variation not sufficiently described by the LES model, Phase 2 will ask **how do DDS combine people and digital technology?** Similarly, Phase 2 will ask **how do some DDS catalyze cleantech?** And so that the SGM is as explanatory as possible, Phase 2 will ask **what is the conceptual basis for the observed variation**?

The international conversation with cleanweb specialists suggested that a classification could offer a range of benefits for the nascent industry, including **raising awareness of its existence**, whilst **helping startups, investors and other stakeholders to coordinate and learn**. The classifications of particular industries presented above, such as the Sharing Economy (Figure 19) and Cleantech (Figure 16) show the value to practitioners of a map of their industry.

In order to succinctly conceptualise the whole of Sustainability by ICT, the Enabling impacts of the LES Model are necessarily high-level, distinguishing a handful of categories that are variations on optimisation, media substitution and externalisation of control (Figure 10). To undertake **quantitative comparisons** between companies, markets and research areas requires a more granular classification than the LES Model. Such a quantitative comparison could help researchers and startups to be more aware of each others' work, and identify impactful research avenues to researchers, whilst making research insights more accessible to practitioners.

In conclusion, the variation in Sustainability by ICT could be better conceptualised with a new classification that is more granular, describing the role of social systems and cleantech catalysts, and thus better reflecting the active innovation in cleanweb entrepreneurship. This will be addressed in Phases 2 and 3 in the remainder of the thesis.

CHAPTER 4 QUALITATIVE CLASSIFICATION METHODS

4.1 INTRODUCTION

The AR and literature review of Phase 1 concluded that a more granular classification of DDS than the LES Model enabling impacts could be useful to cleanweb practitioners, enabling the social variation in such systems to be investigated, and how some systems catalyse cleantech. This chapter begins **Phase 2,** investigating **how Sustainability by ICT system can be classified effectively**, the central research question of the thesis, leading to the central contribution, a **two-dimensional classification of Sustainability by ICT systems** called the **Smart Green Map (SGM)**. This chapter outlines the qualitative methodology by which the classification of cleanweb systems was developed (K. D. K. Bailey, 1994). The next chapter derives the first component of the SGM, the **Enablers,** which distinguish the social variation in such systems, and Chapter 6 derives the second component of the SGM, **Decoupling Directness (DD),** which distinguish how ICT systems catalyse cleantech.

Section 4.1 details the classification methodology, employing some of the principles of grounded theory (GT) (Glaser & Strauss, 1999). The main data analysed were descriptions of cleanweb companies from various sources, primarily CrunchBase. An evaluation framework for the resulting classification was developed, both to focus efforts on theory development, and enable evaluation of the results. Section 4.3 develops a framework for evaluating the resulting classification. Section 4.4 considers the limitations of this methodology.

4.2 METHODOLOGY

This section describes the methods employed to develop the classification. The results are detailed in the next two chapters. The research steps and interim results are detailed in Section 5.1.

4.2.1 TYPOLOGY DEVELOPMENT

Bailey distinguishes between two major types of classification: conceptual **typologies** that are common in the social sciences and empirical **taxonomies** that are often computationally-derived and are common in the biological sciences (although usage of the terms is sometimes confused). (K. D. K. Bailey, 1994). Whilst computational taxonomies are arguably more objective, they lack the conceptual depth of typology. Computational taxonomies are often represented as continuous dendrograms e.g. (N. Shadbolt et al., 2013).

Typologies are generally distinguished from generic classifications for being multidimensional and conceptual (K. D. K. Bailey, 1994). Typologies are often 2 x 2 matrices that combine two carefully selected dimensions to describe the possibility space, characterized by labels or names in their cells. As a conceptual classification, a typology has the advantage that it *"can transform the complexity of apparently eclectic congeries of diverse cases into well-ordered sets of a few rather homogeneous types, clearly situated in a property space of a few important dimensions."* (K. D. K. Bailey, 1994). Owyang's classification of the Sharing Economy is an example of a typology (Figure 25). Bailey charts the history of typologies in the social sciences:

"Typological theorising, or the development of contingent generalisation about combinations of configurations variables that constitute theoretical types, has a long history in social sciences significant developments date back to Max Weber's discussion of "ideal types" early in the 20th century (George & Bennett, 2005) *and Paul Lazerfeld's analysis of property spaces in the 1930s* (Lazarsfeld, 1937). *Its advantages include its ability to address complex phenomena without oversimplifying, clarify similarities and differences among cases to facilitate comparisons, provide a comprehensive inventory of all possible kinds of cases, incorporate interactions effects, and draw attention to "empty cells" or kinds of cases that have not occurred and perhaps cannot occur"* (George & Bennett, 2005).

To benefit from some of the advantages of both taxonomies and typologies this investigation pursued an intermediate form that Bailey terms an **operational classification**: "*This ... consists of first forming empirical clusters, and then subsequently formulating conceptual labels for them. Whether one begins with theory or empirical data, when the two are combined the result is an operational or indicator level classification."* (K. D. K. Bailey, 1994) Bailey states that an operational classification can be generated from a process of categorisation from coding as undertaken in GT.

A typology is essentially the combination of its dimensions, and its creation is the identification of those dimensions. However, there is no perfect method to do so. *"A classification is no better than the dimensions or variables on which it is based. One basic secret to successful classification, then, is the ability to ascertain the key or fundamental characteristics on which the classification is to be based. ... Unfortunately, there is no specific formula for identifying key characteristics, whether the task is theory construction, classification, or statistical analysis. In all of these diverse cases, prior knowledge and theoretical guidance are required in order to make the right decisions"* (K. D. K. Bailey, 1994).

4.2.2 PRINCIPLES

The classification was developed inductively from qualitative company description data. Empirical categories were identified and then developed into conceptual classes defined by functional models. The overall classification development methodology, shown in Figure 21, integrates elements from a number of approaches including Grounded Theory (GT), as well as classification strategies from social science (K. D. Bailey, 1984; K. D. K. Bailey, 1994) and from information systems (Nickerson, Muntermann, Varshney, & Isaac, 2009). The diagram shows two stages of development: the first was more linear, identifying the need for a classification, gathering the data, and analysing it to produce a first version; and the second stage cycled through various methods, in parallel, in order to refine and conceptualise the classification.

In contrast to the traditional hypothetico-deductive scientific method, AR and GT are both inductive research methods that begin with data and work towards a hypothesis or theory (Bryman, 2001; Glaser & Strauss, 1999). The development of categories is intrinsic to the GT method, so it lends itself to classification development. Although this application is beyond the usual purview of GT - as discussed Section 4.4 - a number of GT principles proved useful (Charmaz, 2006; Glaser & Strauss, 1999).

- **Constant comparison** is the central tenet of Grounded theory. As successively more abstract ideas were developed from the data (codes, concepts, and categories), and new data was sourced, they were compared to existing data, codes, concepts, and categories, and ultimately to literature. In particular, as new digital systems were encountered they were classified within the developing categorization in order to test its scope, clarity and explanatory power. Ongoing development of the theory meant that individual systems were re-categorised as the definitions of the categories were developed, which were captured in memos. Constant comparison integrated with the AR of the overlapping Phase 1.
- The principle that **all is data** also aligned with the AR. The main source of data was qualitative company descriptions from CrunchBase. However, a rich variety of other sources were used, and notes were taken throughout Phase 1 from cleanweb meetups with startups, academic presentations, business events, newspaper articles, company websites, semi-structured interviews and informal conversations. This included writing down my own reflections and analysing them (Charmaz 2006).
- Phase 1 began the identification of tentative **core variables** around which the rest of the theory could be built: "web approach" and "sustainability outcome". The core

explains the behaviour of the participants in resolving their main concerns. The "behaviour" is the "web approach" they employ, and their main concern is the "sustainability outcome".

- As the core variables emerged, Phase 2 began **theoretical sampling,** selecting data samples that related to the core variables by filtering the CrunchBase data (Section 4.2.4). This continued with new theoretical samples being gathered and analysed, such as the most prominent UK cleanweb companies.
- Similarly, **selective coding** was employed, so only those aspects of the data that related to the core variables were coded.
- Theoretical ideas were developed about the emerging categories by **writing and comparing memos**.
- Theory was developed by **sorting concepts and diagramming.**
- **No taping and transcribing** was undertaken as GT deems this counter-productive and wasteful of time. Instead field notes were amassed in Phases 1 and 2.

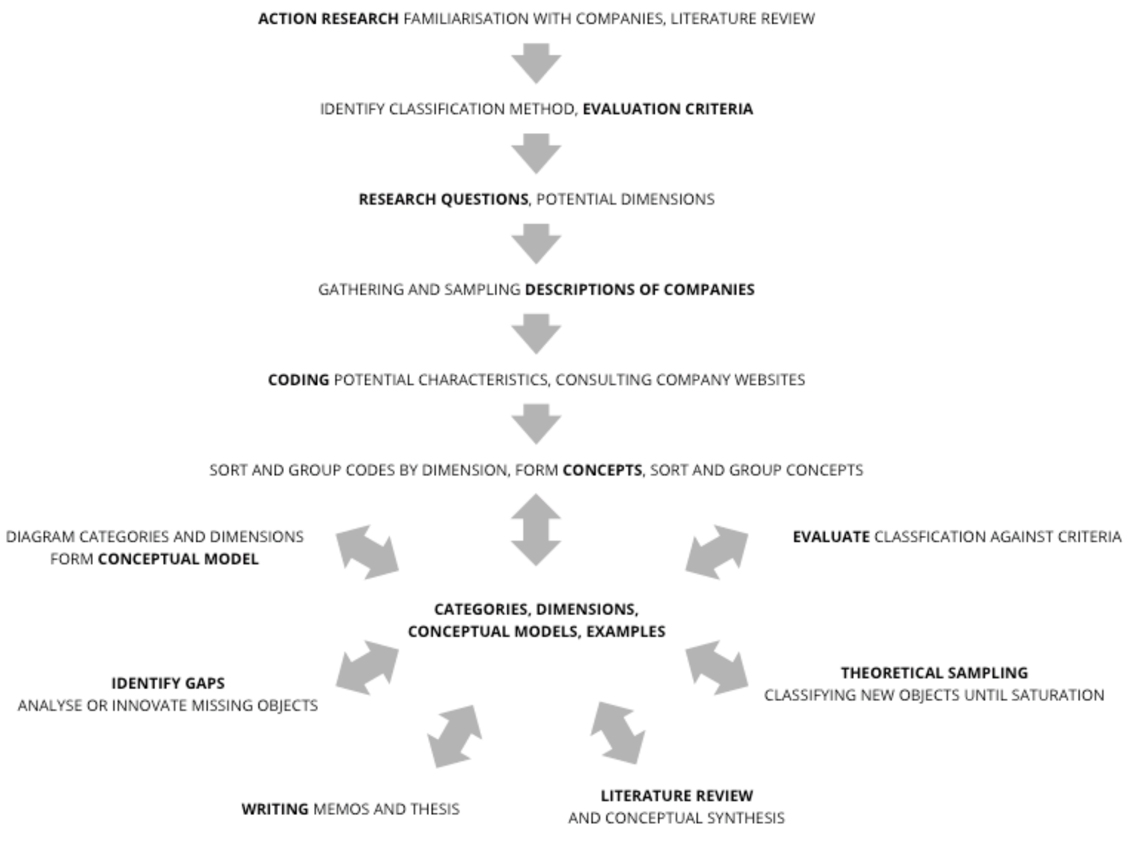

Figure 21 The classification development method that produced the SGM.

4.2.3 SOURCING COMPANY DESCRIPTIONS AS SECONDARY INTERNET DATA

Data was source from CrunchBase (TechCrunch, 2013) a large directory of technology companies, and complemented with rich data from many sources, particularly during the Action research of Phase 1. As the CrunchBase data was sourced externally, rather than created during the research process, this was secondary analysis of Internet data (Smith, 2008), a new but increasingly established method in the social sciences (Carmichael, 2008; Smith, 2008). *"Secondary analysis allows researchers to go beyond the limitations of their own resource, time and place, reduces respondent burden and provides more research transparency"*(Williams & Vogt, 2011). This method can only become more popular with the rapid growth in digital data (Nagy et al., 2011), and the rapid development of areas such as big data (Mayer-Schonberger & Cukier, 2013), data science (Dhar, 2013) and open data (Davies, 2013).

The specific benefits of using Crunchbase are extensive size, broad reach, rich content and timeliness. The latter is particularly important in a young and fast-moving industry like Sustainability by ICT. Another key benefit is the Creative Commons license that allows sharing online and reuse of the data from this analysis as part of further research, making CrunchBase open data. The limitations of secondary analysis of crowdsourced Internet open data are discussed in Section 4.4 below.

CrunchBase (TechCrunch, 2013) is a directory of technology companies created and maintained by TechCrunch, a Californian technology news company. According to the CrunchBase website, it is *"the free database of technology companies, people, and investors that anyone can edit"* (TechCrunch, 2013). CrunchBase holds profiles of 182,000 technology companies, as well as associated people, financial organisations, service providers, funding rounds, and acquisitions. Company profiles include extensive qualitative data including a description, an overview and a list of user-generated tags. CrunchBase is ranked as the 1,289th most popular website globally (Alexa, 2013). Content is updated by users, and moderated by staff. Data on all companies were downloaded from the CrunchBase API over a two-week period in October 2013. Techcrunch data is crowdsourced, with anyone able to contribute (Howe, 2009). Whilst anyone can edit, changes do not appear until they have been approved by Techcrunch staff.

A high quality source of cleanweb company descriptions that supplemented the Crunchbase data was a shared online list of over 100 cleanweb companies created by Pascual with some input from the wider European cleanweb community (Pascual, 2014). Sometimes new examples of companies were found by web search. Many relevant companies that had been identified during the action research of Phase 1 within the Cleanweb community were also analysed. Where more information was needed about a particular company, the *About Us* section of the company's own website and other Web sources was found via Google search.

4.2.4 SAMPLING

To extract a theoretical sample of the CrunchBase database of 182,000 companies for qualitative coding, search terms were used within the three major qualitative data fields: description, overview and user generated tags. The search terms developed are listed in the Appendix. Companies were selected whose entries included terms from either (1 AND 2) OR 3:

1. Environmental sustainability e.g. renewable, climate change, rainforest, pollution, recycling, solar, public transport, biodiversity.
2. ICTs, Web and open knowledge e.g. Internet, social media, online, SaaS, software, artificial intelligence, open data.
3. ICT4S and cleanweb e.g. cleanweb, green IT, building management system, smart city, intelligent building, telepresence, sharing economy.

Regex, a computer syntax for pattern-matching complicated sequences of characters, was used to allow for word stemming (e.g. sustainable, sustainability) and variations in word presentation (e.g. landfill, land-fill, land fill). The lists of search terms were developed by gathering documents of particular relevance to each domain.

1. For sustainability these included Rio+20 Our Common Vision (United Nations, 2012) and an EU report on sustainable development strategy (European Commission, 2013).
2. For digital systems, this included proceedings of the WWW 2013 and Web Science 2013 conferences, the Oxford Internet Survey 2011, and the EU Digital Agenda 2010 and commercial reports on digital trends.
3. For ICT4S and cleanweb this included the proceedings of the first ICT for Sustainability conference 2013 (Lorenz M. Hilty, Lohmann, Aebischer, Andersson, & Lohmann, 2013).

These documents were then analysed for word frequency using NVivo qualitative research software[71]. The 500 most frequent word stems for each category were examined, and assessed both for specificity to the topic and low ambiguity. Words were also included from the action research experiences, especially for search #3, as the nascent cleanweb community uses novel terms and has yet to produce many large documents. Ambiguous terms were excluded or replaced with more specific terms (e.g. "hazardous waste" instead of the

[71] http://www.qsrinternational.com/products_nvivo.aspx

ambiguous "waste"), especially those for which the required meaning was not the dominant one. Dialectical differences in language use were included e.g. *railway* and *public transport* in the UK, as opposed to *railroad* and *public transit* in the USA. The resulting list of around 200 search terms, and the corresponding regex expressions, are listed in the Appendix.

The lists of search terms were used to filter the CrunchBase data using OpenRefine data processing software[72]. The list of search terms was refined in an iterative process. In a process analogous to snowball sampling, existing search terms were used to identify further search terms through word frequency analysis of the sample resulting from each search, visualised as word clouds[73] (Bryman, 2001). The entire Crunchbase list was then re-filtered using the refined search terms, and this process was repeated several times to increase the quality of the search terms and ultimately the sample of companies.

6000 possible DSS companies were extracted from the Crunchbase data, and prioritised in order of the number of relevant terms found for each. Even with iterative refinement of the search terms, many entries did not sufficiently qualify as DSS, and were discarded. The company descriptions and other metadata were then examined individually. If the company's product was indeed a DSS then it was coded. Eventually over 400 ICT for sustainability companies were found and coded. These were combined with other sources described in the previous section, the list of 100 cleanweb companies identified by Pascual and others in the cleanweb community (Pascual, 2014), web search, and those identified in the action research of Phase 1.

As the central body of categories and theory were developed and prioritised theoretical sampling and selective coding were employed. Categories were used to further refine search terms, to gather more data and reapplied to recode the data. They were used for targeted web search for relevant web content, particularly company descriptions from their own websites. The action research experiences within the cleanweb community and own accumulated knowledge were also integrated. This resampling and recoding was focussed on UK companies, because of the need to contribute analysis to the Cleanweb in the UK report at that time (Masero & Townsend, 2014).

4.2.5 CODING

Coding is the pivotal link between collecting data and developing an emergent theory (Charmaz, 2006). The descriptions of each company and some other relevant qualitative fields were read and coded entry-by-entry. The coding process analysed the Crunchbase list,

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[72] OpenRefine data processing software http://openrefine.org/
[73] Word Cloud visualization tool http://www.wordle.net/

starting with those items that matched the most search terms. The main field that was coded was company description. Other fields were company name, website, the tags of the Crunchbase folksonomy, and the identified search terms.

The coding was initially open, but most entries contained large quantities of information not relevant to the research questions, so coding quickly became selective to efficiently address the research questions. Two research questions were asked of each entry, forming two tentative core variables: the web approach: **how does the combination of digital technology and people achieve the sustainability benefit?** And the sustainability outcome: **how does the system benefit sustainability?**

Not all the initial open codes fit into these two high level categories. Other variables were identified including the types of actors involved (such as business, consumers, lenders, donors, landlords) and the incentives for actors to participate. Fewer codes appeared in these categories and they were judged of much less direct relevance to the research question. Open coding thus moved to **selective coding** based on these tentative core variables of web approach, and sustainability outcome. Companies that weren't sufficiently in scope were excluded. Table 64 in the Appendix shows the coding of the first four companies by the tentative core variables. Coding was undertaken with constant comparison, comparing new codes with previously adopted codes. Eventually saturation was approached when the codes and categories seemed to sufficiently describe the data.

4.2.6 DEVELOPING THE CLASSIFICATION, CONCEPTUALISATIONS AND TERMINOLOGY

Codes were sorted and resorted to find common themes, forming a higher order commonality called a concept (Allan, 2003). Sorting and resorting continued to find yet higher order commonalities called categories. Employing the constant comparative method, as new digital systems were identified they were categorised with the latest version of the classification, so the theory could be honed to the target evaluation criteria (Section 4.3). When questions arose and gaps in the categories appeared, data was sought that answered the questions and might fill the gaps (Charmaz, 2006). Examples with ambiguity tested the validity of the definition and delimitation of each category. Hypothetical digital systems were even concocted as thought experiments. Thus, initial attempts at definition became increasingly nuanced. Diagrams, theoretical memos and sticky notes were used to describe and develop the categories, and understand their properties and dimensions, leading to the development of the classification and underlying conceptualisations. Charmaz states that diagrams can enable you to see the relative power, scope, and direction of the categories in your analysis as well as the connections among them (Charmaz, 2006).

Many iterations of terminology were experimented with, as detailed in Table 65, in the Appendix. As well as using terms from the data itself, the thesaurus was used regularly to find terms with the following advantages: a strong relationship between the concept and the popular understanding of the term; that people are sufficiently able to interpret the meaning without prompting; avoiding confusingly ambiguous secondary meanings in popular usage; and consistency across the classification.

4.3 EVALUATING THE CLASSIFICATION

A set of criteria was developed to assess the effectiveness of the classification, and qualitatively assessed for the SGM as a whole and for each of its dimensions, as summarised in the Conclusions Chapter. The criteria are: **exhaustiveness, mutual exclusivity, utility for practitioners, utility for researchers** and **originality.**

Bailey states that the *"only basic rule [of categorization is] that the classes formed must be both exhaustive and mutually exclusive."* (K. D. K. Bailey, 1994). The classification must also be original, as should any contribution to knowledge.

Utility was assessed for two major groups of target users - practitioners and researchers – and according to the potential benefits identified during the international conversation with cleanweb specialists (Section 3.4.2): **raising awareness of the sector's existence**; **helping startups, investors and other stakeholders coordinate;** and enabling **quantitative comparisons** between markets and fields. The assessment of utility to the target communities completes the largest cycle of Action Research.

4.4 LIMITATIONS

Secondary analysis of crowdsourced Internet open data is a relatively new method. Carmichael states that secondary data analysis may be less established in qualitative, rather than quantitative research due to greater concerns of misinterpretation and data sharing (Carmichael, 2008). Charmaz states that Internet research offers endless opportunities for textual analysis, but poses enormous methodological issues of provenance, context, and the intention and profile of the authors (Charmaz, 2006). However, this contextual limitation is not significant for this investigation because the results are so abstracted away from the original data that they do not depend significantly on the motivations and identity of the authors who created them. Also, the high level of participation in these communities provided the context to interpret them effectively.

CrunchBase data is a crowdsourced, although edits are moderated by TechCrunch employees. This may limit accuracy. However, it is possible for crowdsourced data on popular open websites to be higher quality than data curated by traditional commercial methods, because there is a constant process of revision by "many eyes". One celebrated study found that the accuracy of science pages on Wikipedia was close to that of the traditional Encyclopaedia Britannica (Giles, 2005). Papers have been published in a number of disciplines using Crunchbase data (Xiang, Zheng, Wen, Hong, & Rose, 2005), and Techcrunch has published some analytical evidence that the coverage of Crunchbase data matches or exceeds that of rival providers (Gallagher, 2013).

This was a convenience sample; the qualitative nature of this research made representative sampling less important than with quantitative research. Both environmental sustainability and digital systems are complex and contested concepts. There was an inevitable subjectivity of the sampling process due to the contested nature of sustainable development manifested in "grey areas" of sustainability, where the positive or negative consequences for sustainable development are controversial, such as for organic food, nuclear energy, genetically-modified food, and efficiency of private road transportation. However, the ultimate dimensions of the resulting SGM classification make these decisions inconsequential.

Many of the principles of GT have proved useful, but the methodology has gone beyond the purview of GT in a number of ways.

GT has been developed to theorise lived **human experience** such as terminal illness, drug addiction or leadership stress. GT produces constructivist theories of social reality (Charmaz, 2006). There is a social dimension to this investigation; indeed one of the produced dimensions, the Enablers, precisely describes the social variation in digital systems. However, what the Enablers distinguish is a very basic level of sociality based on micro-scale models that are mechanistic and universalist. Neither are these models purely "grounded" in the qualitative data, and they barely touch on the subjective experience of creating and using digital systems. There is some similarity between GTs analysis of the behaviour of participants in resolving their main concerns, and the tentative core variables of "web approach" (behaviour) and "sustainability outcome" (main concern) that are developed into the two axes of the classification.

In GT, the researcher aims to free themselves of preconceptions in the collection and analysis of data, ignoring the **existing literature**. (Glaser & Strauss, 1999) This investigation began with literature review and has not tried to ignore existing literature. However, it has allowed the emerging theory to determine which interdisciplinary literature is worth exploring further. Indeed, the field of ICT4S was emerging in parallel with the investigation.

GT recommends not to talk about interim results to prevent contaminating the developing theory, but interim results of this investigation were presented to different audiences to gain feedback.

4.5 SUMMARY

This chapter introduced the qualitative method by which the typology of cleanweb systems is developed. This method aims to crowdsource the ingenuity of digital startups, in order to sample the space of opportunities for ICT to address environmental sustainability, and thus to generate original insights that advance ICT4S theory. This exploring of the space of possibilities via proxies is analogous to mapping out the road network by recording the movements of the cars. The overall classification development methodology, shown in Figure 21, integrates a number of approaches, notably some principles of GT, to gather data, code it, and develop the classification categories and underlying functional models. An evaluation framework was identified that the classification development could aim towards.

CHAPTER 5 THE ENABLERS: DISTINGUISHING THE SOCIAL VARIATION BETWEEN DIGITAL SYSTEMS

5.1 INTRODUCTION

This chapter continues the qualitative empirical investigation of the main research question: **how can Sustainability by ICT systems be classified effectively and usefully**? A conclusion of the AR and literature review of Phase 1 was that leading conceptualisations of Sustainability by ICT do not sufficiently account for the wide **social variation** observed between cleanweb systems such as Sharing Economy platforms.

This chapter applies the qualitative classification development methods of Chapter 4 to develop the Enablers, a three-category typology distinguishing the social variation in Sustainability by ICT systems. The Enablers address the question of **how DDS combine people and digital technology,** and a model of their function is developed as a **conceptual basis for the observed variation in DDS**. This three-category Enablers typology forms a dimension of the Smart Green Map in its first version, the SGM1. This is an interim result, which will be refined in Chapter 8 into the final four-category Enablers typology. The other dimension of the SGM1, Decoupling Directness (DD), will be derived in the following chapter concluding Phase 2.

Section 5.2 details the derivation of the initial Enablers classification from company description data. Section 5.3 then models the function of a digital system as Enabling Impact Chains (EICs), from which the distinction between these three Enablers can be defined. The concept of a digital system is developed to include both billion-user social networks and individual pieces of digital hardware, allowing both be classified together. Section 5.4 uses the Enablers typology to organise DDS, showing that it can be a useful way of thinking about Sustainability by ICT. The section argues that the dominant themes of ICT4S research and practice can be understood as the application of these three forms of enabling effect. Section 5.3 then steps back from the specific challenges of sustainability within ICT4S. The section describes the disciplinary context of each Enabler, illustrated with images from reality and fiction, arguing that the Enablers are generic properties of all ICT (Figure 29, Figure 30 & Figure 31). The discussion Section 5.6 deduces whether the Enablers are exhaustive and mutual exclusive from the developed definition, and develops a simple mechanistic model of their function, the Enabling Impact Model (Figure 35).

5.2 RESULTS

This section describes the derivation of the Enablers classification from the initial codes relating to "web approach".

5.2.1 WEB APPROACH: CONNECTING ACTORS VS GATHERING AND ANALYSIS

Codes relating to "web approach" for each company captured **how the combination of digital technology and people achieve the sustainability benefit.** The web approach codes are shown in Table 62 in the Appendix. The initial web approach codes were sorted and resorted until commonalities could be identified between them from which a first version of higher-level concepts was developed, shown in the left column of Figure 22.

Concepts	**Categories**
Data Analysis and Dissemination	Gathering and analysis
Sensors and Controllers	
Behaviour Change	
Telepresence	
Knowledge Dissemination	Connecting actors
Community Sourcing	
Connecting People	
Related services	N/A

Figure 22 Web approach concepts and categories

Further sorting and grouping of these concepts lead to the identification of two high level categories into which all the concepts within the research scope appeared to fit (Figure 22 right column). Examples from the CrunchBase company descriptions that helped identify these two categories are shown in the columns of Table 23.

- **Gathering and analysis** – one major group of "web approach" concepts related to using digital systems to analyse data. They included "optimisation algorithms", "data visualization", "designing", "decision support systems", and "resource planning". These systems gather data, often about a resource such as energy, or about the environment. They provide insight based on data to inform more effective action.

- **Connecting actors** – the other major group of concepts related to using digital systems to broker relationships between people and help them communicate. These included "Crowdsourcing", "Peer-to-peer", "Marketplaces", "Collaborative consumption", "videoconferencing" and "Social networking". These codes were assigned to the concept "communities", which was further refined into the top-level category "connecting actors".

	CONNECTING ACTORS	GATHERING AND ANALYSIS
RESOURCE EFFICIENCY	"…supports a number of crowd-sourced data collection projects, which allow users to actively engage with transport provision in exciting new ways." "…at the core of our business is a belief that there are disconnects between demand and supply between transport users and providers, and if this can be improved, then significant savings can be generated." "…is a peer-to-peer Internet video and voice calling service that offers free calls." "…the first and leading peer-to-peer carsharing marketplace…"	"…offers a unique User Engagement platform for interpretation, visualization and control of Smart Home and Metering applications." "Energy monitoring tools enable this data to be visualized via web portals, wall-mounted devices or iPhone applications in a consumer-friendly and trendsetting way." "territorial and environmental planning, network management and maintenance for roads, water [and] electricity …"
CLEANTECH CATALYSTS	"…is a business community providing insight, orientation, and opportunities for the CleanTech community." "…crowd-funding platform that brings people together to back great ideas with money and support… So far £40k has been raised in 6 days by a Bicycle Academy…" "first car-sharing service company … with Nissan automobiles Leaf (100% electric)"	"an online suite of knowledge driven decision support services based on knowledge extraction from historical and real-time worldwide news and information sources. The initial focus is on risk reduction for large, costly, complex, high risk, cross disciplinary projects such as renewable energy and sustainability." "an independent website about rail travel to ski resorts… it contains extensive information about train journeys [and] advice on how to find the lowest fares"

Table 23 Examples of company description data upon which were based the "connecting actors"/"gathering and analysis" distinction (in this chapter) and "resource efficiency"/"cleantech catalysts" (in the next chapter).

This distinction was used as the vertical axis of Figure 24, a matrix mapping out examples of DSS for a conference paper (Townsend, 2014).

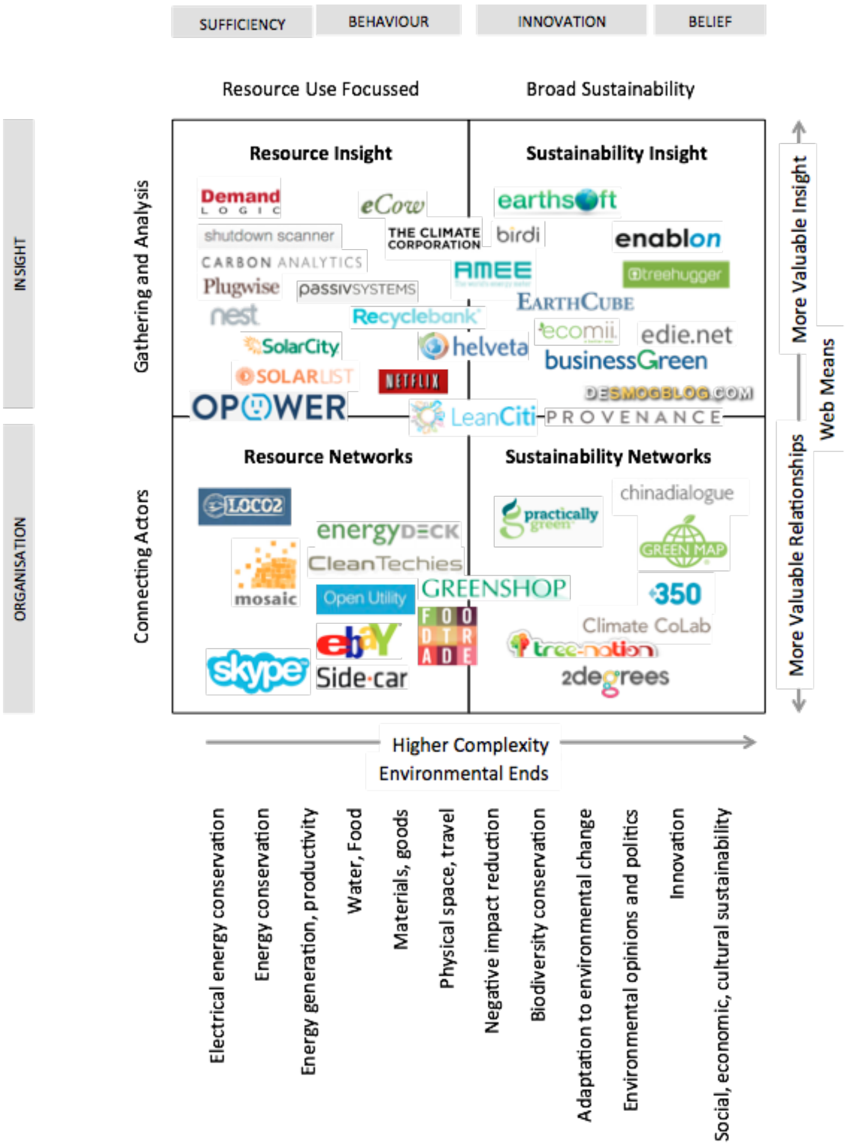

Figure 24 A first attempt at a map of Sustainability by ICT systems employing the distinction in "web approach" codes between "connecting actors" and "gathering data" as the vertical axis ("web means"), as described in this chapter. The horizontal axis distinguishes the "sustainability outcome codes" between resource-use focussed systems (DDS) from "broad sustainability" systems (other DSS), as discussed in the following chapter (Section 6.2.2).

5.2.2 OVERLAP LEADS TO IDENTIFICATION OF THIRD CATEGORY: GUIDING

Considering the target criteria for the classification (Section 4.3), the dichotomy between "gathering and analysis" and "connecting actors" appeared exhaustive, but not sufficiently distinct and thus mutually exclusive. Data is gathered and analysed in categories such as "Behaviour Change", "Knowledge Dissemination", "Community Sourcing", but they are also about people, and therefore seemed to sit at the intersection of the two categories (Table 62). Gathering and analysis of data is also performed by "connecting actors" systems, except that the subject of the data is primarily the network of actors themselves, rather than some resource such as energy, or the environment. For instance, rail ticket sales site Loco2[74] relies on the generation of insight about not just the train system, but about the companies that sell tickets, and about the needs of its users.

The category "gathering and analysis" appeared a miscellaneous category for all those systems that were not "connecting actors", with little conceptual consistency. Two contrasting types of systems were identified within the category:

- Systems near the top of Figure 24 are characterised by limited human involvement. The ICT "provides" the required action itself, with little effort required of a human except to set the parameters for success. For instance, the Google Nest smart thermostat efficiently heats the home by optimizing a personalised heating schedule automatically without the need to program the device, thus reducing the cognitive effort for the customer.

- Many systems placed near the middle of Figure 24 involve an actor interacting with an ICT but not primarily to connect with other actors. They operated as individuals, and the ICT supported and guided them. For instance, SolarCity's online solar planner helps individual household's estimate their capacity generate solar energy profitably, in part by measuring the roof area of the house using aerial imagery.

For these reasons the "gathering and analysis" category was divided, to describe the data more fully with three categories. Different terminology was tried, resulting in the first version of the three Enablers:

- **Providing,** the automatic part of "gathering and analysis".

- **Guiding,** the human-facing part of "gathering and analysis".

- **Connecting**, previously "connecting actors".

[74] https://loco2.com/

5.2.3 UK DATA ANALYSIS AND DEVELOPMENT OF DIGITAL GENRES

Around 200 companies were coded in the initial analysis of the most relevant companies on CrunchBase. Reflecting the content of the database, these were primarily US companies. An opportunity arose to contribute to a report on the British cleanweb industry (Masero & Townsend, 2014). To do so a set of around 200 British cleanweb companies were identified. To the British examples identified from CrunchBase were added various companies individually identified by co-author Masero – a leading figure within the UK Cleanweb industry. The initial codes and concepts identified during the first analysis were consolidated, refined and added to, to create the more granular level classification below the three Enablers, termed “digital genres”. The list of digital genres continued to grow as new examples were encountered of companies, systems and research.

Table 25 shows the major digital genres identified after this process. The scope of Table 25 is limited to “sustainable resource use” i.e. to DDS or cleanweb systems as discussed in the following chapter (Section 6.2.2 & 6.3.1). The identification of new digital genres became harder as saturation was approached, with most uncategorized companies relating well to existing codes.

CONNECTING	Collaborative funding e-Marketplaces and directories Job listings Community adoption Offers and discounts Sales team coordination Redistribution markets Ratings and comparison Peer-to-peer rental and sharing Redistribution markets Social Behaviour Change and gamification Teleconferencing Efficient virtual services Distributed autonomous corporations (EICs)
GUIDING	e-Marketing and advertising Customisation, installation planning CRM and services e-locks and access control Recommender systems Cleantech diagnostics Sales gamification Cleantech knowledge-bases Resource behaviour feedback Efficiency diagnostics Individual Behaviour Change & gamification Business intelligence & process management Real-time user guidance and navigation Knowledge-bases for efficiency
PROVIDING	Auto cleantech optimization Cleantech user control Maintenance and manufacture drones and robots Installation assessment drones and robots Automated resource optimization Robotics and drones for efficiency Efficient distributed manufacturing Resource user control Dematerialised content Efficient crypto-currency

Table 25 Identified "digital genres" relating to each of the three Enablers

5.2.4 CONCEPTUALISING ENABLING IMPACT

The three categories were identified empirically from qualitative data, and characterised by gathering notes into memos. A conceptual basis was sought to explain the observed variation, a simple model that could distinguish the three modes. Comparing the categories it was noted that two of the three Enablers involved a human actor, whilst "providing" did not. A number of questions were considered whilst seeking a conceptual model. What does a guiding system influence an actor to do? What is it that a "connecting" system links an actor to? What does a "providing" system do on an actor's behalf? The result appeared to be the adoption of an opportunity to be sustainable. The concept of a "sustainability opportunity" offered a conceptual basis to distinguish the Enablers, resulting in the Opportunity Model (Figure 26), a significant milestone towards a parsimonious model.

Figure 26 The Opportunity Model that provided the first conceptual basis to distinguish the three types of digital system.

Nevertheless, a conceptual issue was later identified with the Opportunity Model: it does not distinguish unambiguously between guiding an actor towards an opportunity, and finding the opportunity and connecting the actor with it. To resolve this, the concept of "digital action" was developed. Instead of the concept of a "sustainability opportunity", the goal of the actor or digital system is an action that the digital technology helps them undertake individually or collectively. Digital action was later equated with the concept of "enabling impact" in the LES Model (Section 2.3.3), actions enabled by the application of ICT.

The concept of enabling impact (digital action) allows connecting and guiding to be distinguished more rigorously: "connecting" entails the collective action of more than one actor together by brokering their relationship via digital technology; "guiding" entails "augmenting" the action of an individual actor with digital technology; whilst "providing" entails "artificial" action by a machine i.e. with little effort from the human actor. The modified conceptualisation of the Enablers based on the concept of enabling impact is shown in Figure 27.

Table 65 in the Appendix captures the various iterations of terminology employed during the development process. The term "enablers" was ultimately selected to align with the enabling impacts of the LES Model (Section 2.3.3). The company descriptions included many terms relating to "intelligence", such as "smart cities", "smart homes", "artificial intelligence", and "intelligent transport systems". The "providing" category could be associated with artificial intelligence as it was about the ability of the digital technology to be intelligent without people. A similar parallel was identified between "connecting" and "collective intelligence", a prominent theme of digital research. Drawing on the concept of "augmented reality", "guiding" could similarly be associated with an "augmented intelligence" where the digital technology supports and influences an individual person. The terms "artificial", "augmented", and "collective" were thus adopted for the next version of the Enablers, as presented in Figure 27 and Figure 34.

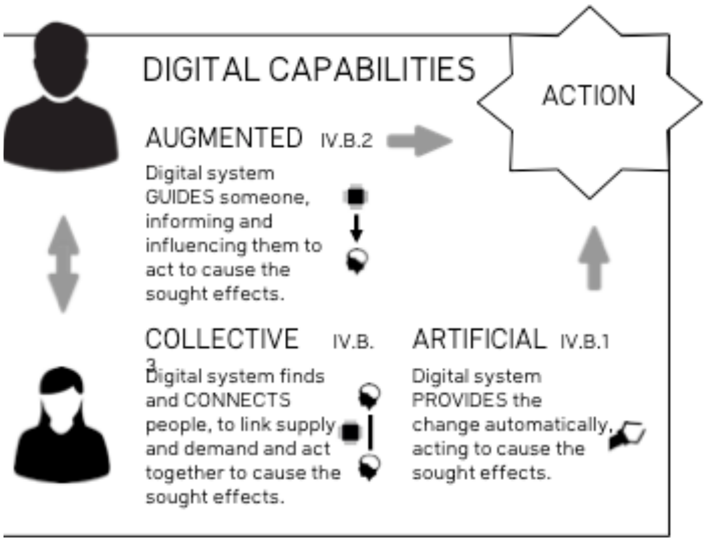

Figure 27 Three enablers theorised as three ways of driving digital action/enabling impact.

5.2.5 DEFINING THE PHENOMENON OF STUDY: THE DIGITAL SYSTEM

The companies identified from the CrunchBase data produce a wide variety of digital products ranging from tiny components such as sensors, to vast social networks. How could these all be understood as a single class of phenomena, and what should that phenomena be called? What defining feature did these entities share as a category? The Masters thesis used the clumsy expression "the Web and Related Technologies". All the entities contained hardware that processed digital information. However, some are enormously complex social machines that are emergent from relatively simple digital hardware. These social machines are characterized by their many human participants, as well as their technology. The ICT4S community uses the term "ICT", but this arguably overemphasises the devices rather than the complex sociotechnical systems they enable. On the other hand, the term "social machine" from Web Science does not apply to simple technical components.

The most obvious characteristic that all these systems share is the employment of information in digital form. The term "digital" is also used widely to describe the "digital industry". "Digital" However, is just an adjective, what was the noun? As this was commercial data, these were almost all products. However, the categorization being developed was not purely commercial, so "digital product" was too limiting a term. The term "solution" was common in the company description later, and is broad enough to describe great range of phenomena from micro component to global social machines, which was why it was adopted for the cleanweb definition (Section 6.3.2). However, “solution” lacks a precise meaning, and is sometimes disparaged as a term[75].

The term “system” was chosen as it is both generic and scientific. It is fully applicable, as all these phenomena are a “regularly interacting or interdependent group of items forming a unified whole”[76] It brings a relevant history of connotations, from systems theory and many other disciplines and related fields such as control theory, systems thinking, complex adaptive systems, and cybernetics. The term chosen for the phenomena of interest was therefore “digital system”. Unfortunately, the term “digital system” does have a history of use to describe digital electronics in a purely technical sense, which is different from the meaning developed here.

To clarify the concept of the digital system in order to analyse it, a model was developed. This began by analysing the components that make up a digital system, of which two types were identified:

- Technical hardware that is able to process digital information directly i.e. ICT itself. Or some other device that is controlled by an ICT, such as a modern car engine that is controlled by an Engine Control Unit. All these were termed “**digital devices”.**
- Digital systems often involve people, sometimes in large numbers. These people interact with the rest of the system via some digital device with an interface, such as smartphone. They can act as individuals or as part of an organisation. These were termed **“human actors”.**

From these observations, it was possible to construct the simple model of a digital system in Figure 28. It has two types of component: digital devices and human actors. The devices interact via digital information flows, and interact with the human participants and the systems’ environment – which may include people, the natural environment, or resources such as heating in the home. The people interact with the digital devices and with the rest of their environment.

The Enablers were ordered and reordered, identifying a clear progression of increasingly social digital systems. They were also renamed, again:

1. **Automation** (providing), because the digital technology undertakes the enabling impact without people.

[75] Wikipedia: On Wikipedia, solutions are mixtures and nothing else https://en.wikipedia.org/wiki/Wikipedia:On_Wikipedia,_solutions_are_mixtures_and_nothing_else
[76] http://www.merriam-webster.com/dictionary/system

2. **Augmentation** (guiding), because the action involves individual people not connected to others through the system.

3. **Coordination** (connecting), because it involves multiple people connected together through the system.

An analysis of the sequence of events that occur within typical digital systems helped explain this spectrum of increasing sociality. The digital action/enabling impact of the digital system could be modelled as the interaction of digital device, human actor and environment. These chains of action and interaction were termed "enabling impact chains"(EICs) (see Appendix for examples). Considering the EICs that relate to the three Enablers offered a simple quantitative means to distinguish the Enablers, and also to prove the mutual exclusivity and exhaustiveness (Section 5.6.1). The number of human actors in a typical EIC could be defined as: 0 for automation, 1 for augmentation, and many for coordination.

5.2.6 CLASSIFYING THE ACM CCS WITH THE ENABLERS

A comparable classification of digital systems was sought for comparison with the Enablers model. The ACM Computing Classification System (CCS) (2012) is a subject classification system of the field of computing devised by the Association for Computing Machinery (ACM). The ACM CCS was first published in 1964, and last updated in 2012 with many new categories focussed on social computing i.e. coordination. The classification has 13 top-level categories and many subtaxa in a four-level hierachy. Each category references recent literature, although there is little literature logged for those added in 2012.

As the ACM CCS is a taxonomy with numerous categories, whilst the Enablers are a typology with only three categories, they are not directly comparable. However, as a limited test of the three Enablers classification, they were used to organise the categories ACM CCS. The top-level categories could be categorised amongst the Enablers as follows[77]:

- Understandably for a computer science categorisation, most top-level categories relate most strongly to **automation** and the digital hardware and software that enables it ("Hardware, Computer systems organization", "Networks", "Software and its engineering"). A number of top-level categories are primarily focussing on automation aspects but also contain some of the other three enablers ("Information systems", "Security and privacy", "Applied computing").

[77] All quotations from ACM Computing Classification System (CCS) (2012)

- One top-level category ("Human-centred computing") fits directly with **augmentation**, relating to the field of Human-Computer Interaction. Also, within "Security and privacy" is "Human and societal aspects of security and privacy", and within "Applied computing" and then "Education" is "E-learning, Computer-assisted instruction, and Computer-managed instruction".
- One subcategory of "Human-centred computing" relates very directly to **coordination** ("Collaborative and social computing"). Also, within "Security and Privacy" and then "Human and societal aspects of security and privacy" there is "Social aspects of security and privacy", and within "Applied computing" there is "Electronic commerce", as well as "Education" in which there is "Collaborative learning".
- The remaining top-level categories (and a many of the subcategories across the whole categorisation) are about the **theory and practice of creating digital systems** in general rather than specific digital systems (Computing methodologies, Theory of computation, Mathematics of computing), or are about computer science as a community and entire academic field (Social and professional topics, and General and reference).

The types of digital system described by the ACM CCS could be readily classified into the three Enablers and the structure of the ACM CCS does significantly reflect the three Enablers, such as the distinction between "Hardware, computer systems organization", "Human-centred computing" and "collaborative and social computing".

5.3 THE EIC MODEL

This section defines the three Enablers derived empirically above with the EIC conceptualisation of the function of digital systems. Sections 4.2.6 and 5.2.4 describe the conceptualisation development method.

5.3.1 DEFINITIONS

This section presents a series of definitions that model the enabling impact of digital systems as Enabling Impact Chains (EIC).

An **action** is purposeful change, change that occurs in order to achieve some goal. It is “the process of doing something, especially when dealing with a problem or difficulty”[78].

A **human actor** is an individual person or group of people acting together as single unit, such as an organisation.

A **device** is an "object or machine that has been invented for a particular purpose.”[79] It is non-human and has been shaped by humans. They are generally composed of other devices.

Digital information is information expressed as 0s and 1s and readable by an electronic device.

Digital devices are devices that contain ICT hardware and software able to send, receive and use digital information, and potentially to control a non-digital device. They may be made up of component digital devices, and also component non-digital devices, which they control.

Non-digital devices are devices that are not able to send, receive and use digital information. They may have moving parts and operate mechanically i.e. they may be a machines. They can be controlled by digital devices.

A **digital system** is a system that can perform an action, composed of a group of digital devices mediated by digital information and the human actors that use them, if any. All the digital devices within the digital system form a single contiguous network of digital information flows (not via a bridging human being). This is shown in Figure 28. The concept of a digital system is similar to that of an ICT.

The **components of a digital system** are the digital devices and any human actors within the digital system. They interact through flows of digital information or via an interface with a digital device to a human. The human actors interact with the digital components in the chain; they both act upon digital devices and are acted upon by them. A particular digital device or human can be a component in many different digital systems simultaneously.

[78] http://dictionary.cambridge.org/dictionary/english/action
[79] http://dictionary.cambridge.org/dictionary/english/device

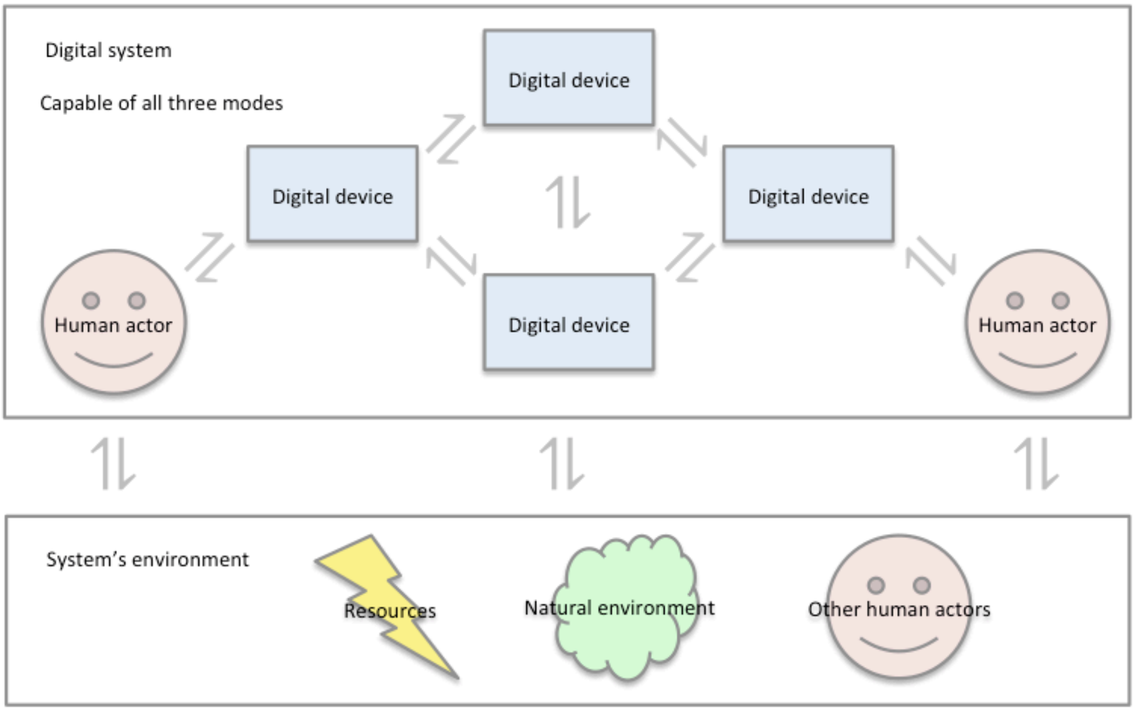

Figure 28. Model of a digital system. This digital system functions through three Enablers: automation (devices only), augmentation (one actor only), and coordination (two or more actors interacting).

Enabling impact is any and all action of a digital system. It is goal-directed change that is enabled or mediated by digital information. It is how the digital system purposefully acts upon its components and the environment. A particular digital system can undertake a range of enabling impacts. Enabling impact is the application of a digital system. Hilty & Aebischer define enabling impacts as "actions enabled by the application of ICT" (L. Hilty & Aebischer, 2014).

Enabling impact chains (EICs) are the causal chains of actions and interactions between components of a digital system that together make up the resulting gestalt enabling impact. All enabling impact is therefore created by EICs. These chains of interaction are symbolised on Figure 28 with arrows. A particular enabling impact can be caused by multiple enabling impact chains. The Appendix gives examples of EICs for each of the Enablers.

N is the number of human actors interacting within a particular enabling impact chain. N is therefore a positive integer.

The **typical EIC** is the EIC most representative of a particular enabling impact or digital system. This could be the most frequently undertaken EIC. As a particular digital system can undertake multiple enabling impacts, and each enabling impact can entail multiple EICs, determining **N** for a particular digital system (or action) requires the typical EIC to be identified, which requires interpretative prioritisation. An alternative approach to classifying a digital system or action into just one enabler through interpretative prioritisation, is to consider all the various EICs of that digital system or enabling impact, and classify them each by enabler, thus building up a full picture for the one system across all three Enablers. This is employed by the investor in the case study (Chapter 7).

The **enabler** of a particular EIC is automation if N=0, augmentation if N=1 and coordination if N>1. To identify the enabler of a digital system or action requires the identification of its typical EIC.

Automation is any EIC for which N=0, and any enabling impact or digital system whose typical EIC has N=0. **Augmentation** is the equivalent for N=1, and **Coordination** for N>1.

5.3.2 PREMISES

Underlying assumptions include the following.

There are three types of entity that can undertake action: human actors; devices; and non-human organisms, although these are not considered in this model.

The world can be modelled as human actors, devices and their environment (i.e. everything else that cannot undertake action).

Human actors and devices are able to interact with each other and act on their environment.

A typical EIC can be identified that is most representative of a particular digital system or enabling impact. This may require interpretive observation by an observer.

5.4 THE ENABLERS IN ICT4S

This section argues that the Enablers typology is a useful and effective way of organising DDS and thus thinking about Sustainability by ICT. This suggests that the dominant themes of ICT4S research and practice can be understood as the application of the three forms of enabling impact. For each Enabler, this section describes the most active areas of research and entrepreneurship and the conceptualisations of ICT4S that distinguish that enabler.

The areas of research and entrepreneurship are based on the "submarkets" identified empirically in Chapter 8 (Table 44, Figure 45). Chapter 8 classifies recent samples of literature from ICT4S conferences and of cleanweb startups from the Ecosummit conferences. A full catalogue of the literature and startups classified with the SGM is presented in Table 52.

A full analysis of strategic conceptualisations of ICT4S is presented in Chapter 9 and pre-empted here (Table 58). It identifies five overarching themes.

5.4.1 AUTOMATION FOR SUSTAINABILITY

The LES Model distinguishes the **technological level** from the human level of process optimisation. *"Process optimisation can occur either at a level where people are involved (e.g. organisational changes in production, behavioural changes in consumption) or at a purely technological level by making physical changes"* (L. Hilty & Aebischer, 2015). The technological level appears equivalent to automation because it is about technology acting without the involvement of people, through digital devices alone i.e. ICT hardware and software.

ICT4S research into automation for sustainability has primarily focussed on **resource computation**, the term used here for the analysis of large data sets about the production and consumption of resources, using sophisticated computational techniques often referred to as **big data**, **data science** or **data mining**. Resource computation underlies many other categories of DDS, but this category emphasises the analysis itself rather than a particular action that it will enable. Some ICT4S papers have presented data sets for use by future researchers (Pereira, Quintal, Gonçalves, & Nunes, 2014) or data standards to structure future work (Reznik et al., 2015). Some papers have described analyses of domestic heating use (Tabatabaei, Thilakarathne, & Treur, 2014), product life cycle assessment (Capitanescu, Igos, Marvuglia, & Benetto, 2015), agriculture (Reznik et al., 2015) and waste management (Shahrokni & Heijde, 2014).

Other forms of automation have been the subject of much entrepreneurship but more limited research, including **consumption auto-optimization**, **usage automation** and **automated resource coordination** systems. **Consumption auto-optimization**[80] is used here for those digital systems that actively and autonomously improve efficiency by controlling resource use for a consumer. Many cleanweb companies create such systems to control domestic heating in the **smart home** (e.g. Nest[81], Tado[82], OpenTRV[83]). Other applications optimise energy storage in a domestic battery (e.g. Sonnenbatterie[84]) or water use whilst showering

[80] **Consumption auto-optimization** is referred to as the "Automatic Optimisation" submarket in Chapter 8.
[81] https://nest.com/
[82] https://www.tado.com
[83] http://opentrv.org.uk/
[84] https://sonnenbatterie.de/

(e.g. Hamwells[85]). ICT4S papers have also investigated the automation of home heating (Alan, Shann, Costanza, Ramchurn, & Seuken, 2015) and of lighting systems (Al-Anbuky, 2014).

Usage automation systems also automate the usage of a product, but it is some form of “cleantech” and that is how they benefit sustainability. They are “push systems” (Chapter 6). For instance, the startups Siqens[86] and Ubik[87] are automatically optimising small-scale renewable energy generation, whilst Tesla[88] and Tevva[89] optimise the motors of electric vehicles and the routes they follow.

Another prominent form of automation is **automated resource coordination** such as **aggregators of supply or demand-response** associated with the **smart grid** e.g. Sympower[90] (Sonnenschein et al., 2015). These are even better classified with the four Enabler typology identified in Section 8.4.4 as **autination systems**.

5.4.2 AUGMENTATION FOR SUSTAINABILITY

Augmentation involves individuals, unlike coordination that involves multiple interacting people. The human level of process optimisation within the LES Model is either augmentation and coordination for sustainability, *“where people are involved (e.g., organizational changes in production, behavioural changes in consumption)”* (L. Hilty & Aebischer, 2015). Zapico similarly identifies **behavioural change** as a major theme of ICT4S (Jorge Luis Zapico, 2013).

There has been much ICT4S research into augmentation for sustainability, largely concentrated in three areas: **consumer behaviour optimisation, resource administration** and **individual media substitution**.

Consumer behaviour optimisation is when digital technology gathers information about the resources controlled by an individual consumer, their behaviour, their possessions and their environment. This information is then used to support, inform and influence them to use resources more efficiently, preventing waste, saving costs and reducing the environmental impact. The large amount of research into **consumer behaviour optimisation** made it the largest submarket in the comparison of Chapter 8[91] (Figure 45). Within the LES Model, consumer behaviour optimisation is, unsurprisingly, behavioural optimisation at the level of the individual consumer.

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[85] https://www.hamwells.com/
[86] http://www.siqens.com/solutions/
[87] http://www.ubiksolutions.eu/technology
[88] https://www.tesla.com/
[89] https://www.tevva.com/
[90] https://www.sympower.net/
[91] Consumer behaviour optimisation is referred to as “individual behaviour change” in Chapter 8.

Following the work of Fogg (2003), **persuasive technologies** have been a popular tool for consumer behaviour optimisation (Costanza, Bedwell, Jewell, Colley, & Rodden, 2015; Jakobi & Stevens, 2015a; Katzeff & Wangel, 2015). Di Salvo *et al.* found that persuasive and ambient awareness made up 70% of SHCI research papers in 2010 (Disalvo et al., 2010). A common method of persuasion has been **gamification** of behaviour change. Cleanweb startups have applied gamification techniques to home energy consumption (Opower[92]), driving (Dash[93]), cycling (Changers[94]) and recycling (RecycleBank[95]) (Huber & Hilty, 2015; Jia, Xu, Karanam, & Voida, 2015; Weiser, Bucher, Cellina, & De Luca, 2015). Another approach have been **travel planning and navigation tools** such as CityMapper[96] (Nyblom & Eriksson, 2014).

Resource administration systems support, inform and influence an employee to employ their organisation's resources more efficiently (Gomez & Teuteberg, 2015; Rizzoli, Montemanni, Bettoni, & Canetta, 2015; Stefan & Letier, 2015). Resource administration is also behavioural optimisation and works similarly to consumer behaviour optimisation but at a larger scale. Cleanweb startups have created systems for **supply chain management** (AMEE[97]), **carbon accounting** (Carbon Analytics[98]), **agricultural optimization** (CropX[99]) **building management systems** (BMS systems e.g. Demand Logic[100]), and **Environmental Health & Safety management** (EHS systems e.g. Intelex[101]).

An alternative mechanism to process optimization in the LES Model is **media substitution**, which replaces the material medium of an immaterial resource with a digital electronic medium e.g. replacing a paper book with an e-book. This process is also termed "substitution" in the Three-Levels model and is often called "dematerialisation" (Berkhout & Hertin, 2004; Fuchs, 2008). Like process optimisation, media substitution can also occur through each of the three Enablers.

Individual media substitution[102] is the form of media substitution that works through augmentation. Zapico (2013) describes "dematerialisation of culture and knowledge artefacts" such as music, books, magazines and journals, which can now be downloaded

[92] https://www.oracle.com/industries/utilities/products/opower-energy-efficiency-cloud-service/index.html
[93] https://dash.by/
[94] https://changers.com/
[95] https://www.recyclebank.com/
[96] https://citymapper.com/
[97] https://www.amee.com/
[98] http://www.co2analytics.com/
[99] https://cropx.com/
[100] https://www.demandlogic.co.uk/
[101] https://www.intelex.com/
[102] Individual media substitution is referred to as "publications and broadcast" in the comparison of Chapter 8 (Figure 45).

online in purely digital formats. "Dematerialization" in this sense is also distinguished by Mitchell (1999) and Pamlin & Pahlman (2008). Notable companies include Amazon's Kindle[103] e-books, video-on-demand streaming service Netflix[104] and music streaming service Spotify[105]. Some of the ICT4S papers examined in Chapter 8 address individual media substitution, but not many of the cleanweb startups at Ecosummit (Arushanyan, Moberg, Nors, Hohenthal, & Pihkola, 2014; Coroama et al., 2015; Delanoe, Chavalarias, & Anglade, 2014).

Three other submarkets comprise considerable cleanweb entrepreneurship, but only limited research within ICT4S: **design tools** (e.g. building efficiency tool Sefaira[106]), **marketing and choosing systems** (e.g. solar rooftop assessment tool Sungevity[107]) and **usage monitoring and guidance systems** (e.g. optimised solar-powered internet booths SolarKiosk[108]). Further augmentation submarkets are identified empirically in Chapters 8, and many more by the SGM3 in Chapter 9.

5.4.3 COORDINATION FOR SUSTAINABILITY

Coordination is distinguished from augmentation because these systems involve multiple interacting users. ICT4S research into coordination appears highly focussed on just one area, **social behaviour change**, which is the multi-user equivalent of individual behaviour change. The move from individual to social behaviour change within ICT4S has been noted by Huber & Hilty, who suggest that behaviour change research should now "introduce the social level" and "enable collective action" (Huber & Hilty, 2015). This demonstrates the need to separate coordination from augmentation in the Enablers.

Kamilaris *et al.* also describe the emergence of more social behaviour change technlogy. *"Numerous green online social applications have emerged in recent years, aiming to motivate citizens towards pro-environmental behavior. These applications exploit emerging new technologies, such as mobile computing, online social networking and the web, in order to affect their users in their everyday lives."* (Kamilaris, Pitsillides, & Fidas, 2015). Social behaviour change has been investigated for building energy use (Denward, de Jong, & Olsen, 2015), car use (Hasselqvist, Hesselgren, & Bogdan, 2015), renewable energy (Ferrario, Forshaw, Newman, Simm, & Friday, 2014) and food consumption (Kuznetsov, Santana, & Long, 2015).

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[103] https://www.amazon.com/Kindle-eBooks/
[104] https://www.netflix.com/gb/
[105] https://www.spotify.com/us/
[106] http://sefaira.com/
[107] http://www.sungevity.com/
[108] http://solarkiosk.eu/

None of the major strategic conceptualisations of ICT4S clearly distinguish between coordination and augmentation for process optimisation. However, several make the distinction for media substitution, distinguishing individual media substitution from **social media substitution,** also termed "telepresence" (Jorge L. Zapico et al., 2010), "demobilisation" (W. Mitchell, 1999), "smart work", "telework" (Pamlin & Pahlman, 2008), and "virtual networks" (Chapter 8). Social media substitution is *"moving bits instead of moving people and goods"* (W. Mitchell, 1999). This recognition of the distinction between individual and social media substitution validates the separation of coordination from augmentation in the Enablers typology.

The distinction between coordination and augmentation in media substitution is also clearly made by Coroama *et al.* (2015) who divide "*The media sector as the traditional domain of unidirectional media, delivering content in one direction, usually from one sender to many receivers"* from *"Videoconferencing as an application of bidirectional (or multidirectional) media, connecting two or more people in either direction."* Coroama *et al.* quantify the resource saving of an example of social media substitution. These systems have also been investigated by Vandromme *et al.* (2014) and Kramers *et al.* (2015).

Other forms of coordination system that are being developed by cleanweb entrepreneurs but have been less researched include **market and finance** systems such as crowdfunding rooftop solar panels (WeShareSolar[109]), **usage coordination** such as systems for matching drivers with charging points for electric cars (Ubitricity[110]), and **sharing economy** platforms, as described in Section 3.4.3.

5.5 THE ENABLERS IN DIGITAL THEORY AND PRACTICE

The Enablers are high-level concepts that cover large domains of technology and society. It is therefore straightforward to identify fields and literature addressing each of the Enablers described in the following sections, remaining very high level. Each enabler is illustrated with images from reality and fiction (Figure 29, Figure 30 & Figure 31).

Searching computer science and the wider academic literature did not identify analogous threefold models of the enabling impacts of digital systems. However, the enabler model is so simple that it would be surprising if it has not been arrived at in other contexts. It can be asserted with more confidence that its application to ICT4S is original.

[109] http://wesharesolar.com/
[110] https://www.ubitricity.com/

5.5.1 AUTOMATION

Figure 29 Examples of the Automation Enabler: car factory robot arms; the Nest Internet-of-Things smart-home thermostat; and a driverless car.

In the common usage, automation is when a device or process works by itself with little or no direct human control[111]. The word "automatic" comes from the Greek *automatos* 'acting of itself'. The concept of the **algorithm** developed from the algebra of Ancient Greece and the Islamic Golden Age. In the Middle Ages, town clocks and clockwork puppetry were created from **mechanical automata** (Scheffer, 2016), inanimate objects that were made animate, that controlled themselves. In the industrial revolution, mechanical automation was applied to mills, ships, and guns, long predating the emergence of digital systems.

Computation is the automation of information processing through a well-defined model such as an algorithm. In the 19th Century, the Babbage designed the first **computer** and Lovelace the first **software,** but it was mechanical rather than digital and was never built. Meanwhile, mathematical **control theory** was developed in physics and engineering to create accurate industrial control systems. By the mid-20th formal **information theory** (Farajallah et al., 2016; Shannon, 1948) had been developed. The word **robot** was coined to describe an autonomous or semi-autonomous electromechanical device controlled by an embedded electronic system.

Cybernetics emerged as a transdisciplinary approach to exploring regulatory systems, their structures, constraints, and possibilities (Heylighen & Joslyn, 2001). Cybernetics is now little researched, but it laid the groundwork for many other areas including computer science. **Computer science** is a *"branch of science that deals with the theory of computation or the design of computers"*[112]. *"Unlike electrical and computer engineers, computer scientists deal mostly with software and software systems; this includes their theory, design, development, and*

[111] http://www.oxforddictionaries.com/definition/english/automaton
[112] http://www.merriam-webster.com/dictionary/computer%20science

application"[113]. **Artificial intelligence (AI)** is intelligence exhibited by machines. AI is an area of computer science that develops flexible rational agents that perceive their environment and take actions that maximize their chances of achieving their goals (Russell & Norvig, 1995).

The 20th Century development of the Internet has enabled the **Internet of Things** to emerge in the 21st, "the network of physical devices, vehicles, buildings and other items—embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data" (Atzori, Iera, & Morabito, 2010). 98% of all microprocessors are now manufactured as components of such embedded systems (Ebert & Jones, 2009). Recent advances in automation such as **driverless cars** and **algorithmic trading** are prompting considerable concern about the socioeconomic impact of job losses due to automation (Farajallah et al., 2016; D. Spreng, 2013).

There is an annual IEEE conference on 12th Conference on Automation Science and Engineering (CASE) which is in its 12th year [114], and covers sub-topics including: Manufacturing Automation, Automation in Logistics and Supply Chain Management, Networked and Control Systems, Assistive Technologies, Automation in Meso, Micro and Nano-scale. There are similar commercial events such as the Automation Conference and Expo[115] and magazines such as Automation World[116]. Moreover, there are innumerable other events on related domains such as Artificial Intelligence[117], and within the many taxa of the ACM CCS which related to automation.

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113 https://undergrad.cs.umd.edu/what-computer-science
114 http://case2016.org/
115 http://www.theautomationconference.com/
116 http://www.automationworld.com/
117 http://www.aaai.org/Conferences/AAAI/aaai.php

5.5.2 AUGMENTATION

Figure 30 Examples of the Augmentation Enabler: Douglas Engelbart giving the Mother of All Demos; the personal computer of the 1980s; the ubiquitous smartphone user; wearable running monitor FitBit; a transhumanist image from Time magazine; augmented reality game Pokemon Go; the Phoenix robotic exoskeleton; and cooking with help from the Amazon Echo smart speaker.

Augmentation brings together a single user and a device, and was arguably been the dominant enabler from the popularisation of the personal computer in the 1980s until the rise of social networking in the 2000s, and the advances in automation in the 2010s. Interaction with the individual user has been a primary concern of **Human–Computer Interaction (HCI)**. As early as 1962, HCI pioneer Doug Engelbart gave this definition of augmentation:

"By augmenting human intellect we mean increasing the capability of a man to approach a complex problem situation, to gain comprehension to suit his particular needs and to derive solutions to problems. Increased capability in this respect is taken to mean mixture of the following: more rapid comprehension, better comprehension, the possibility of gaining useful degree of comprehension in situation that previously was too complex, speedier solutions, better solutions, and the possibility of finding solutions to problems that before seemed insoluble" (Engelbart, 1962).

Following from Engelbart, research into **hypertext** lead to the emergence of the **World Wide Web**. Throughout its history HCI has developed **interfaces** to interact with the user, and these are becoming increasingly sophisticated with the maturation of **voice recognition**. The ubiquity of **mobile devices** and now **wearable technology** enables **persuasive technologies** such as **gamification** to shape human behaviour, and record the "**quantified self**". **Augmented reality** and **virtual reality** technologies are beginning to find a mass market. Building upon the ideas of **cybernetics**, the term **cyborg** was first coined in the 1960 for a living organism that has enhanced abilities or restored function due to the integration of some artificial component or technology. There is now a **transhumanist** movement that aims to transform the human condition by developing and spreading technologies that enhances people's intellectual, physical, and psychological capacities.

5.5.3 COORDINATION

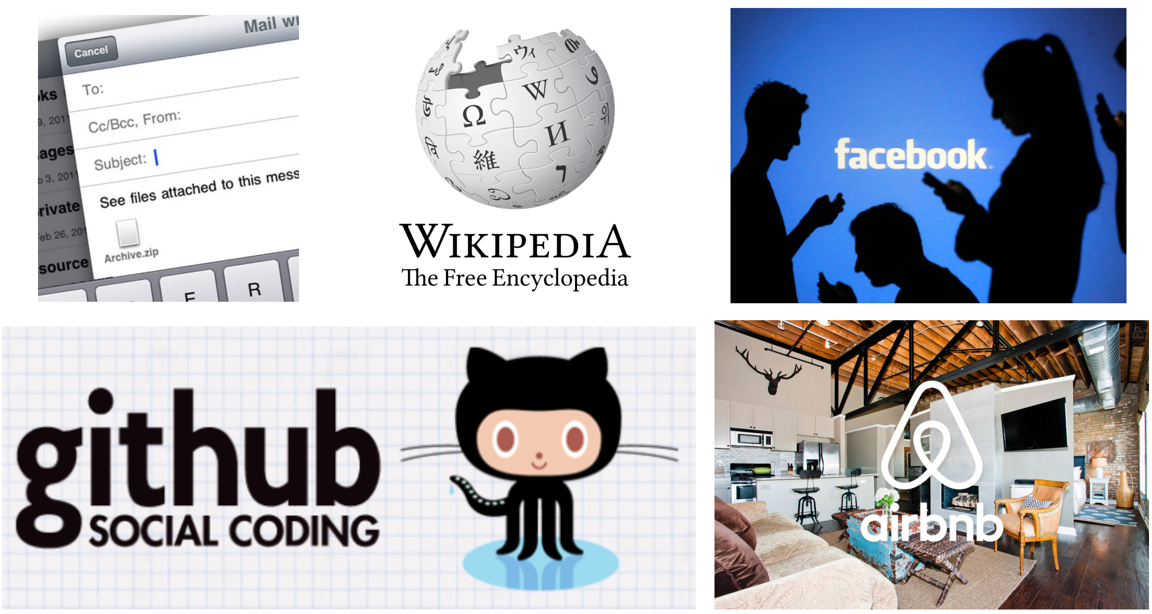

Figure 31 Examples of the Coordination Enabler: email; Wikipedia the wiki-based encyclopaedia; Facebook the social network; Github the software version control system; AirBnB the peer-to-peer accommodation marketplace.

Telecommunications technology has allowed multiple human actors to coordinate over long-distances for at least two centuries. The history of telecommunication can be traced through fixed **semaphore** systems, the **telegraph** and the **telephone.** The growth of the **Internet** provided a medium for **digital communication** such as **email** and then **teleconferencing**. The potential for **many-to-many communication** spurred research into **Computer-Supported Cooperative Work (CSCW)**, but it wasn't until the 2000s that **social computing** grew to become a dominant form of human interaction, with the rise of **social networking.**

"In just a few years, use of social technologies has become a sweeping cultural, social, economic phenomenon. Hundreds of millions of people have adopted new behaviours using social media – conducting social activities on the Internet, meeting and joining virtual communities, organising political activities. All the rituals and rights in which individuals and groups in society participate – from personal events such as weddings or daily gossip, to global happenings such as the Arab Spring – play out on social platforms. Indeed, many behaviours that sociologists study – performing, maintaining, and breaking social bonds – are now taking place online" (Chui et al., 2012).

Peer-to-peer digital communication has enabled **disintermediation** of **knowledge** and **marketplaces**, and the growth of **collaborative forms of production and consumption** within the **sharing economy.** Researchers are now investigating the **collective intelligence** of such **social machines**. Shirky has argued that the drastic reduction in transaction costs and organizing overhead due to these tools, now enables the formation of loosely-structured geographically-disparate groups with limited managerial oversight (Shirky, 2009).

5.5.4 AUTINATION

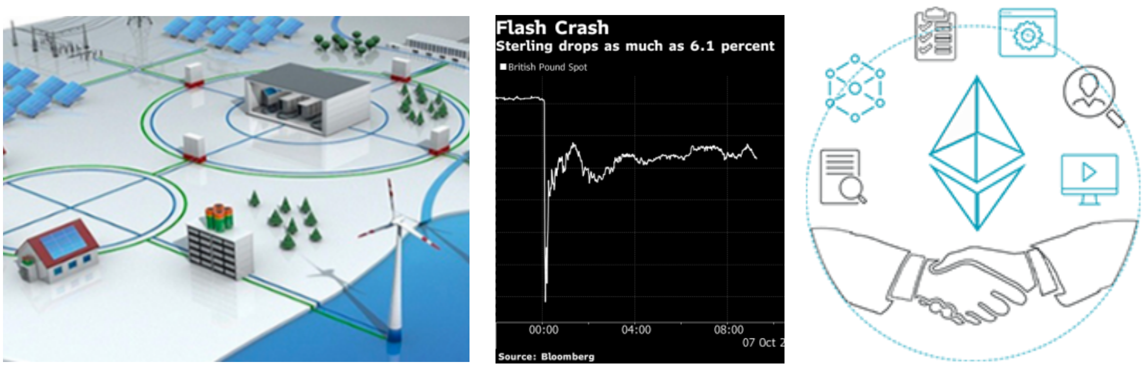

Figure 32 Examples of the Autination Enabler: a smart grid of autonomous agents controlling distributed energy sources and sinks; trading bots causing a flash crash in sterling; and human interactions regulated by Ethereum smart contracts.

Autination is the fourth Enabler which will be identified in Chapter 8. For completeness, it is included here. In Autination, different human actors' digital technology automates the interaction between them. Examples are given in Figure 32. The word "autination" is proposed here, as short for "automated coordination".

5.6 DISCUSSION

This section discusses the properties of the Enablers derived and defined above, and summarises it in a diagram of the social variation in enabling impact, the Enabling Impact Model (Figure 35). The Enablers will be compared with leading conceptualisations of ICT4S in Chapter 9.

5.6.1 PROPERTIES OF ENABLERS

Exhaustiveness and **mutual exclusivity** of the Enablers classification can be proven from the definitions above. All EICs have a value N that is a positive integer.

The three Enablers map to the entire set of positive integers N exhaustively and mutually exclusively (automation if N=0, augmentation if N=1 and coordination if N>1). Therefore, all EICs map to one, and only one enabler. All enabling impact (i.e. all the actions of digital systems) is created by EICs. Therefore, all enabling impacts and digital systems do indeed map **exhaustively** to the Enablers.

For digital systems or enabling impacts to be classified mutually exclusively into the three Enablers requires a one-to-one relationship between the digital system or enabling impact and their typical EIC. If this can be established for all enabling impacts and digital systems, then the Enablers are mutually exclusive with respect to enabling impacts and digital systems. However, this may rely on interpretative prioritisation of the typical EIC for an enabling impact or system, which may be a subjective judgement.

In summary, the Enablers are exhaustive with respect to all digital systems and enabling impact, and are mutually exclusive as long a one-to-one relationship between the digital system and enabling impact and their typical EIC can be established. ICTs always function through automation, augmentation or coordination, but require prioritisation to be classified uniquely as either automation, augmentation or coordination systems.

The distinction between augmentation and coordination also shapes the **topology** of relationships within the system (Figure 34). An archetypal augmentation system could have many users, but each user is treated as an individual and does not interact with other users (i.e. N=1 in each EIC). Therefore, augmentation systems are likely to have a **star-shaped** topology in which many users interact independently with a central system. Coordination systems on the other hand allow multiple users to interact and communicate with each other (N>1 in each EIC). This user-to-user communication allows more complex **network** topology to emerge. The distinction between augmentation and coordination can also be understood as a continuum of popularity. A single source broadcasting to many users within the "head" of the Web creates the star topology of augmentation. In contrast, small groups of users interacting within the "long tail" of the Web creates the network topology of coordination (Anderson, 2006).

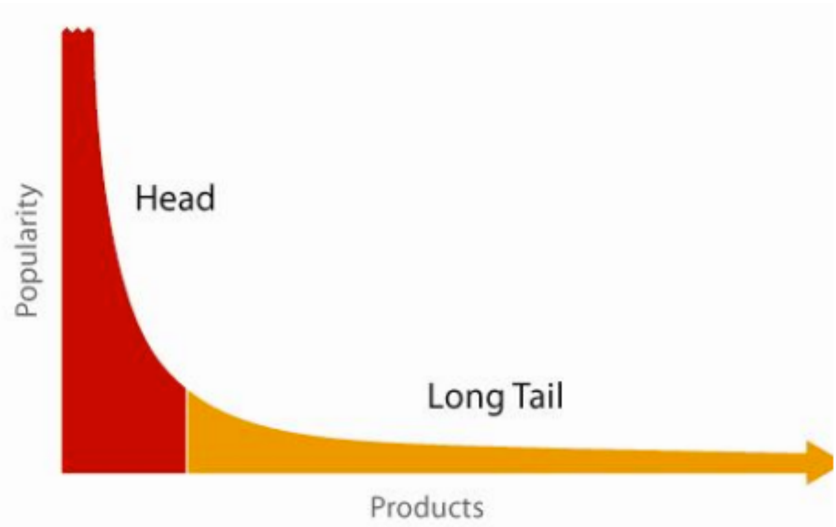

Figure 33 How large differences in the popularity of web content creates the head and long tail of the Web (Anderson, 2006).

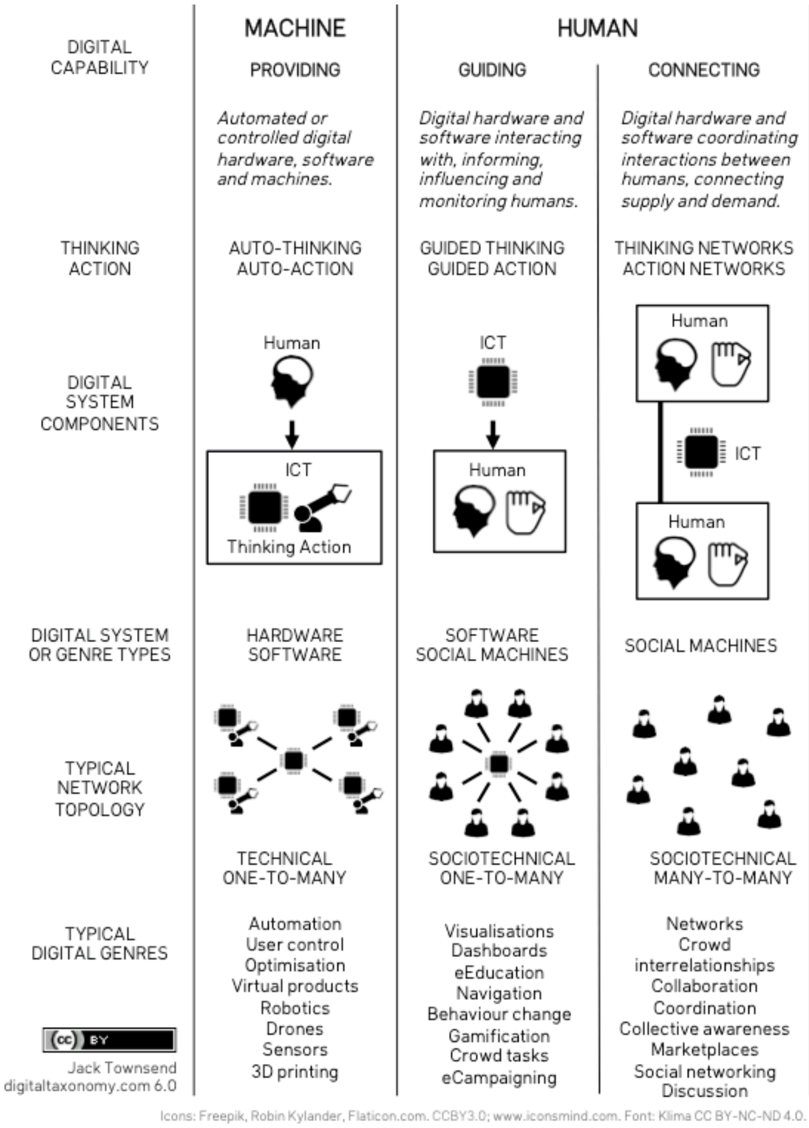

Figure 34 A table that compared the properties of the three Enablers (previously "digital capabilities") afforded by different digital systems, depending on how participants are involved.

5.6.2 ENABLING IMPACT MODEL

According to the definitions above: EICs contain only digital human actors and digital devices; automation EICs contain only digital devices; in addition to digital devices, augmentation EICs contain one human actor; whilst coordination EICs contain two or more human actors. If an EIC is subdivided into fragments, then its fragments are also EICs. Therefore: any augmentation EIC there will contain fragments without any human actors, which are therefore automation EICs. Similarly, any coordination EIC will contain fragments with only one human actor, which are therefore augmentation EICs.

For example, a social network such as Facebook, which is a coordination system, enables interactions between multiple users. But each Facebook-mediated interaction between users can be broken down into a series of augmentation interactions between each user and the Facebook system. Furthermore, each of augmentation interaction between the user and the Facebook system can be broken down into the actions of the human actor, and automation chains of actions of digital devices alone, including the user's computer hardware, the browser, the operating system, the keyboard, the Internet infrastructure, the cloud-based Facebook software, and the data centre hardware. This is illustrated in the examples of EICs in the Appendix.

It can therefore be deduced that any process of coordination is always composed of multiple processes of augmentation, and that any process of augmentation is based upon multiple processes of automation. Coordination systems can be decomposed into multiple augmentation systems, augmentation systems into multiple automation systems, and automation systems into further automation systems. This can be summarised as follows: **coordination is based on augmentation, which is based on automation.** This relationship is illustrated in Figure 35 as a pyramid.

Another relationship was also identified between the Enablers. Any piece of digital technology (i.e. instance of automation) is the responsibility of some individual human actor, such as a person or organisation, who normally has some control of it. This human actor exists within a web of other human actors i.e. a social context. Therefore, any digital device inevitably exists within an individual human context, which in turn sits within a mesh of social relationships that can be personal, economic, cultural or political. This is true whether a smartphone, a data centre of a piece of software. The goals of a particular digital device are shaped by the individual goals of its owner, the goals of other people and societal goals. This social context means that **automation exists within an individual context of augmentation, and augmentation within a social context of coordination.** This is illustrated with circles of individual and social context in Figure 35. The data gathered about people by automation systems enables augmentation, and the data gathered by augmentation system enables coordination.

That automation sits within an individual context of augmentation, and augmentation within a social context of coordination can be shown with the EIC model. Defining the beginning and end of an EIC is an interpretative process. If further steps are considered at the beginning or end of the EIC, then new human actors may be included. Automation might then become an augmentation, or augmentation coordination.

Davenport and Kirby (2015) note that the distinction between automation and augmentation is about placing automation in its human context, and that such a framing by managers might address fears of unemployment due to automation.

"Automation starts with a baseline of what people do in a given job and subtracts from that. It deploys computers to chip away at the tasks humans perform as soon as those tasks can be codified. Aiming for increased automation promises cost savings but limits us to thinking within the parameters of work that is being accomplished today… Augmentation, in contrast, means starting with what humans do today and figuring out how that work could be deepened rather than diminished by a greater use of machines" (Davenport & Kirby, 2015).

Consider a smart thermostat. It automatically controls the heating in the home, by gathering data on a number of physical variables such as the temperature of the house and perhaps the forecast weather. However, it also uses sensors to gather data on whether people are in the house. It therefore could also be considered to be augmenting the action of the residents. Moreover, like any complex automation system, it needs an augmentation mode when it can be controlled, with an interface for a resident to set the desired temperature. If multiple residents set this differently in different locations or different times of day, then it becomes a coordination system between there different goals.

Similarly, a driverless car is a prominent example of automation. However, the passenger initially needs to instruct it where to go, so the overall effect is to augment the passengers' ability to travel. And whilst it is on the road, the car is interacting with many drivers, effectively coordinating between them and its own passenger. The parameters that set the operation of the driverless cars are both the individual goals of the passenger and the societal goals that shape the laws of the road.

The autonomy of automation systems is rarely an absolute. Highly autonomous devices exist, such as computer viruses, but even these are designed to fulfil the goals of their original creator. Moreover, they replicate within the individual context of someone's digital hardware and software.

Two contrasting relationships have been identified between the three Enablers based on the EIC model. **Automation is the basis of augmentation, which is the basis of coordination.** Automation can be applied to augment change in individual actors. In turn, augmentation can be applied to coordinate social change. Coordination systems can be decomposed into augmentation systems, and augmentation systems into automation systems. **Automation sits within an individual context of augmentation, and augmentation within a social context of coordination.** The social context means that automation systems often act as augmentation systems, and augmentation systems often act as coordination systems. This bidirectional relationship between technological automation at the micro-scale and society at the macro-scale, is illustrated in the Enabling Impact Model (Figure 35).

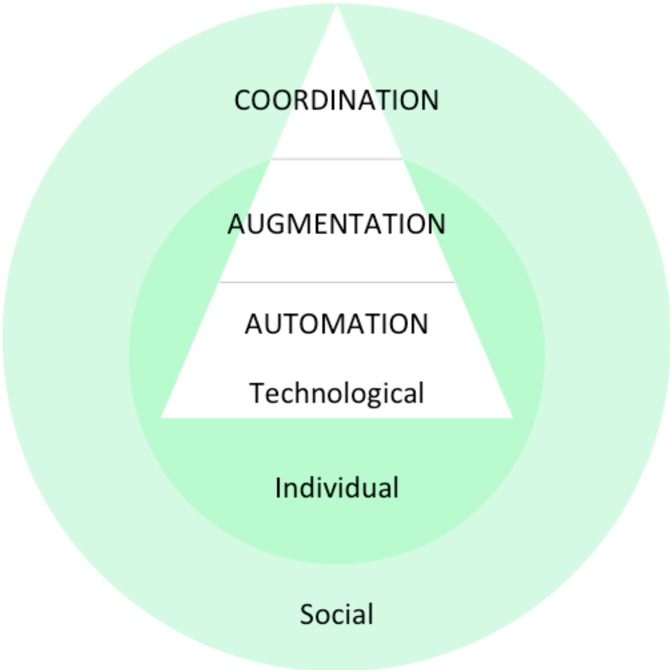

Figure 35 Enabling Impact Model of the different ways that digital systems combine people and digital technology to have impact

5.6.3 LIMITATIONS

The limitations of this classification development methodology were discussed in Section 4.4. A critique of the resulting Enabler classification is that it is mechanistic or even reductionist. It seeks to understand macro-scale behaviour of large and complex digital systems by modelling their micro-scale structure. This will always be an approximation, and placing the whole system in one category requires interpretative prioritisation that can be subjective. This interpretative prioritisation can be reduced with the approach employed by the investor in the case study (Chapter 7), who identifies multiple enabling impacts across the three Enablers for each digital system.

5.6.4 CONCLUSION

This chapter has developed the Enablers classification of digital systems from cleanweb company description data. It has shown that the enabling impacts of ICTs either 1) automate 2) augment individual human action or 3) coordinate collective human action. Rather than considering the technology in isolation, the Enablers make an important distinction between how digital systems incorporate people or substitute for them to achieve change in a complex social world. The distinction between the Enablers is important because human actors are an important component of digital systems. The number of human actors in a digital system, and the level of interaction between them, greatly changes the character of the digital system, and it is this critical social variation that is distinguished by the Enablers.

By organising the ACM CCS classification of computing (Section 5.2.6) and exploring the disciplinary context of each enabler (Section 5.4) this chapter has gained further evidence for the validity of the Enablers classification. It was deduced that automation is the basis of augmentation, which is the basis of coordination, whilst conversely automation sits within an individual context of augmentation, and augmentation within a social context of coordination, as illustrated in the Enabling Impact Model diagram (Figure 35). The following chapter now derives the other dimension of the SGM1, Digital Decoupling. Section 8.4.4 will refine the Enablers into a four-category typology.

CHAPTER 6 DECOUPLING DIRECTNESS: DISTINGUISHING SAVE AND PUSH IMPACTS

6.1 INTRODUCTION

Phase 1 found that leading conceptualisations of Sustainability by ICT do not sufficiently account for the many observed cleanweb systems that catalyze cleantech, i.e. that support sustainable products such as renewable energy. This chapter addresses this by deriving the second dimension of the SGM, **Decoupling Directness (DD)**, which addresses the question of **how DDS catalyse cleantech.** This chapter ends Phase 2 by completing the derivation of the first version of the Smart Green Map (SGM1) to address the main research question: **how can Sustainability by ICT systems be classified effectively and usefully**?

This chapter describes the second strand of the Phase 2 research that led to the derivation of the DD from the qualitative company description data, from the same method described in Chapter 4. Section 6.2 details the derivation of the DD classification from the company description data. Having derived definitions of the categories, certain properties of the Decoupling Directness distinction could be deduced. Unlike with the Enablers, this chapter will not model the function of Save and Push systems. They will be modelled in Section 9.4 by integration with the LES Model theory.

6.2 RESULTS

6.2.1 THE DECOUPLING DIRECTNESS DISTINCTION AND SGM1

Chapter 4 and Chapter 5 have described the sourcing of company description data from CrunchBase startups and other sources, sampling, coding and classification development. Codes relating to “web approach” for each company captured **how the combination of digital technology and people achieve the sustainability benefit.** From these were identified three Enablers, each containing an list of tentative subcategories called empirical “digital genres”. Whilst sorting and resorting the digital genres identified in Table 25 and reviewing the company description data, it was noted that some DDS work by creating resource efficiencies, whilst others involve a form of cleantech such as renewable energy, identifying a second dimension with which the digital genres could be organised into two groups (Table 36). This new dimension encompassed all the DDS encountered. Example

CrunchBase company descriptions are shown in Table 23. The memos written about each category lead to the following definitions:

- One type of DDS decouples resource use **more directly**, primarily by controlling machines or influencing peoples' behaviour to be more resource efficient. This category was initially entitled **sustainable resource efficiency,** but was later simplified to "**save"** systems, because they save resources.

- The other type of DDS also enhances the adoption, construction and operation of other products that themselves use resources more sustainably i.e. "cleantech" (Section 3.4.1). This category was initially entitled **catalyzing cleantech** based on the cleanweb theme identified by Pure Energy Partners (Figure 17), but was later simplified to "**push"** systems, because they drive the adoption of more sustainable products such as renewable energy, bicycles, train journeys or even plants in cities[118]. Ultimately, this category also decouples resource use, but **more indirectly**.

These two categories form the **Decoupling Directness dimension (DD)**. Combining this new dimension with the Enablers allows the digital genres identified in Table 25 to be organised into Table 36, the earliest version of the Smart Green Map, the main contribution. The term "smart green" follows its use by Ecosummit (Hess & Butter, 2016). The SGM is a matrix that identifies six contrasting "markets" that map out all DDS (cleanweb systems).

[118] E.g. http://greencitysolutions.de/

DIGITAL CAPABILITIES *Power of digital systems to influence people or machines*	CATALYZING CLEANTECH *Spreading low-impact resource technologies, fabricating and maintaining them*	SUSTAINABLE RESOURCE EFFICIENCY *Making resouce use efficient and low-impact*
HUMANS DIGITAL CONNECTING *Digital tech coordinating interactions between humans, connecting supply and demand to influence collective actions.*	CLEANTECH NETWORKS *Connecting people to spread resource technologies* Collaborative funding e-Marketplaces and directories Job listings Community adoption Offers and discounts Sales team coordination Redistribution markets Ratings and comparison	EFFICIENT NETWORKS *Connecting people to use resources efficiently* Peer-to-peer rental and sharing Redistribution markets Social behaviour change and gamification Teleconferencing Efficient virtual services Distributed autonomous corporations (DACs)
DIGITAL GUIDING *Digital tech interacting with people individually, monitoring and informing them to influence their actions.*	GUIDED CLEANTECH *Guiding people to spread low-impact resource technologies, fabricate and maintain them* e-Marketing and advertising Customisation, installation planning CRM and services e-locks and access control Recommender systems Cleantech diagnostics Sales gamification Cleantech knowledge-bases	GUIDED EFFICIENCY *Guiding people to use resources more efficiently* Resource behaviour feedback Efficiency diagnostics Individual behaviour change & gamification Business intelligence & process managemnt Real-time user guidance and navigation Knowledge-bases for efficiency
MACHINES *Automated or controlled digital tech and machines.*	AUTO-CLEANTECH *Automated or controlled machines fabricating and maintaining low-impact resource technologies* Auto cleantech optimization Cleantech user control Maintenance and manufacture drones and robots Installation assessment drones and robots	AUTO-EFFICIENCY *Automated or controlled machines using resources more efficiently* Automated resource optimization Robotics and drones for efficiency Efficient distributed manufacturing Resource user control Dematerialised content Efficient crypto-currency [Green computing, low-impact ICT]

Table 36 The earliest version of the SGM formed by sorting the digital genres of Table 25 into save (right) and push (left). The terminology has been superseded. The rows are an early version of the Enablers, and the columns an early version of the Decoupling Directness dimension (DD).

A primary motivation for the development of the SGM was to map out the cleanweb industry, so the commercial term "market" was used for each cell. A nomenclature was required for the six markets of the SGM (Figure 37), according to the requirements of Section 4.2.6. Many iterations of terminology were experimented with, as detailed in Table 65 in the Appendix. The terms ultimately selected were the following: automation systems are referred to with the affix "auto-"; augmentation systems with the affix "i-" to refer to "oneself" as well as "information"; and coordination systems with "we-" to refer to the collective human action they enable. Combining enabler affixes with decoupling directness suffixes generated names for the six markets:

- **autoSave** systems – such as smart thermostats that automatically control home heating more efficiently e.g. tado°[119] and Nest.
- **iSave** systems - such as resource use feedback systems, e.g. Advizzo[120] which help people understand and control their water use.

[119] https://www.tado.com/

- **weSave** systems – such as ridesharing platforms that can make travel more efficient e.g. BlaBlaCar[121]
- **autoPush** systems – such as solar panel cleaning robots e.g. SolarBrush[122].
- **iPush** systems – such as home solar panel installation planning through a website with Sungevity[123].
- **wePush** systems – such as renewable energy crowdfunding platforms e.g. Abundance[124].

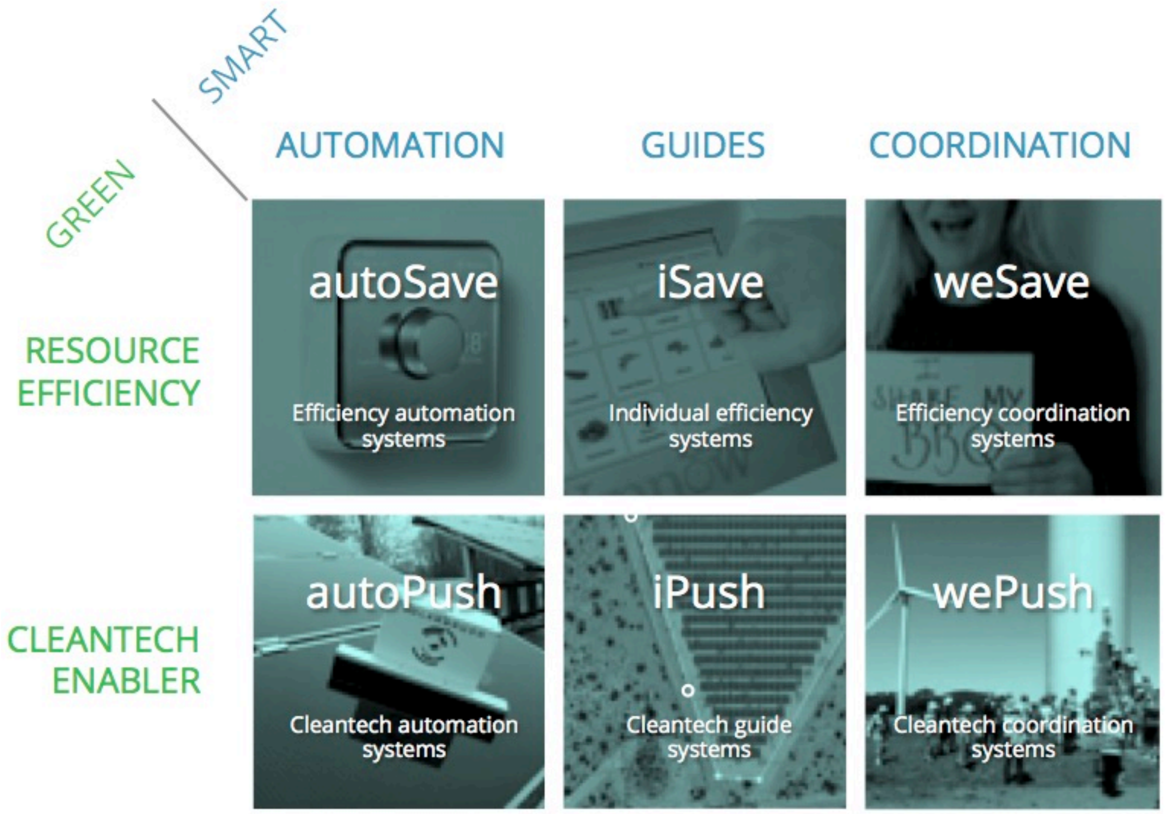

Figure 37 The first major version of the Smart Green Map, SGM1, as presented on the website smartgreenmap.com. Some terminology is superseded: guides = automation; Smart Axis = enablers; Green Axis = Decoupling Directness; resource efficiency = save; cleantech enabler = push

120 http://www.advizzo.com/
121 https://www.blablacar.com/
122 https://www.aerialpower.com/
123 http://www.sungevity.com/
124 https://www.abundanceinvestment.com/

6.2.2 SUSTAINABILITY OUTCOMES

The SGM1 has been derived from the "web approach" codes that answered the following question for each company: **how does the combination of digital technology and people achieve the sustainability benefit?** The other codes related to "sustainability outcome": **how does the system benefit sustainability?**

The initial "sustainability outcome" codes for each company were sorted and resorted to find commonalities between them, following the methods of Section 4.2, and a first version of higher-level concepts were identified. The left column of Table 38 shows the concepts derived from the initial codes (Figure 63). Further sorting and resorting, memo-writing and diagram lead to the emergence of two high level categories into which all the concepts encountered could be encompassed. These formed a spectrum of increasing complexity. At one end were many systems that focus on resource use, most typically efficient use of electrical power. At the other end, systems considered even social, economic and cultural objectives of sustainability, which was termed "broad sustainability". This distinction was used as the horizontal axis of Figure 24, a matrix mapping out some prominent DSS identified in a conference paper, which stated: *"This constructed scale illustrates the great contrast between, on the one hand, narrow reductionist views of ICT for sustainability as increasing efficiency of resource use, and on the other, more holistic understandings that recognise the social and physical complexities of the challenges. Whilst the former takes a positivist approach that engineers technology, the latter must consider more normative questions"* (Townsend, 2014).

Concepts	**Categories**
Energy and carbon	Resource use focussed *Resource use focussed* *Increasing efficiency* *Narrower focus* *More reductionist*
Energy efficiency	
Offsetting carbon	
Renewables	
Space (i.e. real estate and storage)	
Stuff (i.e. physical assets and consumables)	
Sustainability behaviours and persuasion	
Transport and logistics	
Water quantity	
Air and water quality	Broad sustainability *Social complexities* *Physical complexities* *Holistic understanding*
Biodiversity	
Cash fundraising and financing	
Local economy and self sufficiency	
Sustainability knowledge and opinions	
Effective environmental industries	
Innovation	

Table 38 Sustainability outcomes: concepts and categories with key points from memos

6.3 DISCUSSION

The DD dimension will be compared with leading conceptualisations of ICT4S in Chapter 9.

6.3.1 DDS ARE RESOURCE-USE FOCUSSED DSS

Table 38 allowed two groups of Digital Sustainability Systems (DSS) to be distinguished: those that decouple resource use, which were termed Digital Decoupling Systems (DDS), and the remainder, termed "broad sustainability". DDS form the left half of Figure 24.

In the LES Model, DDS are therefore those digital systems that contribute to **dematerialization**, the *"special case of decoupling based on the substitution of immaterial resources for material resources… In broad terms, dematerialization is the aggregate result of many process optimizations and media substitutions, moderated by rebound effects"* (L. Hilty & Aebischer, 2014). Dematerialization is viewed as a necessary but insufficient condition for sustainable development.

On the other hand, the remaining "broad sustainability" DSS can largely be equated with **institutional change** that shapes action, that is to say law, policies, social norms, and anything that can be regarded as the "rules of the game." However, it is not clear institutional change can encompass sustainability outcomes such as biodiversity conservation.

This investigation now narrows its focus onto DDS alone, those digital systems that advance sustainability by making resource use more sustainable, which are termed Digital decoupling systems (DDS). This is the scope of the Smart Green Map.

6.3.2 CLEANWEB SYSTEMS ARE EQUIVALENT TO DDS

During the action research of Section 3.4.2, I worked with an international group of cleanweb specialists to develop a definition of the term cleanweb:

Connected information technology solutions that address resource and sustainability challenges.

"Connected information technology solutions" can be largely equated with "digital systems" as modelled in Figure 28, and "address resource and sustainability challenges" can be largely equated with "address sustainable resource use". Cleanweb systems can therefore be equated with DDS, which are the scope of the SGM, and of the enabling impacts of the LES Model. The Smart Green Map is therefore a definition and a classification of all cleanweb systems i.e. all DDS.

The equivalence is sufficiently good, but not entirely perfect as the term "solutions" emphasises the full commercial product, which may not be entirely digital. As Section 3.4.2 discussed, "resource and sustainability challenges" was left purposefully ambiguous. Defining cleanweb systems as DDS means excluding "broad sustainability" systems, which might arguably have been included under the definition quoted above. However, it can be argued that the affix "clean-" in "cleanweb" implies a means of using a resource.

6.3.3 RESOURCE TYPE IS A USEFUL ORTHOGONAL DIMENSION TO THE SGM1

Section 6.2.2 has confirmed that type of resource is a useful dimension for analysing DDS (cleanweb). This is unsurprising as cleanweb is a form of cleantech, and Sections 3.4.1 and 3.4.4 showed that type of resource is a popular method of classifying cleantech. DDS in each of the six markets were applied to many different types of resource. There is no reason why the Enablers cannot be applied to any form or resource, and do so by saving the resource directly, or pushing a "cleantech" specific to that resource. Therefore, resource-type is an **orthogonal** dimension to the two dimensions of the SGM1, and offers a useful complementary dimension.

6.3.4 PROPERTIES OF SAVE AND PUSH

This analysis has not attempted to account for all the initial "web approach" codes so it has not generated clear evidence that the classification is **exhaustive**. Neither has **mutual exclusivity** been clearly demonstrated.

Contrasting properties of the save and push systems can be deduced from the definitions above. These properties are summarised in the Table 59 in the Conclusion Chapter.

Save and push are alternative forms of enabling impact, which the LES Model equates with the decoupling of resource use. By creating resource efficiencies, save systems decouple directly. The success of save systems would therefore be measured in resources saved through efficiencies, which can be directly compared to the contributions of other forms of cleantech such as renewable energy generation and insulation. By enabling other decoupling technologies i.e. cleantech, push systems decouple indirectly. For push systems, success is measured in the amount of cleantech they enable, which can then save resources. Push systems are ICT enabling some other form of cleantech, whilst save systems are a form of cleantech themselves.

Save systems optimise the ways that we use resources with existing products, helping us use products better. Push systems on the other hand substitute one product for a more sustainable one, helping us use better products. Whilst save systems are discouraging the consumption of resources whose use is in some way harmful to the environment, push systems actually encourage the consumption of different resources which are assumed to be beneficial i.e. cleantech.

How can the Decoupling Directness dimension itself be conceptualised, what is it that varies between the two categories? It is the proximity of the enabling impact to the decoupling process. Save systems enable decoupling more directly, by saving resources through efficiencies. Push systems have a more indirect enabling impact that is mediated via another clean technology. Indeed, push systems can be more than one stage removed from the decoupling technology. For instance, JPM Silicon[125] use digital technology to improve the production of silicon, which can then create solar panels, which can then decouple.

The distinction in directness between save and push systems is more subtle that the seminal distinction made by Berkhout & Hertin between direct effects (i.e. first order or life-cycle effects) and indirect effects (i.e. second order or enabling effects) (Berkhout & Hertin, 2004). Save and push are different forms of enabling effect. Although Smarter 2020 does not distinguish save and push, it touches on the distinction: *"Although all proposed GHG abatement potentials are related to ICT, some of the mentioned abatement sublevers are much more strongly linked to ICT (e.g. telecommuting) while others play a more indirect role (e.g. integration of renewables)"* (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012).

6.3.5 CONCLUSIONS

This chapter completes the qualitative derivation of the first version of the Smart Green Map, the SGM1, the main contribution of the investigation that addresses the main research question, how can **Sustainability by ICT systems be classified effectively and usefully?** The previous chapter developed the first component of the SGM – the Enablers – whilst this chapter has developed the second "Decoupling Directness" dimension, and put them together to form the SGM1, distinguishing six different "markets". Whilst not encompassing all Sustainability by ICT systems (DSS), the SGM1 is a classification of all DDS, DSS focussed on resource-use, which Section 6.3.2 equated with cleanweb systems. The Decoupling Directness dimension is a two-category typology that organises DDS by the **directness of the enabling impact** by which they contribute to decoupling. Save systems decouple resource use more

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[125] http://www.jpmsilicon.de/consulting/?lang=en

directly, primarily by controlling machines or influencing peoples' behaviour to be more resource efficient. In contrast, push systems also decouple resource use but more indirectly by enhancing the adoption, construction and operation of other products that themselves use resources more sustainably i.e. "cleantech". These two definitions provide a **conceptual basis for the observed variation in DDS,** and a dimension of how **DDS benefit sustainability**. Based on these definitions, this chapter has analysed the distinction between save and push, as summarised in Table 59. Section 9.3.1 will develop the conceptual basis further with a model of the mechanism underlying save and push, based on the resource-use hierarchies theory of the LES Model. The effectiveness of DD as a classification will be evaluated for properties such as exhaustiveness and mutual exclusivity in Section 8.4.5.

Chapter 8 will compare a sample of Sustainability by ICT research and entrepreneurship and show that save and push systems are equally well represented amongst the startups, but research into push systems is much less common. Similarly, Chapter 9 will compare the DD dimension with leading strategic conceptualisations of Sustainability by ICT and show that save is much more prominent than push. As save systems are already well represented in ICT4S research, it is the concept of the push system that is the contribution of the DD dimension.

CHAPTER 7 USING THE ENABLERS: VENTURE CAPITAL CASE STUDY

7.1 INTRODUCTION

This chapter begins **Phase 3** of the thesis that evaluates whether the SGM1 **is effective and useful,** whilst also developing the classification further. This chapter presents a case study of the adoption of part of the SGM by Zouk Capital LLP, a venture capital investment firm within the nascent cleanweb sector. The Enablers, which describe **how DDS combine people and digital technology**, were integrated by the firm into a two dimensional analytical tool called the Sustainability Impact Assessment Methodology (SIAM) (Higelin, 2016). The SIAM is used to identify and quantify the sustainability and efficiency impacts of digital companies, and thus inform investment decisions, and communicate investment policies to existing and potential investors in the fund. Section 7.2 describes the method, 7.3 describes the investment company, 7.4 describes the SIAM, and 7.5 discusses the implications for the SGM and LES Model, and draws conclusions, evaluating the Enablers and SIAM.

7.2 METHOD

This case study investigates how and why the Enablers were integrated into Zouk's Sustainability Impact Assessment Methodology 2016 (SIAM). Case studies *"are the preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context"* (Yin, 1994). Case studies are often used for evaluation, primarily of public or educational programs (Reason & Bradbury, 2001; Robert Stake, 1995). They can describe interventions and the real-life context in which they occur, and illustrate topics within an evaluation in a descriptive mode or even from a journalistic perspective (Yin, 1994).

There were three sources of data. The primary source is materials that describe the SIAM, which were provided by the firm (Higelin, 2016) (Figure 39 - Figure 41). Two unstructured interviews took place with the investor responsible for development of the new assessment methodology, during which notes were taken. Quotes within this chapter are from these interviews and the SIAM document (Higelin, 2016). To describe the company itself for context, this data was supplemented with material from the corporate website (Zouk Capital

LLP, 2016), the financial press (Daniel Schäfer, 2011) and CrunchBase whose structured company data had been updated by a Zouk employee (TechCrunch, 2013).

7.3 ZOUK CAPITAL LLP

Zouk Capital LLP is a private equity venture capital firm founded in 2000 with offices in London and the Far East. Zouk invests in companies with revenues between €10m - €150m which are likely to be able to scale rapidly.

In 2005, the firm focused on emission-curbing and nature-preserving technologies (Daniel Schäfer, 2011). Zouk has a total of €600 million under management. Funds originate from limited partners (LPs) such as pension funds with a commitment to environmental, social and corporate governance (ESG), a sector that has developed strongly over the last decade (Escrig-Olmedo, Munoz-Torres, & Fernandez-Izquierdo, 2010).

Zouk aims to facilitate the expansion of resource efficiency measures across the global economy. Sustainability is seen as key to each stage of the investment process. Zouk seeks to be an active investor, providing investment capital, industry knowledge and contacts to the management team. Zouk see resource efficiency as both environmentally and economically advantageous (TechCrunch, 2013), and perceive a *"near-perfect alignment between ESG metrics and the commercial performance."*

The primary fund, called Growth Capital, has a value of €230m invested in companies applying industrial and information technology to realise resource efficiencies. Major investments of the Growth Capital fund include paperless mobile payments company iZettle[126] (which forms the example in Figure 39), online collaboration and project management platform Huddle[127], and provider of magazines via tablets and smartphones, Readly[128]. Zouk also has an Infrastructure team that finances the construction of renewable energy and environmental assets.

7.4 THE SUSTAINABILITY IMPACT ASSESSMENT METHODOLOGY

To remain competitive, venture capitalists must keep up with innovation in their industry, and aim to lead it. When new types of company emerge, investors' methodologies must evolve so they can assess novel products, technologies and business models. In addition, ESG investors must analyse sustainability impacts as well as commercial considerations. This

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[126] https://www.izettle.com/
[127] https://www.huddle.com/
[128] https://gb.readly.com/

applies to the rapid emergence of cleanweb startups at the intersection of the digital and cleantech industries. The specific focus of the Zouk Growth Capital is digital systems that deliver resource efficiency i.e. the Save row of the SGM which makes up about half the cleanweb sector. Zouk's Growth Capital Fund is therefore a cleanweb investor.

As the cleanweb sector is relatively new, Zouk sought a novel methodology to assess digital products and their sustainability impacts, a coherent and transparent company assessment framework as a basis for Growth Fund's investment decisions. As well as decision-making, the framework will communicate the company's investment principles to existing LPs in the fund, and the wider ESG investment industry of potential investors, as it "cannot be done in a vacuum." There is an implicit goal to develop awareness of cleanweb startups as potential investments for ESG investors by developing new, rigorous assessment methodologies, which could be adopted more broadly. More than just principles, the framework needs to offer a basis for quantification so that regular performance updates on each company can be provided to LPs investing in the fund.

Although there are "many different ways to measure ESG performance", the company did not find any established cleanweb company assessment framework that fulfilled these requirements. Zouk began a project to develop their own framework. This began with background research, which came across a paper from this investigation, presenting an early version of the classification (Townsend, 2015b). The paper presented the Enablers as one dimension of the classification (although using superseded terminology). The Enablers were adopted by the investor as a component of a matrix for assessing the efficiency and sustainability impacts of a digital company. The result is the draft Sustainability Impact Assessment Methodology 2016 (SIAM, Figure 39).

The basis of the SIAM is a matrix used to identify and quantify the sustainability and efficiency impacts of a digital company. Initially these impacts are assessed qualitatively but Zouk aim to develop "systematic and quantifiable metrics that we can track", to provide ongoing performance measures. It has two dimensions: the "Methods" columns that incorporate the Enablers, and the "Factors" rows, introduced and discussed in the following two sections. Once a company of potential interest has been identified, the sustainable impact assessment has seven stages.

1. Identify the Impact Methods of the business (the columns that incorporate the Enablers).

2. Describe the range of sustainability factors amongst the business inputs/outlets value proposition and externalities (the Impact Factors that form the rows).

3. Establish the resulting impact scope based on which methods are applied to which factors.

4. Select and measure metrics for each quantifiable component of the scope (impact metrics) – with guidance from the impact reporting and investment standards (IRIS) promoted by the Global Impact Investing Network. (Global Impact Investing Network, 2014).

5. Qualify any non-quantifiable component of the scope (impact effects).

6. Assess the impact potential of the business based on the above analysis (investment committee requirements).

7. Monitor the realised impact of the business over time (reporting requirements).

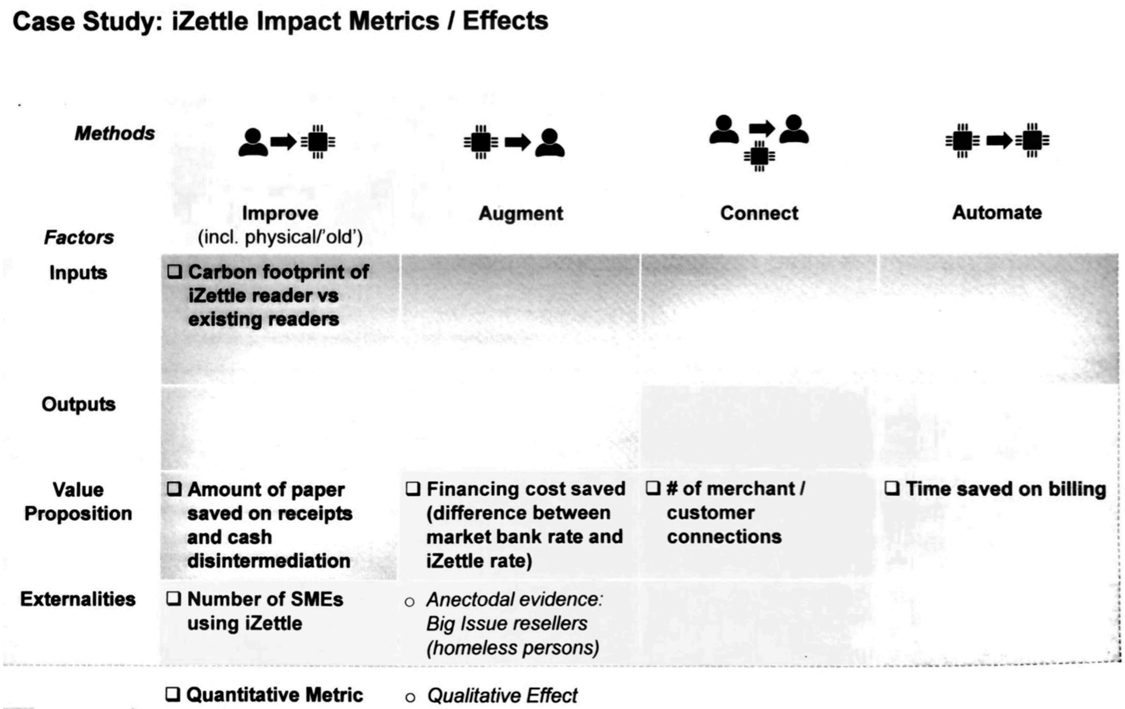

Figure 39 The Zouk SIAM Matrix, used to assess paperless mobile payments company iZettle © Zouk Capital LLP

1.1.1 THE IMPACT METHODS AXIS, INCORPORATING THE DLS

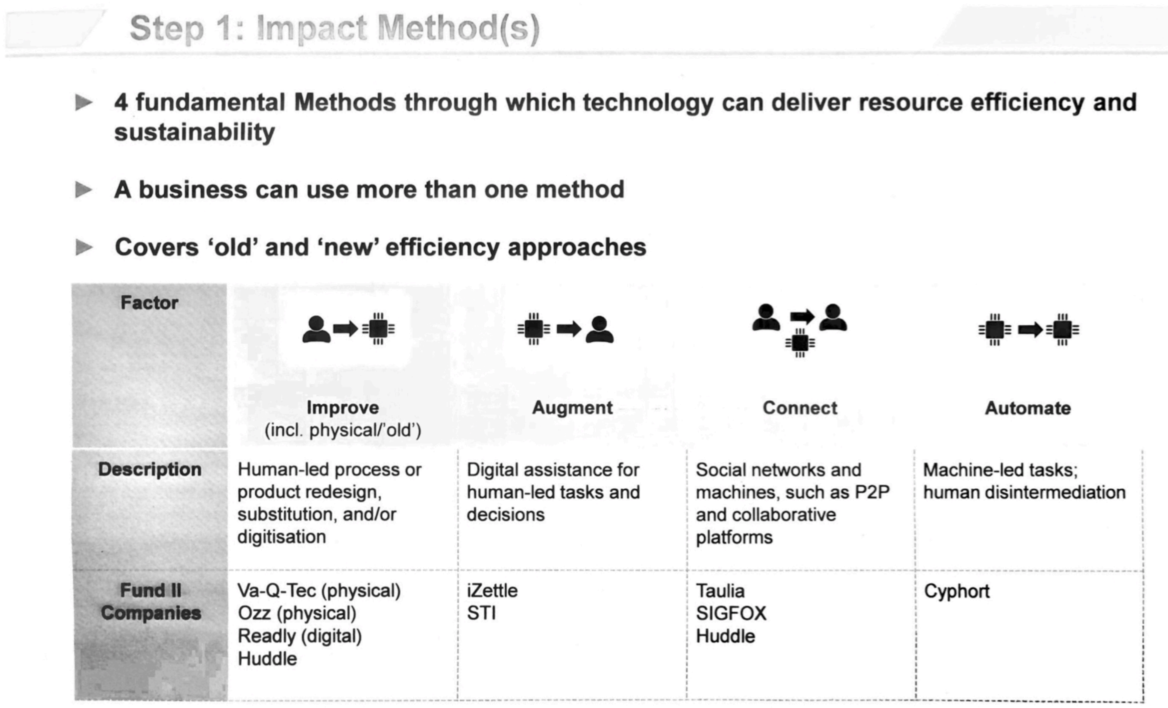

Figure 40 The Impact Methods axis of the SIAM © Zouk Capital LLP

The horizontal axis (the "Methods") identifies "four fundamental methods through which technology can deliver resource efficiency and sustainability". This is equivalent to the Enablers and is thus identical to them, except however, that a fourth category is included called "Improve". The four categories are described as follows:

- Improve (including physical / "old") – "human-led process or product redesign, substitution, and/or digitisation."
- "Augment – digital assistance for human-led tasks and decisions". This is the augmentation enabler.
- "Connect – Social networks and machines, such as P2P and collaborative platforms". This is the coordination enabler.
- "Automate – Machine–led tasks; human disintermediation". This is the automation enabler.

The following subsections discuss this fourth category and other questions around the Methods Axis, comparing it with the enabler theory developed here.

1.1.2 THE IMPACT FACTORS AXIS

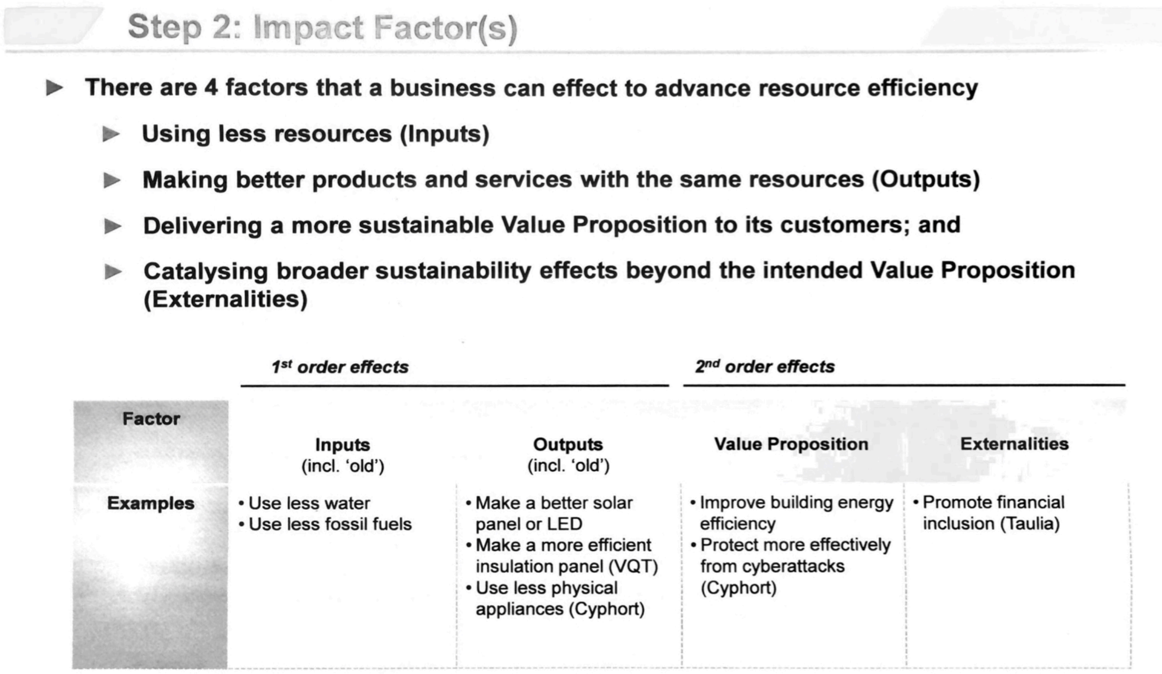

Figure 41 The Impact Factors axis of the SIAM © Zouk Capital LLP

The second axis of the SIAM identifies four factors that a business can effect to advance resource efficiency:

- Inputs (including "old") - using less resources.
- Outputs (including "old") - making better products and services with the same resources
- Value Proposition - delivering a more sustainable Value Proposition to its customers
- Externalities - catalyzing broader sustainability effects beyond the intended Value Proposition

As with the Impact Methods, a distinction is made between the first two "old" factors - i.e. those established within the industry – and later two "new" ones.

7.5 DISCUSSION

7.5.1 THE "IMPROVE" CATEGORY AND OLD VS NEW RESOURCE EFFICIENCY

Having a fourth Impact Method would appear to cast doubt on the exhaustiveness of the Enablers. The fourth category appears to be a heterogeneous category that incorporates at least three components. Does the Improve category show that the Enablers are not an exhaustive classification?

- Media substitution - what Hilty refers to as media substitution (Section 2.3.3), but is commonly called "dematerialisation", replacing atoms with bits (Negroponte 1996). Placing media substitution as a separate category is a logical alternative arrangement. The LES model shows that media substitution works in a different way from the data-driven process optimisation of resource use. Nevertheless, the three Enablers are applicable for media substitution. Teleconferencing is coordination, whilst e-books are augmentation (Section 9.4). Rather than a fourth enabler, Section 9.4 will argue that it better sits on an orthogonal dimension, the Production/Consumption axis, as described in the ultimate SGM3.

- Physical cleantech. A small number of the Growth Capital funds investment produce physical products e.g. pipework insulation manufacturer Va-Q-Teq[129]. Similarly, some companies in this category provide human-led services that are not digital, such as Ozz electric, contractors that install building energy efficiency measures[130]. These do not call the exhaustiveness of the Enablers into question as they are not digital, and therefore outside of the scope of the SGM.

These two contrasting concepts are combined in order to distinguish "old" from "new" resource efficiency. The practical purpose of the Improve category appears to be distinguishing "old" types of energy efficiency that are well-established amongst resource-efficiency investors, from "new" types, which are based on data-driven resource optimisation, distinguished by the three Enablers in the SIAM. It is the aim to distinguish old from new that leads to media substitution to be organised differently than in the SGM. We can conclude that it does not call into question the exhaustiveness or general fit of the Enablers to their defined scope (digital systems).

7.5.2 CLASSIFICATION BY COMPANY OR BY IMPACT

The SIAM states that *"a business can use more than one method".* The SIAM is used to categorise by company and by impact.

- Classifying by company allows multiple companies to be compared, as with the SIAM in Figure 40, and with the SGM in Chapter 8.
- Classifying by impact allows multiple impacts to be analysed for one company.

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[129] http://www.zouk.com/technology/portfolio-company-details/va-q-tec
[130] http://www.zouk.com/technology/portfolio-company-details/ozz-electric

Both are valid, and the SGM could also be used in either way. This agrees with the original definition of the Enablers in Chapter 5. One company can have multiple digital systems and one digital system can have multiple enabling impact chains, from which the three Enablers are derived (Section 5.3).

7.5.3 IMPACT FACTORS, VALUE PROPOSITIONS AND ENABLING IMPACTS

The value proposition of a product is the benefit that it offers its customers. This can be equated with "enabling impact" as defined theoretically in Chapter 3 and as described by the LES Model, but in a more commercial sense. The SIAM, LES and SGM all consider the application of the digital system, the Value Proposition. The LES and SIAM consider the efficiency of the digital system itself (the Life Cycle Impact), but the SGM does not. The SIAM also considers the inputs of the company as a whole, such as its supply chain and employees, which may not be included in the Life Cycle Impact in the LES Model.

The Impact Factors Axis is similar to the Production/Consumption distinction of the LES Model that will be incorporated into the SGM3 in Section 9.2. This similarity helps validate the LES Model, Impact Factors and SGM3.

7.5.4 STRUCTURAL IMPACT AND EXTERNALITIES

The Externalities category of the SIAM is similar to macro-scale Structural Impact, the third level of the LES Model. The SGM does not explicitly describe this third level. However, it is valid to analyse the macro-scale externalities of each of the Enablers as undertaken in the SIAM (Chapter 9). In principle, macro-scale structural impacts/externalities can be assessed separately for each of the micro-scale enabling impacts that caused them, within each of the three Enablers (automation, augmentation or coordination).

7.5.5 EVALUATING THE ENABLERS

The evidence from this case study suggests that the Enabler classification is **effective and useful**. Usefulness to practitioners is one of the criteria for assessing the classification identified in Section 4.3. The international conversation with cleanweb specialists suggested three specific potential benefits to practitioners (Section 3.4.2).

Enabling quantitative comparisons between systems, markets and fields. The Enablers offer a simple model to conceptualise and structure the impacts of a particular digital system. The Enablers help the investor to make an important distinction between the substitution of humans through automation and the brokering of social connections online. The SIAM is being used to make business critical investment decisions by developing insight specific to each Enabler. The Enablers have facilitated the analysis of the distinction between "old" methods and factors that the resource efficiency investment industry already considers, and "new" methods and factors that can now be identified by the SIAM. However, this was helped by the addition of the "Improve" category.

Helping startups, investors and other stakeholders coordinate. Zouk found the Enabler conceptualisation "very helpful", and note that investment "cannot be done in a vacuum." They intend to use the SIAM as a tool for communicating about investments with existing stakeholders such as LPs in the fund, as well as the many different stakeholders in the wider ESG and investment industry, especially potential future investors. As well as communicating the specifics of individual investments, the SIAM will also express the company's investment principles.

Raising awareness of the sector's existence. Similarly, Zouk intend to use the SIAM to develop awareness amongst ESG investors of the cleanweb sector, to help the sector mature and encourage future investment.

The primary difficulty that Zouk encountered with the Enablers is that they do not distinguish media substitution from process optimisation, Zouk therefore added a fourth category of "Improve", primarily to distinguish media substitution (Figure 39).

Adoption of the Enablers suggests that they fit the data sufficiently to be usable, with sufficient **mutual exclusivity**. In order to distinguish "old" from "new" approaches to resource efficiency, the SIAM adds a fourth Impact Method ("Improve"). This does not question the **exhaustiveness** of the Enablers because the media substitution that is distinguished can alternatively be described as an orthogonal dimension rather than a fourth category, as in the SGM (Section 9.2).

7.5.6 EVALUATING THE SIAM

The SIAM appears a strong basis for the sustainability analysis of resource efficiency and cleanweb companies. Two potential issues with the SIAM are that, to be even-handed, it should capture potential negative impacts for sustainability as well as positive ones, and that if efficiency measures are to be quantified, the counter-productive impact of rebound effects should be considered (Section 2.3.4).

7.5.7 LIMITATIONS

The main limitation of this case study is that the adoption of the assessment methodology is still at an early stage, and so data is not yet available to further assess the success of its implementation.

7.5.8 CONCLUSIONS

This case study shows that the first component of the SGM, the Enablers can be an **effective and useful classification for practitioners.** Although the implementation is still at an early stage, the spontaneous adoption of the Enablers by a significant investor in cleanweb companies as a basis of their investment policy builds confidence in the validity of the classification and the underlying theory, and particularly their **utility** to practitioners.

CHAPTER 8 COMPARING THE DISTRIBUTION OF RESEARCH AND ENTREPRENEURSHIP

8.1 INTRODUCTION

The observations of Sustainability by ICT practice and research in Phase 1 lead to the hypothesis that **social systems and cleantech catalysts are more prevalent in cleanweb entrepreneurship than ICT4S research**. Phase 2 has developed the enabler and DD axes of the SGM1 classification of DDS that can now test this hypothesis, as they distinguish social systems as **coordination systems**, and cleantech catalysts as **push systems**. This chapter commences Phase 3 of the research, which employs the SGM1 to test the hypotheses by investigating **whether coordination systems and push systems are more prevalent in cleanweb entrepreneurship than ICT4S research**. By applying the SGM1, this chapter will also evaluate **whether the Smart Green Map classification is effective and useful.**

This chapter will employ methods detailed in Section 7.2 to undertake a simple quantitative comparison of contemporary Sustainability by ICT. A fresh sample of academic papers from ICT4S and SHCI conferences[131] will be compared with a sample of startups from the Ecosummit conferences[132]. The results are described in Section 8.3, and discussed in Section 8.4. The new data will also enable the development of a lower-level structure of "submarkets" of the SGM, to support more **granular** quantitative comparison between literature and entrepreneurship, so that **Sustainability by ICT systems can be classified more effectively and usefully**.

8.2 METHOD

The aim of this study was to investigate a sample of DDS within recent research and startups, to test out the SGM1 classification developed in the previous chapters and to develop it.

8.2.1 SAMPLING AND COMPARABILITY

To maximise comparability the samples both consist of all the research papers or startups from the leading Sustainability by ICT conferences based in Europe. The startups are from

[131] ict4s.org
[132] ecosummit.net

recent Ecosummit conferences[133] and compared with compared with academic papers are from the recent ICT4S conferences[134], as well as some SHCI papers from the CHI conference.

To sample contemporary ICT4S and SHCI, this investigation gathered all the papers from: the last two ICT4S conferences (2014 & 2015); the "ICT innovations for sustainability" volume (2015); the proceedings of the last CHI conference (2016); and a co-located workshop specific to SHCI. The number of research papers and companies that were successfully classified and the number excluded are shown in Table 42, by source event or publication.

It can be assumed that the annual ICT4S conference is the central forum for research identifying as "ICT4S", which is confirmed by the action research of Phase 1.

ICT Innovations for Sustainability is a seminal volume of papers from across the field of ICT4S (L. Hilty & Aebischer, 2015). Seven papers focused on a DDS, forming most of section IV *Saving Energy And Materials Through ICT–Enabled Solutions.*

A closely related area to ICT4S is Sustainable Human-Computer Interaction (Section 2.2). Research in SHCI is often presented at CHI, the Conference on Human Factors in Computing Systems[135], a general HCI conference. The Proceedings of the 2016 CHI were downloaded, a total of 545 papers. A search term was devised to identify those papers of potential relevance to sustainable resource use.

sustainab[136] (energy OR food OR water OR efficien OR agricultur OR waste OR materials OR carbon OR grid OR transport OR renewable OR power)

80 papers were identified with the search terms. To these were added 8 papers from the co-located workshop on *Design patterns, principles, and strategies for Sustainable HCI[137]*. Many papers were excluded from this study as they did not mention sustainability in the body of the paper, or only in the non-environmental sense. 22 papers were identified of likely relevance, and of these only 10 identified a specific DSS that could be classified. Many SHCI papers were excluded from this study of DSS as they took a high-level strategic perspective on the nature of the field and its challenges, or how to support it, or discussed the design process of ICT4S systems rather than focussing on a type of DDS.

Ecosummit is the largest event encountered during the AR (Section 3.4.1) that showcases startups creating cleanweb systems (DDS). Ecosummit is *"Europe's leading smart green innovation and impact conference for startups, investors and corporates"* (Hess & Butter, 2016).

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[133] ecosummit.net
[134] ict4s.org
[135] http://www.sigchi.org/conferences/index_html#chi-conf
[136] "Sustainab" and "efficien" allows for different word endings like "sustainability" and "sustainable"
[137] https://openlab.ncl.ac.uk/sustainabilitypatternsworkshop/

All the startups at Ecosummit address resource and sustainability challenges, including many notable cleanweb startups from across Europe. Unlike other cleantech industry events, Ecosummit has an explicitly "smart" agenda. Whilst some startups pitch purely physical cleantech such as photovoltaic cells, the majority are developing software as part of their value propositions. Originally called "Green Venture Summit", it was renamed "Ecosummit" in December 2010 when it adopted the digital focus and the slogan "Smart Green Business Network". Since then it has run every year in Berlin, as well as London since 2013, and now also takes place in Amsterdam, Stockholm and Paris. Startups compete for the Ecosummit award[138], incentivising participation. Most startups at Ecosummit are just a few years old, but mature enough to need investment.

All the companies from the last Berlin and London Ecosummits were gathered. This sample was chosen to represent contemporary cleanweb entrepreneurship because it is very comparable to the ICT4S sample. Ecosummit is likely to be as representative of contemporary European DDS-producing startups as the ICT4S conference is of DDS-focussed research papers. That a company is able to participate implies that it has reached a minimum level of development. Ecosummit startups form a fresh sample of contemporary companies to test the SGM, separate from the older Crunchbase data and the other sources from which the SGM was derived.

	Classified companies or research papers	**Including multiple SGM classifications**	**Unclassified**
Research papers	**57**	**62**	**66***
CHI conference	8	8	11*
ICT4S conference 14	19	22	30
ICT4S conference 15	20	22	22
ICT Innovations for Sustainability	8	8	2*
Sustainable HCI Workshop	2	2	1*
Startups	**59**	**68**	**41**
Ecosummit 15 London	25	30	15
Ecosummit 16 Berlin	34	38	26
Total	**116**	**130**	**107***

Table 42 Number of research papers and companies that were successfully classified by source event or publication. Also shows items that were classified in more than one category (second column) and items that were excluded because they could not be classified (third column).
** The CHI conference, SHCI workshop and ICT Innovations for Sustainability samples were pre-filtered so the figures for unclassified papers are not complete.*

[138] http://ecosummit.net/award

8.2.2 CLASSIFICATION

Over 200 papers and companies were analysed individually. A DDS - or more generally some enabling impact with potential resource sustainability benefit - was sought that was the primary focus of the research paper or primary product of the company. Information about the DDS was mostly found in the abstract of the paper, or the "product / solution" section of the company website. Where this was not clear, the rest of the paper or the website was consulted for clarification. The aim was only to identify any DDS, so only relevant information was considered. An encountered DDS was categorised into the six SGM1 markets – the social variation in its enabling impact (Enabler) and the way it supports decoupling (DD) - as well as by the type of resource. Interpretation was required to prioritise the most typical EIC to determine the Enabler, or to prioritise the most valid sustainability claim to determine the DD. Many papers and companies stated explicitly why the DDS was deemed sustainable, but others did not and required interpretation.

116 individual startups or research papers referred to DDS, and all were categorised successfully (Table 42). 14 out of these were categorised in two different markets, so a total of 130 classifications were made. This was for a variety of reasons: some gave two DDS equal prominence, whilst others describe a single DDS that worked in multiple ways.

62 classifications were made for research and 68 were made for startups. Having a similar total number for each made comparison straightforward, and many of the graphs below count total classifications (labelled "startups + research papers"). One research paper is not necessarily equivalent to one startup, but they both represent approximately 1/70 of the full sample.

Papers and startups were classified that focused on a particular DDS or some aspect of enabling impact for sustainable resource use. 109 out of 249 papers analysed were not classified for the reasons shown in Table 43.

Reason	Explanation	Research Papers	Companies
Physical	Companies that didn't focus on digital technology at all. These mostly offered "physical" cleantech such as solar panels or wind turbines (Section 3.5.2)		33
Green in ICT	Research and companies that focused on reducing the first order effects of ICT (Sustainability in ICT)	23	2
N/A	No DSS identified, miscellaneous reasons.	16	2
Institutional or non-resource focussed	Research and companies that focussed on a type of digital system whose primary aims did not include sustainable resource use. They generally addressed another	8	1

	objective of institutional change such as sustainability politics.		
ICT4S design and support	Research that discussed the design of ICT4S systems and supporting ICT4S as a field, rather than a particular DSS.	6	
Strategic	Research that took a high-level strategic perspective on the nature of the field and its challenges rather than focussing on a type of digital system.	6	
Systemic	Research that investigated the macro-scale Structural Impacts (third-order) of digital systems, and rebound effects	6	
Duplicate	Some appeared in two conferences or publications	2	1
Not found	Company now not trading		2
Social pillar	About non-environmental aspects of sustainability	1	
Total		**68**	**41**

Table 43 Research papers and companies that could not be categorised with the SGM.

8.2.3 DEVELOPING SUBMARKETS

In addition, the qualitative classification development process of Phase 2 (Section 4.2) was continued using the fresh sample of DDS, to identify a more granular level of categories below the six markets of the SGM1. The startups and research papers identified within each of the six markets were sorted and resorted to identify a submarket structure. In parallel, the "digital genres" previously identified in Table 25 were reviewed and simplified. Items were categorised, and then through constant comparison, and for consistency and comparability as the submarkets developed, they were later re-categorised with the latest version of the submarkets.

8.3 RESULTS

8.3.1 SGM2: EMPIRICAL SUBMARKETS

A number of new "submarkets" within each market were identified by the qualitative analysis, forming the next version of the Smart Green Map (SGM2, Table 44). This forms an early draft of a submarket structure. At this stage, these submarkets are taxonomic, derived by grouping examples, rather from a conceptual basis.

The most popular submarkets were described in Section 5.4.

autoSave	iSave	weSave
Automatic Optimization	Individual Behaviour Change	Sharing Economy
Efficiency Maintenance automation	Resource Administration	Resource coordination
Resource Computation	Broadcast media	Virtual Network
Automated Resource coordination		Social Behaviour Change
		Efficiency Maintenance coordination
		Resource Crowd Analysis
autoPush	**iPush**	**wePush**
Production automation	Marketing and Choosing	Market and Finance
Usage automation	Usage Monitoring and Guidance	Design coordination
Automated Procurement	Design Tool	Usage coordination
	Production Monitoring and Guidance	Production coordination

Table 44 SGM2 with tentative submarkets developed from the ICT4S literature / Ecosummit startup comparison

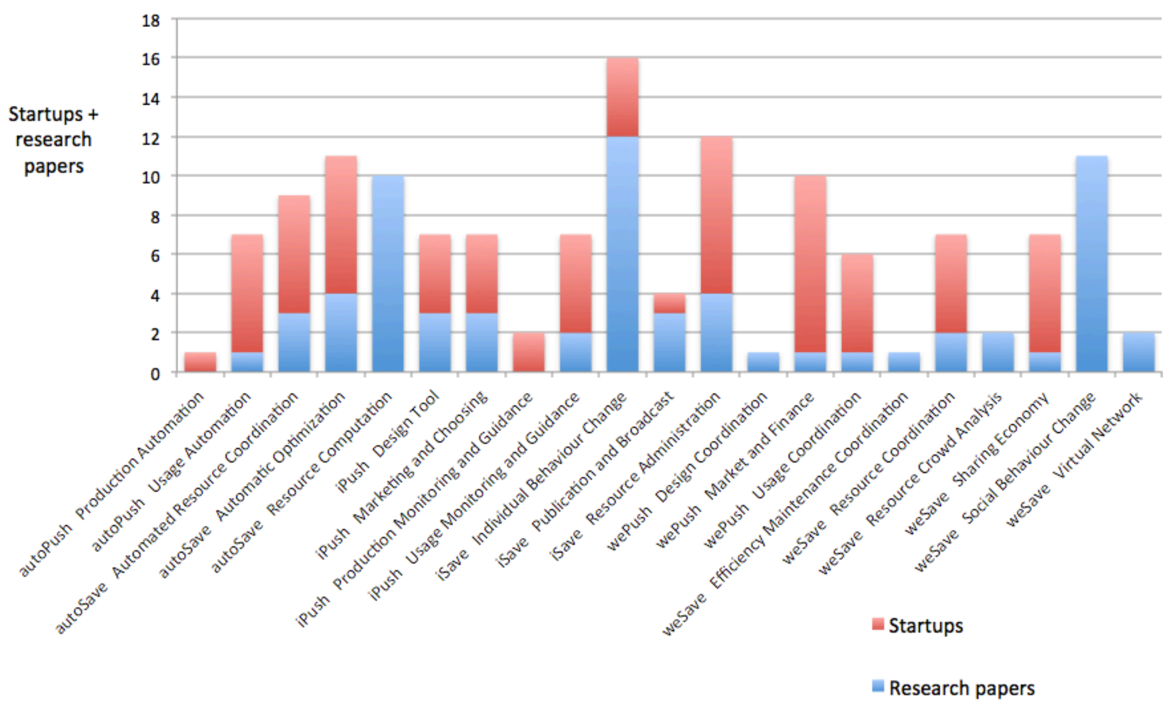

Figure 45 Submarkets by number of Ecosummit startups and ICT4S papers

8.3.2 DISTRIBUTION OF RESEARCH PAPERS AND STARTUPS

The papers and startups that were classified in this study are organised on the final version of the Smart Green Map in Chapter 9 (Figure 61, Table 52).

Figure 46 shows the distribution of research papers and startups between the six markets. Startups were divided equally between save systems (51%) and push systems (49%). In contrast, ICT4S research was heavily focussed on save systems (82%), with much less research on push systems (18%). In particular, there was almost no research on autoPush and wePush systems (Figure 46). This is confirmation of the hypothesis, developed from the literature analysis and action research of Phase 1, that ICT4S research is not covering the range of catalysis of cleantech (push) observed in cleanweb entrepreneurship. The overall distribution between the three Enablers was similar for both research papers and startups, in the ratio automation 27% : augmentation 39% : coordination 34% ±1% (Figure 47). autoPush was the least popular type of system for both startups and papers.

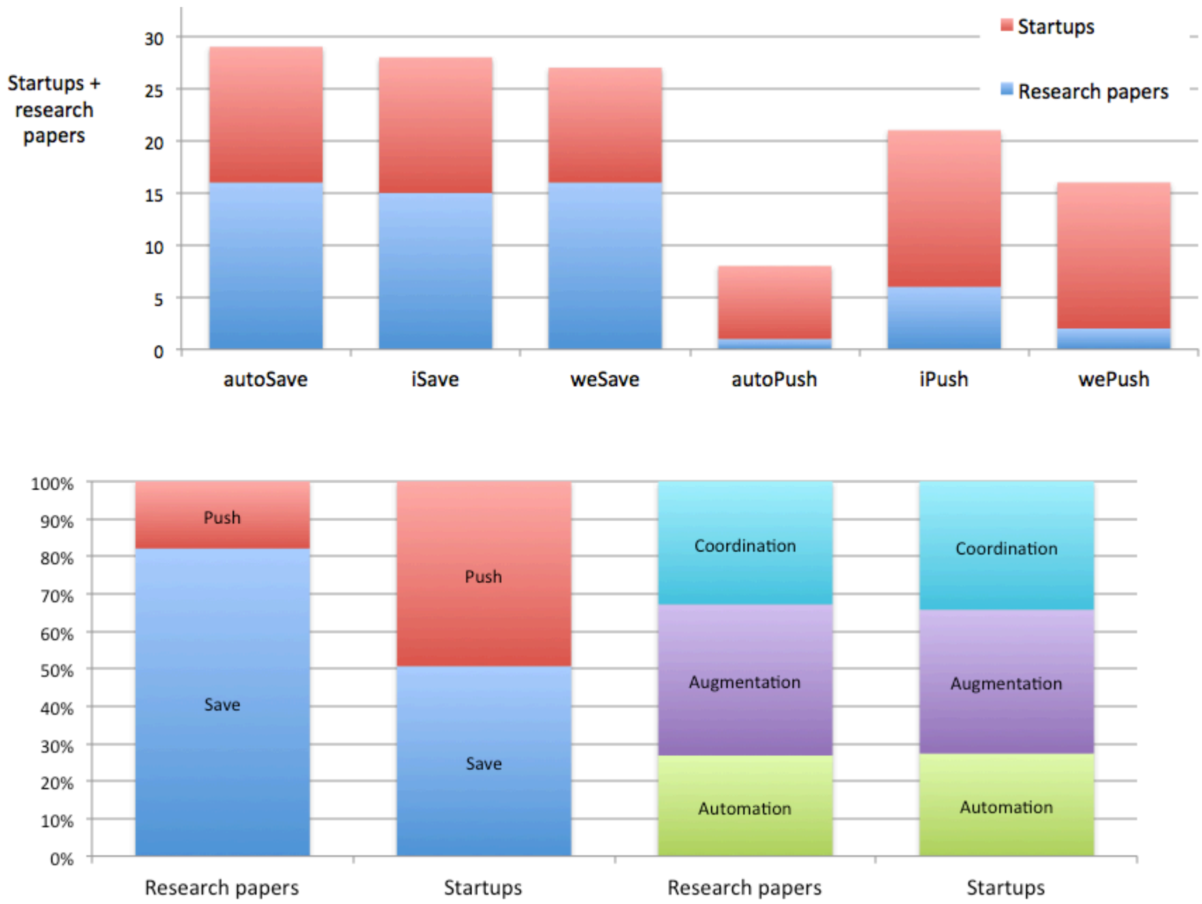

Figure 46 Distribution of ICT4S / SCHCI research papers and Ecosummit startups between the six markets, decoupling directness, and the three Enablers.

Figure 47 shows the distribution of research papers and startups across the submarkets within each of the six markets. Considering coordination systems i.e. social systems, which are the subject of the hypothesis. Coordination startups are distributed across fairly evenly between save systems (weSave) and push systems (wePush), and across a number of submarkets: “sharing economy”, “resource coordination”, “usage coordination” and “market and finance”. In contrast, research papers about coordination systems are largely concentrated in just one submarket of save systems, “social behaviour change”, which describes persuasive technologies that emphasise interactions between participants to facilitate new behaviours. An example is the Social Electricity system of Kamilaris et al. (2015) *“a large-scale green online social application which targets influencing people to reduce their electricity footprint.”* Sharing Economy systems are an example of a submarket of coordination and save systems (weSave). Six companies created Sharing Economy systems, such as Finnish peer-to-peer delivery startup PiggyBaggy[139], but only one research paper investigated a Sharing Economy system.

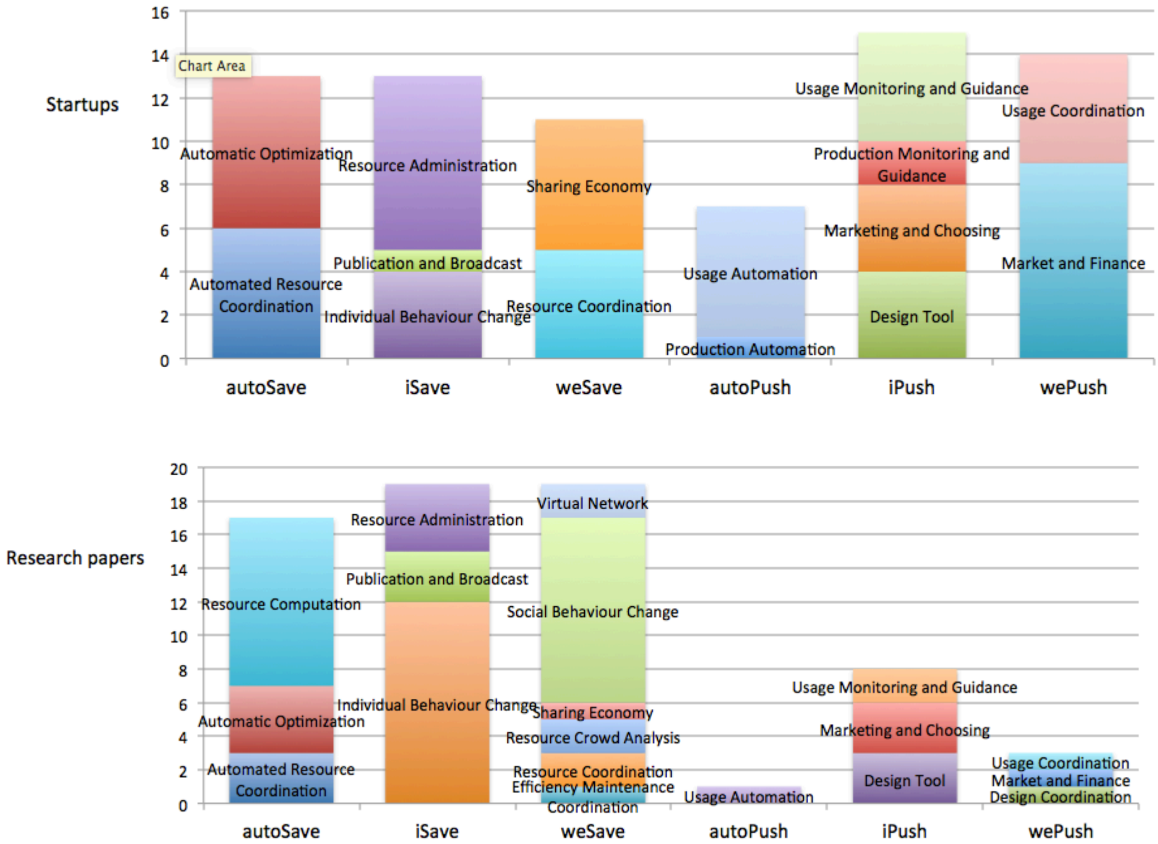

Figure 47 Comparing the distribution of submarkets within ICT4S / SCHCI research papers and Ecosummit startups.

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139 http://piggybaggy.com/

Organising the research papers by event or publication in Figure 48 shows that the papers on both push systems and weSave systems were mainly from ICT4S 2105, suggesting that research into push and weSave systems may be a more recent development.

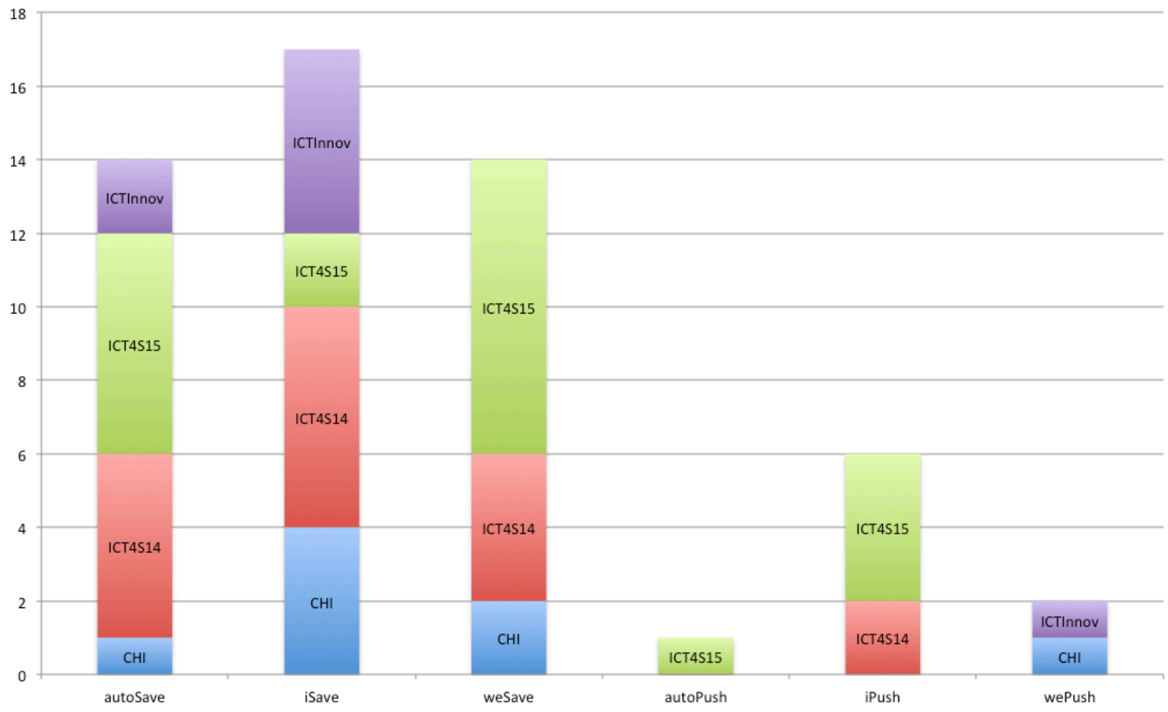

Figure 48 ICT4S research papers organised by event or publication. Research paper sources: ICT4S 2014 conference (ICT4S14); ICT4S 2015 conference (ICT4S15); CHI conference (CHI); and ICT Innovations for Sustainability publication (ICTInnov).

Within the systems classified as automation systems, a subset were identified that also shared much in common with coordination systems. In these systems, the automation coordinated the interests of different actors. Examples include:

- Demand response or smart grid optimisation systems in which assets are automatically modulated in order to balance supply and demand. Such Ecosummit startups included Upside Energy, Kiwigrid, and Sympower.
- Marketplaces in which artificial intelligence agents trade on behalf of human actors.
- Smart contract systems based on blockchain that automate rules of social exchange.
- A motorway of interacting driverless cars.
- Automated peer-to-peer file distribution
- Volunteer computing, where private computer users share processor capacity to form a virtual supercomputer

8.4 DISCUSSION

8.4.1 PUSH SYSTEMS ARE MORE PREVALENT IN ENTREPRENEURSHIP

The results have shown that the ratio of save:push systems for the research papers was around 80:20, whilst for the startups it was 50:50 (Figure 46), supporting the hypothesis that ***push systems are more prevalent in cleanweb entrepreneurship than ICT4S research***. Half of cleanweb startups create push systems, so they likely constitute considerable economic value and sustainability benefit and thus merit investigation. The small amount of research into push systems was mainly that submitted to the most recent sample, the ICT4S 2015 conference, which may indicate that research interest is beginning to increase.

The dearth of ICT4S research into push systems compared to the sample of startups may be because they may function very similarly to most other commercial ICT systems in supporting the growth of a product, rather than the more specifically environmental objective of save systems to increase resource efficiencies. The research problems may therefore be the less specific to ICT4S. The next chapter will clarify this with a model of the Decoupling Directness distinction (Figure 54).

Push systems are also intrinsically consumerist, as they ultimately promote the consumption of a product, albeit one that is more benign environmentally. Nevertheless the antagonism between the consumerism of push systems and the values of sustainability has not deterred a large amount research into save systems that targets "marginal behaviour change through self-interested consumer enticements" as Knowles observes. (Knowles, 2014).

8.4.2 ICT4S AND EXTERNAL RESEARCH INTO PUSH SYSTEMS

Even though ICT4S research into push systems appears limited it encompasses a considerable variety of applications. Most prominent are renewable energy through the smart grid (Sonnenschein et al., 2015) and household retrofitting (Massung, Schien, & Preist, 2014; Christopher Weeks, Delalonde, & Preist, 2015). Bicycles (Claes, Slegers, & Vande Moere, 2015) and organic food (Bohne, Zapico, & Katzeff, 2015) have also been pushed. Retrofitting includes many different forms of cleantech.

"*In standard use, retrofitting is an amorphous term that encompasses a wide range of potential home interventions, from the relatively effortless and inexpensive (draught proofing, insulating hot water pipes and tanks), to the more costly and specialized: installation of high-spec double or triple glazing; insulation of solid walls, cavity walls, floors, and lofts; heat pumps; and solar thermal and solar PV systems*" (Massung et al., 2014).

As it is so generic, research into reducing barriers to retrofitting may have more general applicability to push systems (C Weeks, Delalonde, & Preist, 2014; Christopher Weeks et al., 2015).

The action research experiences suggest that there are many research problems specific to pushing cleantech that require research within ICT4S. They relate to several external fields, but none treats them specifically enough. For instance, one research project is developing a decision support tool to help wind farm developers decide when to schedule blade-lifting operations, given variable British weather conditions and financial constraints (McMillan, 2017). This may require interdisciplinary theory from accountancy, engineering, meteorology and HCI. However, the research problem must integrate all of them to resolve a problem primarily faced by an industry that must move large, expensive and delicate components in windy conditions. There must be a large number of such specifically cleantech push problems for ICT4S to address.

Section 9.4.4 continues this discussion by arguing that the dimensions of the SGM3 can identify which industries are relevant to particular Sustainability by ICT research problems, and the disciplines from which methods and results can be imported and integrated in order to address them. There is an opportunity for future work to develop the SGM into a framework for identifying these fields and industries systematically. This would help ICT4S researchers employ systematic interdisciplinarity to investigate *push systems for sustainability*.

8.4.3 THE DISTRIBUTION OF SOCIAL VARIATION IS MORE AMBIGUOUS

This study has also tested the social variation in DDS, based on the definitions of the Enablers developed in Section 5.3. The results are more ambiguous. Research papers and startups were distributed similarly across the three Enablers in the approximate ratio automation 27% : augmentation 39% : coordination 34%. This suggests **coordination systems are just as prominent in both research and entrepreneurship**, which contradicts the hypothesis. In contrast it is automation systems – the least social systems - that are the less popular category, but this is similarly true for both research and startups. In particular, almost no research focuses on autoPush systems, and not many startups do either.

Further analysis may explain the disagreement between the hypothesis based on the action research observations, and this chapter's results. Research interest in coordination systems appears to have developed rapidly in 2015, after most of the action research was complete (Figure 48). However, these conclusions are speculative as data was not included about earlier research activity.

Furthermore, ICT4S research addresses a relatively narrow range of coordination systems, with almost no research into other coordination submarkets such as Sharing Economy systems. Instead, research into coordination was highly focussed on just one area, Social Behaviour Change. As Kamilaris notes *"Numerous green online social applications have emerged in recent years, aiming to motivate citizens towards pro-environmental behavior. These applications exploit emerging new technologies, such as mobile computing, online social networking and the web, in order to affect their users in their everyday lives."* (Kamilaris et al., 2015) This interest in Social Behaviour Change follows a decade of research into persuasive technologies (Section 2.3.3) (Fogg, 2003), which sit within the Individual Behaviour Change category of the Augmentation Enabler (iSave), and relate to the "Behavioural process optimisation" within the LES Model. Individual Behaviour Change was the most populated submarket of all, due to the large number of research papers (Figure 45).

The move from individual to social behaviour change within ICT4S has been noted by Huber & Hilty, who suggest that such research should now "introduce the social level" and "enable collective action" (Huber & Hilty, 2015). Similarly, Massung *et al.* note the prominence of ICT4S research into the third most popular submarket Automated Optimisation (autoSave) and the most popular submarket Individual Behaviour Change (iSave), before introducing their work on Social Behaviour Change (weSave):

"Sustainability research about using Information and Communications Technologies (ICTs) to reduce household energy consumption has recently focused on two potential strategies: "smart homes" that rely on sensors and technological innovations to automatically reduce the energy load, and tools that seek to persuade users to change their domestic habits, such as by using eco-feedback devices to raise awareness of the amount of energy used. We propose that there is another approach: support and encouragement of existing best practice within a community to spread it more widely" (Massung et al., 2014).

8.4.4 A FOURTH ENABLER: AUTINATION

That there was a subset of automation systems that had much in common with coordination systems shows that digital devices can represent the interests of different human actors, even without their active and conscious participation. So just as automation systems can substitute for one individual, they can substitute for multiple individuals with different interests. Automation can therefore be split into "personal" **automation**, and the new enabler of "**autination"** systems. The word "autination" was created by merging "automatic" and "coordination". The Enablers can then be visualised as a matrix of level of interaction between human actors (level of social interaction), and whether of not the technology supports them or substitutes for them (level of automation) (Figure 49). The level of automation is equivalent to the distinction between the technological and human levels of process optimisation in LES Model (2.3.1).

Autination includes some of the most fashionable areas of digital innovation, including the blockchain, smart contracts, decentralised agents and even driverless cars. Investigating this potential fourth enabler is an opportunity for future work.

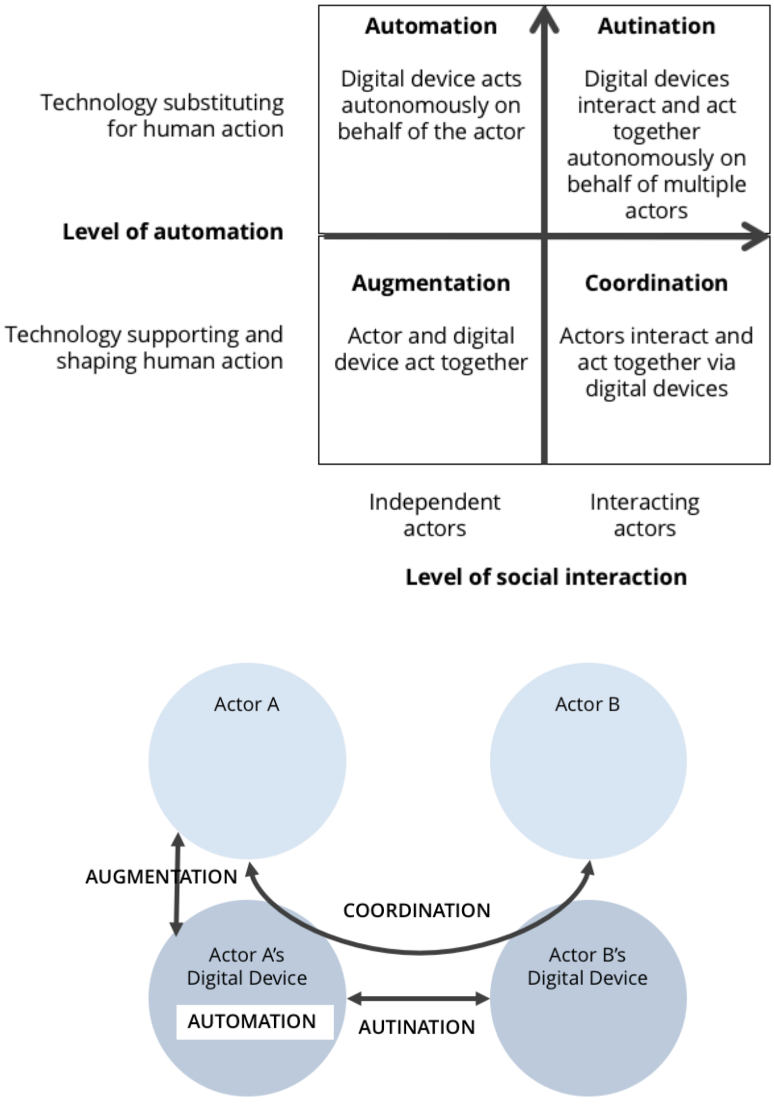

Figure 49   Four enablers, splitting automation into individual automation and autination

As these two new enablers are formed by splitting the previous automation enabler, this does not invalidate the exhaustiveness of the original three Enabler classification.

Autination automates social interaction. It therefore passes directly from the technological (automation) to the social (coordination), without requiring conscious participation on the part of the individual (augmentation). In the Enabling Impact Model (Figure 35), autination forms a "shortcut" by which automation can act upon the social context without first augmenting the action of a user.

8.4.5 SUBMARKET REGULARITIES

Regularities can be identified between many SGM2 submarkets, allowing them to be grouped across the Enablers into twos and three with similar properties (Table 50). These groupings of submarkets achieve similar results but employ different enablers to do so. Each set of two or three submarkets sit within push or save, but not both. This observed pattern suggests another important dimension is shaping the data that is not sufficiently described by the SGM2.

For instance, three push submarkets optimise the usage of a green product. "Usage automation systems" automate usage, such as Sonnen[140] whose algorithms optimise the efficient function of a smart domestic battery. Usage Monitoring and Guidance systems augment a user, such as SolarKiosk[141] which uses data gathering to optimise the user experience of solar-powered internet booths in developing countries. "Usage coordination systems" obviously coordinate usage, such as PlugSurfing[142] that uses a mobile app to coordinate drivers with a network of electric vehicle charging stations.

The regularities appear to relate to processes of production and consumption such as design, manufacture, usage and maintenance.

In terms of the LES Model, almost all the identified submarkets appear forms of process optimisation, whether behavioural or organisational, where information is used to control a process in order to minimise its use of resources. The only exceptions are "Broadcast media" which equates with media substitution in the LES Model, and "Virtual Networks" (i.e. telepresence). Both are what Zapico terms dematerialisation that "replace atoms with bits" (Section 5.4.2). These two submarkets are forms of save system. Therefore, save systems appear to function through both process optimisation and media substitution, whilst push systems function by process optimisation alone.

However, process optimisation works in save systems works quite differently than in push systems. In save systems process optimisation minimises the environmentally harmful resources used to undertake the process. In contrast, in push systems, processes are optimised to maximise the adoption of a more sustainable product. Push systems therefore

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140 https://sonnenbatterie.de
141 http://solarkiosk.eu/
142 https://www.plugsurfing.com/

optimise to maximise the commercial success of the product rather than to minimise the impacts of its production and use.

			autoSave	iSave	weSave
Save	Optimisation and mobilisation	Small scale	**Automatic Optimization**	**Individual Behaviour Change**	**Social Behaviour Change**
		Large scale	**Automated Resource Coordination**	**Resource Administration**	**Sharing Economy Resource Coordination**
		Resource analysis	**Resource Computation**	?? Also resource crowd analysis. Not sure whether to split	**Resource Crowd Analysis**
		Maintainance	**Efficiency Maintenance Automation**	*?? Efficiency Maintenance Monitoring and Guidance*	**Efficiency Maintenance Coordination**
		Disposal	**??**		
	Substitution with ICT (dematerialisation)		??	**Broadcast Media**	**Virtual Network**
			autoPush	iPush	wePush
Push	Substitution through optimisation and mobilisation	Usage	**Usage Automation**	**Usage Monitoring and Guidance**	**Usage Coordination**
		Marketing	**Automated Procurement**	**Marketing and Choosing**	**Market and Finance**
		Production	**Production Automation**	**Production Monitoring and Guidance**	**Production Coordination**
		Design	?? Computational creativity	**Design Tool**	**Design Coordination**

Table 50 An early attempt to organise the submarkets in similar groupings

8.4.6 EVALUATION OF SGM1 COMPONENTS

This classification of Ecosummit startups and ICT4S papers has generated some evidence to assess the SGM1 classification of two axes and six markets (Section 6.2.1) against some of the evaluation criteria identified in Section 4.3.

The SGM has been successfully employed to test the hypotheses about the distribution of research activity, confirming one and largely refuting the other. That this was possible is evidence of the **effectiveness** of the classification. All the DDS identified could be successfully categorised into at least one market, and thus at least one enabler or DD. This is evidence that the SGM is an **exhaustive** classification of DDS.

Most DDS could be categorised straightforwardly into the most relevant market and submarket. Only 14 of 116 were placed in two different submarkets. This is evidence that the process of interpretative prioritisation makes the SGM classification sufficiently **mutually exclusive**. However, this process of interpretive prioritisation may mask systematic overlap.

Indeed, there is clear overlap between save and push systems, which is reflected in the ambiguity of some SGM2 submarkets. There are systems that have a strong claim to different submarkets in both save and push. For instance, Sonnen[143] use algorithms to optimise the efficient function of a smart domestic battery. Because these algorithms save resources, it is an automation "optimisation" system (autoSave). However, by saving resources the algorithms support a green product i.e. the domestic battery, and indeed the uptake of domestic solar energy more broadly. It is therefore also a "usage automation" system (autoPush).

8.4.7 LIMITATIONS

This comparison employed a simple quantitative method as it was sufficient for a basic test of the effectiveness and usefulness of the SGM classification, whilst also developing it. The classification was undertaken by the researcher. Future work could ask a number of participants to undertake the classifying procedure to generate more statistically robust evidence of effectiveness and utility.

Conference-based sampling is an arguable limitation of the study. Valid conclusions can be drawn about the ICT4S and Ecosummit conferences, but generalisations to the whole of scholarship and entrepreneurship globally require the conferences to be representative. Conference content will depend on the processes that formed them, including awareness of the conference brand, self-identification with it, willingness to pay the conference fee, ability to attend, and the interests and vision of the reviewers or curators. Although the ICT4S conference is a sample of self-identifying ICT4S research activity, there will be relevant research within and beyond it communities such as Green IT, ICT for Energy Efficiency, Green Information Systems Environmental Informatics, Energy Informatics, Sustainable HCI and Computational Sustainability (Section 2.2). This process could be improved with a future systematic literature review and analysis of the whole startup sector, which could address this by accessing as complete a sample of the literature as possible via a search engine, or of startups by using a commercial database.

Another possible quantitative limitation of this analysis was that it only considered the main focus of the research paper, not every digital system investigated in the papers, which may possibly have shown a broader range of systems.

Although many HCI papers were examined, few contained an explicit focus on DDS, so the sample was too small to draw reliable conclusions about the distribution of SHCI research within the SGM.

[143] https://www.sonnen-batterie.com/en-us/start

8.4.8 CONCLUSIONS

The action research experiences of Chapter 3 compared communities that address Sustainability by ICT, from which emerged a hypothesis that **social machines and push systems are more prevalent in cleanweb entrepreneurship than ICT4S research**. This chapter has tested the hypothesis by using the SGM1 developed in the previous chapters to classify a sample of ICT4S / SHCI research and compare it to a sample of cleanweb startups from the Ecosummit conference.

This successful deployment is evidence that **the Smart Green Map classification is effective and useful**. Table 52 organises all the literature and startups encountered by the final version of the Smart Green Map, SGM3 forming the final results of this chapter (Figure 61 in Section 10.3 and Table 52 in Chapter 9). To improve the Smart Green Map further, submarkets were identified empirically within each of the six markets, forming the next version, the SGM2 (Table 44). Further analysis also suggested that the enabler classification might better describe **how DDS combine people and digital technology** by defining a fourth enabler called Autination (Figure 49) in which the interests of different interacting actors are represented automatically, such as in demand response systems (Hinrichs, Sonnenschein, Gray, & Crawford, 2015), blockchain smart contracts, and trading with artificial intelligence agents.

In conclusion, this chapter has validated the hypothesis **that push systems are more prevalent in cleanweb entrepreneurship than ICT4S research**, but the same is not now true for social systems. This result depends on the conference-based samples being representative of the industry or research field as a whole.

The next chapter will now compare the results so far with strategic conceptualisations of ICT4S.

CHAPTER 9 DISCUSSION

9.1 INTRODUCTION

This chapter discusses the SGM classification in relation to various conceptualisations of Sustainability by ICT, the state-of-the-art LES Model, the Circular and Sharing Economies, and economic quantifications of the enabling impacts of ICT.

The Enablers and DD were derived and defined in Phase 2, which first classified DDS into a typology of six markets, the SGM1. The classification study of the previous chapter resulted in a more granular level of classification, the submarkets of the SGM2 (Table 44). Unlike the typological SGM1 markets, these taxonomic SGM2 submarkets have been derived empirically, lacking a conceptual basis.

Section 9.2 identifies a correspondence between the SGM2 submarkets derived empirically, the processes of production and consumption of the LES Model, and processes of the Circular and Sharing Economies. This allows the submarkets to be conceptualised as processes of the Circular and Sharing Economy, developing **the conceptual basis for the observed variation in DDS.** This link then forms the basis of a final version of the SGM and the ultimate contribution of this thesis, the SGM3, onto which the literature and startups from Chapter 8 are organised (Figure 61, Table 52). The SGM3 uses the four-category Enablers typology identified in Section 8.4.4, although much of this Chapter still uses the earlier three-category model derived in Chapter 5.

The scope of the SGM3 is the enabling impacts of DDS. It can therefore substitute for the Enabling Impacts level of the LES Model to show **how leading conceptualisations of ICT4S can better describe social systems, cleantech catalysts, the Circular Economy and the Sharing Economy**. This addresses the limitations of the LES Model first identified in the action research and literature review **(**Section 3.7**).**

Section 9.3 develops the **conceptual basis of the observed variation in DDS** with regards to their **catalysis of cleantech** by modelling the save and push impacts with the theory of resource-use hierarchies that underlies the LES Model. This allows the mutual exclusivity and exhaustiveness of the Save and Push categories to be determined.

Section 9.3 uses the SGM to organise quantitative analyses of **DDS's benefit to sustainability.** It identifies ICT4S research that has measured save impacts, and how macroeconomic research into ICT-enabled productivity could be a proxy for push impacts.

The encountered measurements can be organised into the Enablers, adding further evidence that the **SGM classification is effective**. It argues that some DDS can both save and push, so both save and push impacts should be measured for each DDS. It suggests that the enabling impacts at our disposal are growing in line with digital innovation and adoption, but modelling this growth is an opportunity for future work.

The last Section (9.4) returns to the strategic ICT4S literature. The SGM and LES Model are used to identify five themes that encompass almost all the categories within the existing conceptualisations of Sustainability by ICT identified in Section 2.3 as shown in Table 58. The ability to organise existing conceptualisations, which are limited to just part of the SGM adds to the evidence that **it is effective and useful.** The chapter finishes with an opportunity for future work using dimensions of the SGM to develop a typology of those DSS that effect institutional change rather than dematerialisation of resource use.

9.2 SGM AND THE CIRCULAR AND SHARING ECONOMIES

This section identifies a correspondence between the processes of production and consumption of the LES Model, the submarkets identified in Chapter 8, and the processes of the Circular and Sharing Economy. This link then forms the basis for a final version of the SGM, the SGM3, which is then used to organise the literature and startups classified in Chapter 8.

9.2.1 PRODUCTION AND CONSUMPTION, CIRCULAR AND SHARING ECONOMY

Section 8.4.5 identified regularities in the submarkets of SGM2 as shown in Table 50. The regularities appear to relate to processes of production and consumption such as design, manufacture, usage and maintenance. This links the SGM2 submarkets to the enabling impacts of the LES Model, which are organised by processes of production and consumption.

The enabling impacts of the LES Model do not specify the identity of the processes of production and consumption. To map out the possibility space along this production/consumption dimension requires a list of processes. Processes of production and consumption could be grouped or divided in different ways, and different products undergo very different processes, so it may not be realistic to seek a single definitive list. A moderately exhaustive and granular list of such processes would suffice to form a supplementary dimension of the SGM. Where can such a list be found?

One list is given by the linked life cycle model but it is too short. It identifies the role of ICTs in optimising **design, production, use and end of life**, as well as substituting for and inducing **demand** (Section 2.3.5).

A source for more granular list can be found in the concept of the Circular Economy, a community that was engaged with during the action research of Phase 1 (Section 3.4.3). The Circular Economy *"is an alternative to a traditional linear (make, use, dispose) [economy] in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life"* (P. Mitchell & James, 2015). Figure 20 shows two models of the Circular Economy, forming cycles of production and consumption.

Using Circular Economy processes in the SGM has the dual benefits of including both circularity and sharing. Although prominent in Sustainability by ICT practice, neither circularity nor sharing are described by the LES model (Section 3.4.3).

There is a strong link between circularity and sustainability. The most "circular" processes such as recycling, reuse, refurbishment and maintenance have a strong popular association with the concept of sustainability. Blumendorf argued for circularity in ICT4S at the firsr ICT4S conference, being awarded best paper (Blumendorf, 2013).

The Ellen MacArthur Foundation model of the Circular Economy also includes sharing and reuse processes. Therefore, integrating Circular Economy processes with the SGM can also integrate the Sharing Economy, another major community of Sustainability by ICT practice engaged with during the action research, and a major submarket of DDS identified in Chapter 8.

Figure 51 integrates the two models of the Circular Economy with the SGM2 submarkets to form a list of processes of production and consumption. The observed variety of DDS within the SGM2 submarkets (Table 50) could relate to production and consumption processes of generation (power generation/minerals extraction/farming), logistics, design, manufacture, marketing, retail/purchase, use, maintenance, refurbishment, reuse, collection and disposal. Figure 51 combines the processes list with the Enablers dimension to map out the possibility space for ICT enabling impacts on production and consumption.

Two processes that were added to the Circular Economy list were **analysis** and **media substitution**. A prominent area of research identified in SGM2 submarkets was the analysis of data and knowledge by computers or the crowd as a contributing step in the creation of a product. Media substitution is an exceptional category as it functions differently than the process optimization of the other categories.

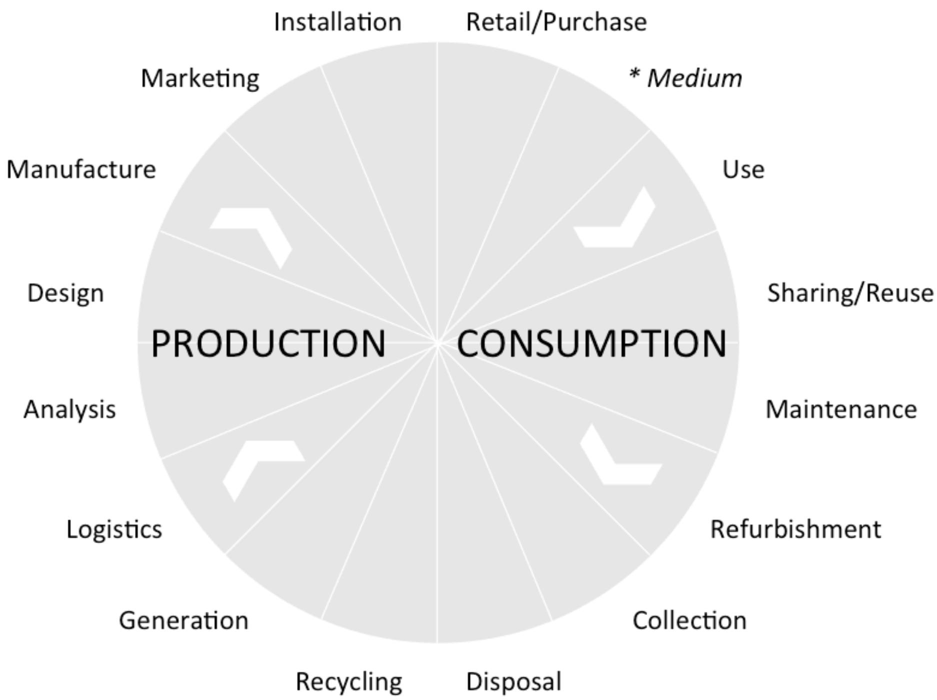

Figure 51 Matrix showing the space of possibilities for impacts on production and consumption: a non-exhaustive list of processes based on the Circular Economy Model and SGM2 submarkets. All are process optimisations, except for "medium" which is media substitution.*

9.2.2 SGM3 MAP OF LITERATURE AND STARTUPS

This investigation has identified five dimensions for classifying cleanweb systems (DDS). All of these categories are important to Sustainability by ICT practice, but none is well described by the LES Model. This section integrates five discrete dimensions to form the final version of the Smart Green Map, the SGM3, as illustrated in Figure 61 (Section 10.3). The values identified along each dimension are listed in Table 60 (Section 10.3). The sample of recent ICT4S/SHCI research and Ecosummit startups identified in Chapter 8 are organised onto the SGM3 in Table 52. The SGM3 is the ultimate contribution of this investigation, mapping out the space of possible Sustainability by ICT systems revealed by cleanweb entrepreneurship and ICT4S scholarship. The five dimensions of the SGM3 are:

- The **Enablers**, which distinguish the social variation in digital systems, as derived and described in Chapter 5. This includes social "coordination" systems that are not distinguished by the LES Model. It also includes the "cutting edge" fourth Enabler identified in Section 8.4.4, "autination", in which digital devices act and interact autonomously to represent different human actors. The Enablers constitute two dimensions: **level of social interaction** and **level of automation**.

- The **production and consumption processes of the Circular and Sharing Economies**. These were first identified as empirical submarkets in Chapter 8 and equated with processes of production and consumption within the Circular and Sharing Economy (Figure 20) in Section (9.2.1), fleshing out the concept of production and consumption processes within the LES Model.
- **Decoupling Directness (DD)** derived in Chapter 6 that distinguishes the “save systems” that have been the focus of much ICT4S research from the cleantech catalysing “push systems” that are common in cleanweb entrepreneurship. Figure 61 represents the SGM3 as two circular matrixes for save and push in which the Enablers form the radial divisions and the processes of production and consumption form the angular divisions. As many DDS both save and push simultaneously (Section 8.4.6), it may be useful to visualise these circles as two sides of the same disk.
- **Resource type.** The action research of Chapter 3 noted that organising by resource is a useful description of cleanweb systems, although not a sufficient one (Section 3.4.4). The list of resource types is based on the sustainability outcomes identified during the classification development of Phase 2 (Table 38 and Section 6.2.2). They are similar to existing classifications of cleantech (Section 3.4.1). Resource type is represented in Figure 61 with some illustrative icons, but omitted from Table 52 for simplicity.

Creating Table 52 was straightforward, as the submarkets of the SGM2 had already been organised by processes of production and consumption (Table 50). Table 52 shows how these DDS from research and commerce **are combining people and digital technology to benefit sustainability by developing a Circular and Sharing Economy and often by “catalysing cleantech”.** Section 5.4 has described the main submarkets i.e. the most populated cells within this matrix.

Within the terms of the LES Model, the subject of the SGM3 is the application of the enabling impacts of ICTs to making resource use more sustainable i.e. to dematerialization (Section 2.3.2). The Enabling Impacts level of the LES Model could therefore be substituted with the SGM3 itself (Figure 61). Key aspects of Sustainability by ICT could then be more clearly acknowledged by the Enabling Level: social “coordination” systems, cleantech catalysing “push” systems, and the Circular and Sharing Economy. The four Enablers agree with the technological/human distinction of the LES Model, but makes also distinguishes the level of social interaction, whether one actor or many.

Integration with the SGM3 would address the limitations with the LES Model identified in the action research and literature review (Section 3.4.6). The SGM3 recognises the divide between process optimisation and media substitution within the LES Model. However, it is not clear how “externalisation of control” fits within the SGM3 framework.

Figure 61 represents the SGM3 as two spinning wheels. The “save” wheel is the existing economy, and the “push” wheel is a “cleaner” economy of more sustainable alternatives. For structural dematerialisation to be successful (Section 2.3.4), DDS must “decelerate” the save wheel and “accelerate” the push wheel. The enabling impacts of DDS can be applied to strengthening the “axle” that recycles resources wasted by a linear economy. Effective save impacts are a “brake” on the save wheel, slowing down the flow of resources by making existing processes more efficient. Effective push impacts are a “motor” that accelerates the innovation and global adoption of environmentally beneficial technologies and products. The effectiveness of save or push impacts is dependent on rebound effects, as will be discussed in Sections 9.3.4 and 9.3.5 below.

	Production			
	Design	**Manufacture, logistics, generation, farming**	**Maintenance, refurbishment, recycling, collection, disposal**	**Analysis**
Coordination **weSave** **wePush**	**Design Coordination** • Creating sustainability through Smart City Projects. Gooch et al. • Everyday Food Science as a Design Space for Community Literacy and Habitual Sustainable Practice. Kuznetsov et al.	**Resource Coordination** • ICT system for SMART CITY management. Studzinski et al • Computational Modeling of Material Flow Networks. Moeller et al. • An Information System Supporting Cap and Trade in Organizations. Maranghino-Singer et al. REstore The CoSMo Company Mindconnect BEN Energy Grundgroen **Production Coordination**	**Maintenance and End-of-life coordination** • The Citizen Field Engineer: Crowdsourced Maintenance of Connected Water Infrastructure. Scenarios for smart and sustainable water futures in Nairobi, Kenya. von Heland et al. • Power law of engagement: Transferring disengaged householders into retrofitting energy savers. Weeks et al. • Big Data GIS Analytics Towards Efficient Waste Management in Stockholm. Shahrokni et al.	**Resource Crowd Analysis** • Citizen observatories of water: Social innovation via eParticipation. Wehn et al. • Toward Collaborative LCA Ontology Development: a Scenario-Based Recommender System for Environmental Data Qualification. Takhom et al.
Augmentation **iSave** **iPush**	**Design Tool** • GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. Mastrucci et al. • Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help. Weeks et al. • A systematic review of environmentally conscious product design. Li et al. The CoSMo Company Sefaira EcoChain OneShore Energy	**Resource Administration** • ICT system for SMART CITY management. Studzinski et al. • Supporting Sustainability Decisions in Large Organisations. Stefan et al. • Software Support for Sustainable Supply Chain Configuration and Management. Rizzoli et al. • Toward the Next Generation of Corporate Environmental Management Information Systems: What is Still Missing? Gómez et al. Mindconnect EcoChain CoControl Sefaira Shine Carbon Analytics Opinum ENIT Systems **Production Monitoring and Guidance** JPM Silicon GreenCom Networks Solandeo	**Maintenance and End-of-life Guidance** • Beyond Behavior Change: Household Retrofitting and ICT. Massung et al. • GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. Mastrucci et al. • Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help. Weeks et al. • GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. Mastrucci et al	
Automation **autoSave** **autoPush**	**Computational creativity**	**Automated Resource Coordination** • Supporting Renewable Power Supply Through Distributed Coordination of Energy Resources. Sonnenschein et al. • A survey on application of maturity models for smart grid: Review of the state-of -the-art. Uslar et al. • Open Data Model for (Precision) Agriculture Applications and Agricultural Pollution Monitoring. Řezník et al. • Assessing the Uses of NLP-based Surrogate Models for Solving Expensive Multi-Objective Optimization Problems: Application to Potable Water Chains. Capitanescu et al. REstore Upside Energy Kiwigrid Sympower Qinous Younicos	**Maintenance and End-of-life Automation** Q-Bot	**Resource Computation** • Big Data GIS Analytics Towards Efficient Waste Management in Stockholm. Shahrokni et al. • Big Data for Big Problems-Climate Change, Water Availability, and Food Safety. Armbruster et al. • GIS-based Life Cycle Assessment of urban building stocks retrofitting- a bottom-up framework applied to Luxembourg. Mastrucci et al. • Computational Modeling of Material Flow Networks. Moeller et al. • Agent-Based Analysis of Annual Energy Usages for Domestic Heating based on a Heat Pump. Tabatabaei et al. • SustData: A Public Dataset for ICT4S Electric Energy Research. Pereira et al. • Open Data Model for (Precision) Agriculture Applications and Agricultural Pollution Monitoring. Řezník et al. • Midpoint vs single score in multi-criteria optimization under life cycle assessment constraints: the case of potable water treatment chains. Capitanescu et al. • Assessing the Uses of NLP-based Surrogate Models for Solving Expensive Multi-Objective Optimization Problems: Application to Potable Water Chains. Capitanescu et al.

	Consumption		
	Usage	***Sharing, reuse, retail, purchase, marketing***	***Medium ****
Coordination **weSave**	**Social Behaviour Change** • Perceptions and behaviour towards climate change and energy savings: the role of social media. Piccolo et al. • Everyday Food Science as a Design Space for Community Literacy and Habitual Sustainable Practice. Kuznetsov et al. • Challenging the Car Norm: Opportunities for ICT to Support Sustainable Transportation Practices. Hasselqvist et al. • On the edge of supply: designing renewable energy supply into everyday life. Ferrario et al. • Power law of engagement: Transferring disengaged householders into retrofitting energy savers. Weeks et al. • Energy matters in buildings: Individual and collective issues. Denward et al. • Potentials of energy consumption measurements in office environments. Jakobi et al. • Social Electricity: The evolution of a Large-Scale, Green ICT Social Application through two Case Studies in Cyprus and Singapore. Kamilaris et al. • Reframing Persuasive Technology for Sustainability. Davis et al.	**Sharing Economy** • ICT-based sub-practices in sustainable development of city transport. Henriksson et al. PiggyBaggy Moveabout eMio Carjump Flinc	**Telepresence** • Life cycle assessment of videoconferencing with call management servers relying on virtualization. Vandromme et al. • Work hubs - location considerations and opportunities for reduced travel. Kramers et al.
wePush	**Usage Coordination** • The Bicycle Barometer: Design and Evaluation of Cyclist-Specific Interaction for a Public Display. Claes et al. GreenCom Networks Tempus Energy Ubitricity eeMobility	**Market and Finance** • An Information System Supporting Cap and Trade in Organizations. Maranghino-Singer et al. Open Utility ConsenSys Ecosummit Market Lumenaza We Share Solar OEEX Pendula Trine	**N/A**
Augmentation **iSave**	**Individual Behaviour Change** • Using Participatory Data Analysis to Understand Social Constraints and Opportunities of Electricity Demand-Shifting. Bourgeois et al. • Just whack it on until it gets hot: Working with IoT Data in the Home. Fischer et al. • A bit like British Weather, I suppose: Design and Evaluation of the Temperature Calendar. Costanza et al. • Integrating the Smart Home into the Digital Calendar. Mennicken et al. • Personality,targeted Gamification: A Survey Study on Personality Traits and Motivational Affordances. Jia et al. • Time is of essence: Changing the horizon of travel planning. Nyblom et al. • Changing Behaviour to Save Energy: ICT-Based Surveillance for a Low-Carbon Economy in the Seventh Framework Programme. Cakici et al. • Energy saving at work - and when not working! Insights from a comparative study. Jakobi et al. • A Taxonomy of Motivational Affordances for Meaningful Gamified and Persuasive Technologies. Weiser et al. • Social Practices, Households, and Design in the Smart Grid. • Gamification and Sustainable Consumption: Overcoming the Limitations of Persuasive Technologies. Katzeff et al. • Gamification and Sustainable Consumption: Overcoming the Limitations of Persuasive Technologies. Huber et al. Advizzo Changers MotionTag Watty		**Publication and broadcast** • Environmental Assessment of E-media Solutions: Challenges Experienced in Case Studies of Alma Media Newspapers. Arushanyan et al. • Dematerialization and Environment: a text-mining landscape on academic, blog and press publications. Delanoë et al. • Dematerialization Through Electronic Media? Coroama et al. Canatu
iPush	**Usage Monitoring and Guidance** • ICT-based sub-practices in sustainable development of city transport. Henriksson et al. • Is there a role for Mobiles to support Sustainable Agriculture in Africa. Batchelor et al. The Mobility House Solarkiosk Pavegen	**Marketing and Choosing** • Investigation into the slow adoption of retrofitting - What are the barriers and drivers to retrofitting, and how can ICT help. Weeks et al. • Beyond Behavior Change: Household Retrofitting and ICT. Massung et al. • The EcoPanel - designing for reflection on greener grocery shopping practices. Bohné et al. ET Index Groenspar Greenergetic	**N/A**
Automation **autoSave**	**Automatic Optimization** • It is too Hot: An In-Situ Study of Three Designs for Heating. Alan et al. • GreenMind - An Architecture and Realization for Energy Smart Buildings. Nizamic et al. • Sensor-Actuator Smart lighting System: System Organizational Concept and Challenges. Al-Anbuky et al. • Pre-installation challenges: classifying barriers to the introduction of smart home technology. Rubino de Oliveira et al. • Agent-Based Analysis of Annual Energy Usages for Domestic Heating based on a Heat Pump. Tabatabaei et al. Shine Sonnenbatterie CoControl Fourdeg Rockethome Tado Cityntel		
autoPush	**Usage Automation** • Self-organizing demand response with comfort-constrained heat pumps Hinrichs et al. Sonnenbatterie Green City Solutions Nomadic Power Tevva Motors Siqens Ubik Solutions	**Automated Procurement**	**N/A**

Table 52 SGM3 Map of ICT4S/SHCI literature (blue) and Ecosummit cleanweb startups (red).

9.3 MODELLING AND MEASURING ENABLING IMPACTS

This section discusses the mechanism and size of the variation in enabling impacts described by the SGM. It models save and push impacts with the theory of resource-use hierarchies that underlies the LES Model. It then identifies some ICT4S research that has measured save impacts, and how macroeconomic research into ICT-enabled productivity may be a proxy for push impacts. The encountered measurements are organised into the three-category Enabler typology. It then shows that both save and push impacts should be measured for any DDS, and that many DDS do both simultaneously. Finally, it shows that enabling impacts are probably growing, however modelling this growth is an opportunity for future work.

9.3.1 MODELLING DECOUPLING DIRECTNESS AS RESOURCE-USE HIERACHIES

The LES Model enabling impacts are based on a theory of resource-use hierarchies and ICT-enabled substitutions (Figure 9, Section 2.3.2). A model has been developed to define the Enablers based on EICs. The DD dimension, however, is defined qualitatively in Chapter 6. To develop the **conceptual basis for the observed variation in DDS**, and to better explain **how some DDS catalyse cleantech**, this section models the SGM using the resource-use hierarchy theory.

By definition, a product is produced by production processes, and consumed by consumption processes. Therefore, any product depends upon a life cycle of production and consumption processes. Expressed in terms of resource-use hierarchies, each of the production and consumption processes is a resource-use hierarchy, a tree of interdependent resources that includes the material resources - such as raw materials, parts and energy – and the immaterial resources – such as designs and calculations – that are required to create the product. A simple model of any product based on the theory of resource-use hierarchies can therefore be described with Figure 53.

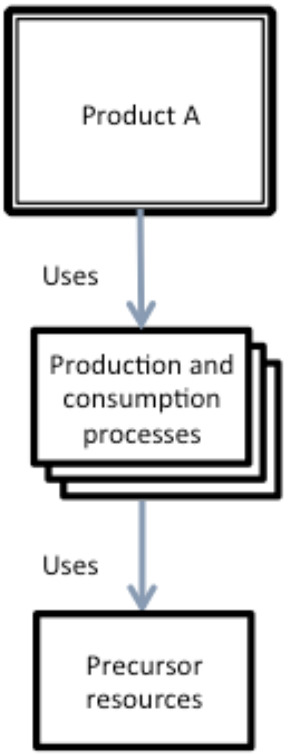

Figure 53 Generic model of any product ("A"), developed using Hilty & Aebischer's resource-use hierarchy diagrams (L. Hilty & Aebischer, 2014; UNEP, 2011)*. The diagram models a functioning product as dependent on a hierarchy of production and consumption processes, which in turn depend on precursor resources.*

The submarkets identified in Chapter 8 suggested that save systems function through both process optimisation and media substitution, whilst push systems function by process optimisation alone. Hilty & Aebischer use the resource-hierarchy model to define these three processes as forms of ICT-enabled substitution in Figure 11. Based on this, the generic model of any product using the resource-use hierarchy model (Figure 53), and the submarket observations, Figure 54 models the Decoupling Directness dichotomy.

Save systems decrease environmental impact through ICT-enabled optimisation of resource use in the production and consumption processes of a Product A, or by substituting its medium for ICT hardware. On the other hand, push systems enable the substitution of Product A with another more sustainable Product B by optimising the production and consumption processes to maximise product adoption.

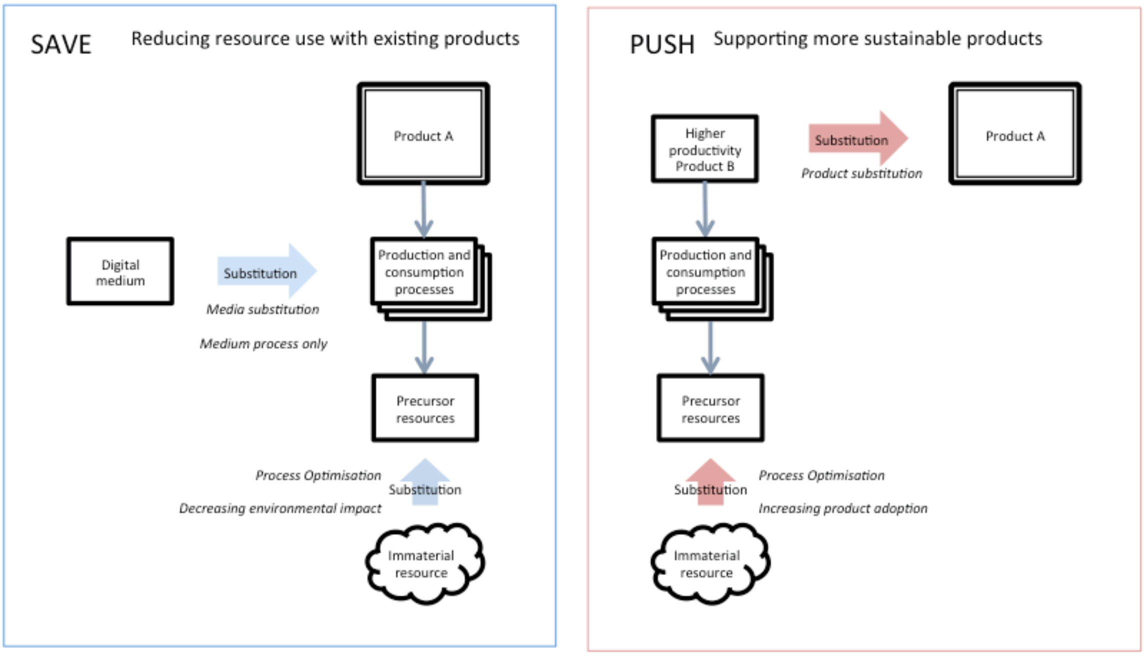

Figure 54 Definition of the SGM submarkets developed with Hilty & Aebischer's resource-use hierarchy diagrams (L. Hilty & Aebischer, 2014; UNEP, 2011)*. Save systems decrease environmental impact by optimising resource use in the production and consumption processes of a Product A, or substituting its medium for a digital one. On the other hand, push systems enable the substitution of Product A with another more sustainable Product B by optimising the production and consumption processes to maximise growth.*

9.3.2 PROPERTIES OF DECOUPLING DIRECTNESS, AND SAVE-PUSH SYSTEMS

If the model of save and push based on resource-use hierarchies in Figure 54 has successfully described all possibilities, then Decoupling Directness is exhaustive for all DDS. However, this is not a proof, and another mechanism of substitution may be possible that has escaped our attention, and could not be fitted within the existing categories of save and push. To the best of my knowledge, all the DDS encountered during the action research and multiple rounds of data analysis can be classified as save or push. Future work could develop more conclusive evidence of exhaustiveness, similar to that for the Enablers.

There is an intrinsic overlap between save and push categories as DDS can both save resources or push a greener product simultaneously. This lack of mutual exclusivity would generally be considered a weakness of this classification. However, a system that is both a save and a push system has two different positive sustainability impacts as it both saving resources and pushes a more sustainable product, which are measured in different ways. Therefore, classifying it in two different categories faithfully reflects the two simultaneous but distinct sustainability claims it can make.

As save and push are not **mutually exclusive** a single DDS can do both. Therefore, a full assessment of the macro-scale sustainability impact of a DDS must consider both its save impacts (direct efficiency of resource use), and push impacts (resource impacts of other systems being adopted, constructed or operated).

For instance, Stratajet[144] is a company that allows private jet owners to rent out their underused private jets to others. The example of Stratajet was discussed during the cleanweb definition and taxonomy conversation during the Action research of Chapter 2. As a Sharing Economy platform this may “save” resources by allowing fewer jets to be used more intensively. However, it may also “push” private jet travel to the exclusion of less energy intensive modes of travel. In terms of the Three-Levels Model, if jet travel is “part of the problem” this is an “induction” effect, rather than a true push impact. Both save and push/induction must be analysed at the systemic macro-level to assess the sustainability or otherwise of Stratajet.

A single DDS - here termed a “save-push” system - can both save harmful resources and push beneficial ones. For example, Sonnen[145] use algorithms to optimise the efficient function of a smart domestic battery. The Sonnen Batterie is a Save system because its algorithms optimise the battery to save energy. However, the algorithms also optimise the battery to support green products i.e. the battery itself and domestic solar energy. It is therefore also a push system.

The smart grid is perhaps the most prominent example of a save-push system, and has been the subject of considerable ICT4S research (Katzeff & Wangel, 2015; Sonnenschein et al., 2015; Uslar & Masurkewitz, 2015), and promotion by Rifkin as the part of the “Energy Internet” that brings together Internet technologies, renewable energy, and energy storage (Rifkin, 2014).

Future work can examine such save-push systems. Are they the most sustainable of all DDS?

9.3.3 PRODUCTIVITY OF ENABLING IMPACTS

This investigation aimed to develop a classification and conceptualisation of DDS and their enabling impacts. It did not seek to create a quantitative model to predict the enabling impact. However, a classification and modelling can form the basis for better quantitative modelling of the micro-enabling impacts and macro-structural impacts of Sustainability by ICT. This

[144] Stratajet https://www.stratajet.com
[145] https://www.sonnen-batterie.com/en-us/start

section argues that such quantification can be based on the concept of productivity. When attempting to quantify enabling impacts it is possible to look beyond ICT4S alone.

In the context of a production process, **productivity** is the ratio of some indicators of output to some indicators of input. The indicators reflect a set of goals: the output is something beneficial that fulfils the goal, and the input is something that must be minimised to achieve it, such as a cost. A variety of indicators may be used in industry to measure inputs and outputs of a production process, including time, costs and materials. Businesses generally aim to maximise production and adoption of their products at minimal cost, so they will use productivity measures such as output per hour or per expenditure**,** termed here "**output productivity".**

Within the LES Model, all action is primarily production. The **productivity of an action** can therefore be measured against particular goals. As enabling impacts are the actions of a digital system, the **productivity of enabling impacts** can be measured according to particular goals, the ratio of output-like indicators to cost-like indicators.

In the context of decoupling, the productivity of a process is the ratio of a well-being-oriented indicator and a resource-oriented indicator over time (L. Hilty & Aebischer, 2014). For clarity, this form of productivity is here termed "**decoupling productivity**". Increasing decoupling productivity at the micro-scale is similar to the concept of **resource efficiency**. The specific goal of decoupling determines specific productivity indicators, so the effectiveness of a particular action of decoupling can be measured.

The **productivity of the enabling impacts of any DDS** is therefore its contribution to dematerialisation, its decoupling productivity at the macro-scale, which will be measured in resource-orientated and wellbeing-orientated indicators. For instance, Achachlouei has modelled the enabling effects of different ICT applications using resource-orientated indicators at the macro level such as greenhouse gas emissions (GHG), materials usage, energy usage, and levels of freight and passenger transport (M. A. Achachlouei, 2015; M. Achachlouei & Hilty, 2015).

9.3.4 SAVE IMPACTS BY ENABLER

This subsection, and the following one, briefly examine quantifications of enabling impacts from literature specific to each "market", helping validate the Enabler and DD classifications.

Save impacts contribute directly to decoupling through resource efficiency improvements, and the productivity of their enabling impacts at the micro scale is therefore decoupling productivity. As save impacts have been the primary focus of ICT4S research, a considerable amount of research has sought to measure them. Much of this work has measured the micro-scale efficiency improvements, whilst some has quantified the macro-scale of structural effects (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012), with some of the best analyses attempting to quantify rebound effects with LCA and system dynamics models (M. A. Achachlouei, 2015; M. Achachlouei & Hilty, 2015). The LES Model states that save systems function by process optimisation, media substitution or externalisation of control.

Automation. autoSave impacts are resource efficiencies due to the actions of digital devices acting autonomously. Bergrath and Spreng found that automated control of a textile mill allowed safety margins to be reduced, allowing it to operate at higher temperatures and thus saving energy required for cooling (Daniel Spreng, 2015). GeSI (2012) have estimated the global greenhouse gas abatement potential of the automation of industrial processes (0.72 $GTCO_2e$); the optimization of variable speed motor systems (0.53 $GTCO_2e$); building management systems that control and monitor the building's mechanical and electrical equipment (0.39 $GTCO_2e$); and voltage optimization which controls the reduction in the voltages received by an energy consumer to reduce energy use, power demand, and reactive power demand (0.24 $GTCO_2e$). Achachlouei (2015) has used both LCA and systems dynamics to model the macro-scale dematerialisation of smart heating, finding that ICT has a reducing effect on energy consumption in the domestic and tertiary sector, which is dominated by heating (Achachlouei, 2015, p39).

Augmentation. iSave impacts are resource efficiencies due to the actions of an individual using digital devices. Much of this research has focussed on media substitution. Laitner *et al.* (2012) found that music streaming has the potential to save 1.8 millions of barrels of oil equivalent in the US, whilst online news could save 0.2 (J. A. Laitner, Partridge, & Vittore, 2012). GeSI (2012) estimated the global greenhouse gas abatement potential of e-paper to be 0.06 $GTCO_2e$, and online media (0.02 $GTCO_2e$).

Other research has examined autoSave process optimisation. GESI have estimated the abatement potential of: eco-driving, the adopting a driving style as a result of alerts and other technology to improve overall efficiency of the car (0.25 $GTCO_2e$); real-time traffic alert that that help drivers avoid traffic delays and drive more efficiently (0.07 $GTCO_2e$). Achachlouei used LCA and systems dynamics to model the enabing effects of intelligent transport systems, finding that rebound effects caused it to stimulate total passenger transport by making it more cost- and time- efficient, whilst logistics management software was found to have a slightly inhibiting effect on the growth of freight transport (Achachlouei, 2015, p39).

Coordination. weSave impacts are resource efficiencies due to the actions of groups of human actors interacting via digital devices. Similarly to iSave, much of this research has focussed on telepresence. GeSI (2012) found that video conferencing can replace in-person meetings that would involve travel (0.08 $GTCO_2e$) and that telecommuting also save energy (0.26 $GTCO_2e$). Laitner *et al.* (2012) found that telecommuting has the potential to save 214 millions of barrels of oil equivalent in the US, whilst online banking could save 8.6 and online shopping could save 7.8. Achachlouei (2015) used LCA and systems dynamics to model the enabling impacts of telepresence/mobile work, finding that the time utilization effects of mobile ICT advantage public transport compared with private car transport.

weSave process optimisation has been analysed by GeSI (2012), who estimated the global greenhouse gas abatement potential of: power demand management that manages consumer and enterprise consumption of electricity in response to supply conditions (0.01 $GTCO_2e$); and asset sharing/crowd sourcing which provides knowledge of assets and how they can be effectively shared or reused through the use of social networks or other communication tools (0.14 $GTCO_2e$). Achachlouei's models found that such product-service systems reduced total material demand.

9.3.5 PUSH IMPACTS BY ENABLER

Whilst both save and push systems must ultimately contribute to macro-scale decoupling to be successful, only push systems contribution is more indirect because it is through supporting a product, and it is this cleantech that decouples at the micro-scale. The goal of push is primarily to maximise the production and adoption of some cleantech, such as renewable energy, bicycles, or home insulation. These are similar goals to any business, aiming to maximise **output productivity** such as output per hour or per unit expenditure. Push systems undertake **process optimisation** to maximise output productivity, unlike save systems that optimise resource efficiencies directly, or substituting media with ICT. Increasing consumption is a counterintuitive sustainability measure, but it is has an important role if these products are to substitute for more harmful ones. Chapter 8 showed that push systems are important as that they may constitute around half of commercial DDS.

As 9.4.3 discusses, within the Three-Levels Model, push impacts are like induction, as they stimulate the consumption of another resource, but they are more like substitution effects (which is equated with media substitution) because that they are "part of the solution" to sustainability rather than part of the problem. They stimulate the consumption of more sustainable products in order to substitute for more harmful ones. For instance a smart grid may push renewable energy installations to substitute for fossil fuels (Sonnenschein et al., 2015), or cycling routing applications may push bicycle usage to substitute for car usage (Claes et al., 2015). Neither the save or push impact need necessarily be an explicit objective of the system creator.

The distinction that Spreng's triangle makes between doing things with less energy and doing thing faster is very similar to the distinction between push and save (D Spreng, 2013) (Figure 8, Section 2.3.1). Save systems use the enabling impacts of ICT to increase resource efficiency, such as energy. Push systems use the enabling impacts of ICT to reduce the production time rather than resource usage, which Spreng argues is equivalent to money. However, in push systems speeding up production can be beneficial for sustainability as the product is a form of cleantech.

As push impacts enable the production and adoption of particular cleantech, they are a specific case of the enabling impacts of ICT to support production generally. Cleantech as defined here is a varied category of products, including both solar farms and organic food. Therefore, the productivity of the enabling effects of ICT when pushing cleantech is likely to similar to the productivity of ICT generally, when pushing any product. Therefore, a good first estimate of the productivity of push impacts is the general productivity of ICT. This can be measured at the micro- or ultimately the macro-scale of the whole economy. It has taken decades for ICT-enabled productivity improvements to appear and be shown macro-economically, an effect known as the "Solow Paradox", but there is now reliable macroeconomic evidence. It has now been shown that 1.0% of overall growth in Europe, the U.S., and Japan between 1995 and 2005 is due to ICT. In comparison, another revolutionary general purpose technology, steam power, generated 0.34% growth between the years 1850 and 1910 (O'Mahony & Timmer, 2009).

Clearly, economy-wide increases in productivity due to ICT do not lead to more sustainable patterns of production and consumption *per se*. They are evidence of productivity improvements that push systems can apply to the specific goals of cleantech production and adoption.

Just like save systems, effective push impacts aggregate to macro-scale dematerialisation and thus sustainable patterns of production and consumption. LCA and systems dynamics models have been developed to quantify the structural impacts of save impacts (M. A. Achachlouei, 2015; M. Achachlouei & Hilty, 2015). There is no clear reason why these cannot be adapted to quantify push impacts instead, and investigate the role of rebound effects in limiting their effectiveness. Future research is required to create such models, adapting causal structures of the second- , and third-order effects of ICT, such as Figure 13.

Automation. autoPush impacts are cleantech production and adoption improvements due to the actions of digital device acting autonomously. Although some research into autoPush DDS was encountered, none of it quantified impact. In terms of generic productivity improvements, Graetz & Michaels calculate that the adoption of robotics has raised countries' average growth rates by about 0.37 percentage points (Graetz & Micheals, 2015). The growing productivity of automation systems is causing significant political concerns about increased unemployment, although there is only limited evidence that the adoption of industrial robots correlates with unemployment (Autor, 2015). Hilty notes that industrial automation is a typical case of ICT-enabled substitution between different material resources, reducing labour at the cost of capital, energy and information (Aebischer & Hilty, 2015). Bergrath and Spreng found that automated control of a textile mill allowed higher speeds without increasing the frequency of yarn ruptures that are a decisive factor in productivity (Daniel Spreng, 2015). Sonnenschein *et al.* have discussed the elements required to measure the sustainability impact of the distributed coordination of renewable energy resources on the smart grid, based on the LES Model. However, they state that such an assessment has yet to be undertaken (Sonnenschein et al., 2015).

Augmentation. iPush impacts are cleantech production and adoption improvements due to the actions of an individual employing digital devices. GeSI have estimated the greenhouse gas abatement potential of apps that improve the adoption of public transportation through increased awareness and information is 0.07 $GTCO_2e$, and of systems that support better building design is 9.8 $GTCO_2e$. In terms of generic productivity improvements, 0.60% of labour productivity growth in Europe, the U.S., and Japan between 1995 and 2005 has been shown to be due to ICT (O'Mahony & Timmer, 2009).

Coordination. wePush impacts are cleantech production and adoption improvements due to the actions of groups of human actors interacting via digital devices. Although some research into wePush systems DDS was encountered, none of it quantified impact. In terms of productivity improvements, McKinsey estimate that social technologies, when used within and across enterprises, have the potential to raise the productivity of high-skill knowledge workers by 20 to 25% (Chui et al., 2012). Shirky has argued that ICTs have created a drastic reduction in the transaction costs of communication, enabling the formation of loosely-structured geographically-disparate groups with limited managerial oversight (Shirky, 2009).

9.3.6 FUTURE WORK: MODELLING THE GROWTH IN ENABLING IMPACT

Following from Hilty and Aebischer (2015), Chapter 5 defined enabling impact as *"any and all action of a digital system… goal-directed change that is enabled or mediated by digital* *information."* Enabling impact is therefore a generic characteristic of all ICT, as is the Enablers classification of enabling impacts. ICT4S is the application of enabling impacts to the specific problems of sustainability, primarily sustainable resource use.

There are on-going productivity improvements due to the adoption of ICT, estimated at 1.0% of overall growth in Europe, the U.S., and Japan between 1995 and 2005 (O'Mahony & Timmer, 2009). As enabling impacts are any and all action of a digital system, this growing ICT-enabled productivity implies that the total enabling impacts available to humans is increasing. An actor can apply these growing enabling impacts to address many challenges, sustainable or otherwise. For ICT4S actors - whether researchers, entrepreneurs or users - growing enabling impacts offer increasingly powerful tools with which to progress sustainability. However, there is little reason to expect that overall growing enabling impacts will benefit sustainability.

Why are enabling impacts growing? One likely reason is that the average performance of each digital system is increasing. Another is that the total number of users and of digital devices is growing. The various exponential trends that characterise the digital industry suggest several mechanisms that may drive growing enabling impact. Such modelling of the growth of enabling impact is an opportunity for future work.

Available computing power is growing, which increases the speed, variety, and quality of information processing actions digital devices can undertake, and the physical actions of non-digital devices that they can mobilise and control. Figure 55 shows that this has been growing faster than exponentially for over a century. Many actors have noted the exponential increase in the computing power. Nagy et al. argue that it is super-exponential (Nagy et al., 2011). Moore's Law famously states that that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented[146]. Similar laws apply for many fundamental digital components such as Internet bandwidth (Nielsen's Law[147]), and disc storage (Kryder's Law[148]). Kurzweil claims that AI will soon surpass human intelligence (Figure 55), and predicts an imminent "singularity" in artificial intelligence (Kurzweil, 2006, 2008).

The **number of connected digital devices is growing** which can be mobilised and controlled (Figure 56). This growth in connected devices is often termed the Internet of Things. Figure 56 shows how rapidly this is growing, with the number of connected "things" to reach five times the human population by 2020, and 2.7% of all devices (things).

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146 http://www.webopedia.com/TERM/M/Moores_Law.html
147 http://www.nngroup.com/articles/law-of-bandwidth/
148 http://www.techopedia.com/definition/28558/kryders-law

Importantly for augmentation, the **number of Internet users is growing** (Figure 57). This is even more important for coordination, as Metcalfe's law states that the value of a telecommunications network is proportional to the square of the number of connected users of the system.

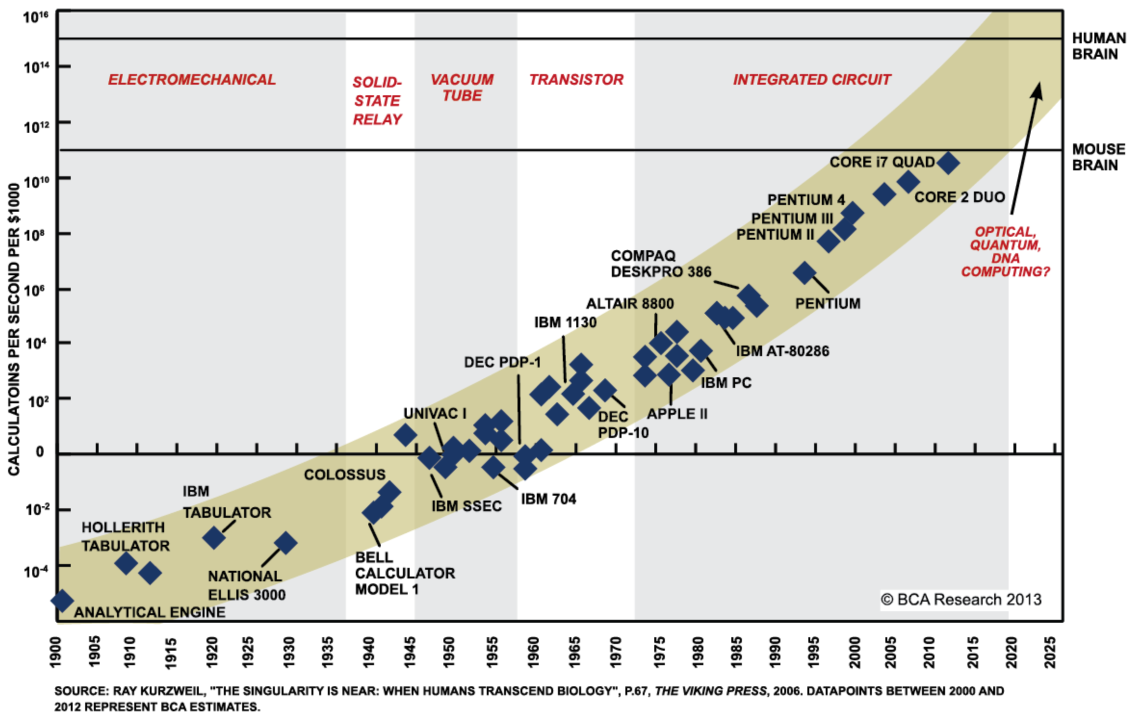

Figure 55 The super-exponential increase in computing power over the last century © Ray Kurzweil

Figure 56 Penetration of connected objects as a proportion of total "things" © CCS 2013

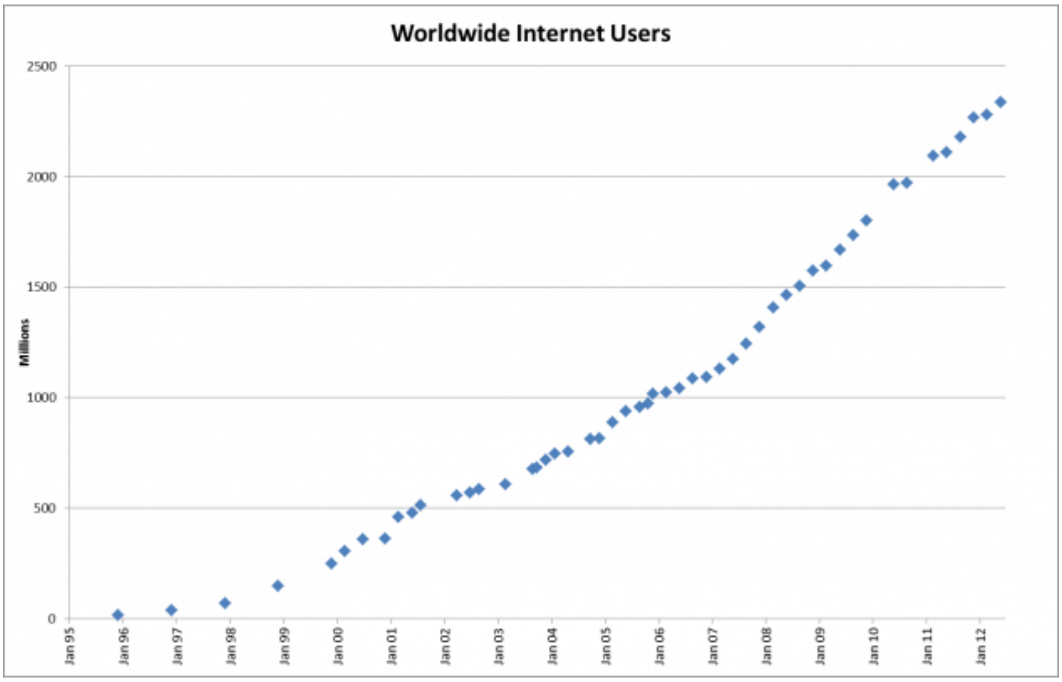

Figure 57 Growth in number of Internet users in the World © Internet World Stats[149]

9.4 SGM DIMENSIONS WITHIN ICT4S THEORY

This thesis has developed a new conceptualisation of Sustainability by ICT, the SGM. This section compares the SGM with existing conceptualisations of Sustainability by ICT from ICT4S and related fields, as identified in Section 2.3, in order to review the existing conceptualisations and evaluate the SGM. It then identifies an opportunity for future work on typologies of DSS that effect institutional change.

9.4.1 CONCEPTUALISATIONS

The conceptualisations were compared by grouping their constituent categories by similarity. This process was relatively easy, as strong themes quickly emerged across all the conceptualisations. The result is Table 58, which identifies five major themes that included almost all the categories encountered. Three of these five themes related directly to the types of enabling impact in the LES Model. Each theme could also be placed within the SGM framework, with some even relating closely to a particular SGM2 submarket:

- **(Individual) Media substitution**, which moves knowledge and cultural products onto digital media. The SGM2 called this "Publication and Broadcast". As these systems involve a single user it is a form of augmentation, and as they save resources directly they are save systems.

[149] http://www.internetworldstats.com/

- **Telepresence**, such as videoconferencing as an alternative to travel. How they are placed in the LES framework is not clear. They are often associated with media substitution, but they do not substituting media in the way that an e-book might. They might therefore be "other behavioural change". As these systems involve multiple users they are a form of coordination, and as they save resources directly they are save systems.
- **Behavioural process optimisation** – a broad category that includes persuasive technologies primarily targeted at the individual (augmentation) or groups (coordination), generally in order to save resources directly.
- **Organisational process optimisation** – a range of applications of the ICT to the production process that tend to emphasise resource efficiency in the production process (save) rather than producing cleaner technologies (push).
- **Push systems –** the only category that is not primarily save systems.

The only important category that could not be readily placed within this list is the LES model's "Externalisation of control" which *"replaces or complements information that previously came from an internal source"* (L. Hilty & Aebischer, 2014). A number of other inconsequential or miscellaneous categories were not classified: the LES Model's "other technological change" and "other organisational change"; the Three-Levels model's "obsolescence effect", which is about ICT as part of the problem rather than the solution; and "New frontiers, new business models and applications for ICT" within the Cleanweb Themes.

Decoupling Directness	Enabler	Market SGM2 Submarket	LES Model (Hilty & Aebischer, 2014)	Three-levels Model (Hilty, 2008)	Five principles for creating “e-topias” (Mitchell, 1999) (Kramers, Höjer, & Lövehagen, 2013)	Prominent trends in ICT4S research (Zapico et al. 2010) (Zapico, 2013)	Smarter 2020 four change levers (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012)	Ten IT Solutions That Will Reduce One Billion Tonnes of CO2 (Pamlin & Pahlman, 2008)	Cleanweb themes (Pure Energy Partners, personal communication, 2013)
Save	**Augmentation**	**iSave** Publication and broadcast	Media substitution is the replacement of the material medium of an immaterial resource with a digital electronic medium	Substitution effect: the use of ICT replaces the use of another resource	Dematerialisation - replacement of big, physical things by miniaturised equivalents accomplishing similar results.	Dematerialization • Knowledge and cultural products: music, films, books, news, and statistics, for example.	Digitalisation and dematerialisation - substituting or eliminating the need for an emission-intensive product, material, process or service. Also the reuse/multiple use of information sources, media, etc. by ICT.	Dematerialisation services	
	Coordination	**weSave** Virtual Network	??? Other behavioural change		Demobilisation – moving bits instead of moving people and goods e.g. telework	• Presence: videoconferences, virtual pres- ence, e-learning, services such as e-banking, e-government, and tele-medicine, for example.		Smart work (teleworking)	Resource cloud - less ownership and more efficient consumption enabled by social and mobile connectivity
Save (primarily)	**Augmentation Coordination**	**iSave weSave**	Behavioural / consumption process optimisation	Optimisation effect: the use of ICT reduces the use of another resource (e.g. less energy is used to heat a smart home that is senses if people are home, what weather is forecast etc.).	Intelligent operation – optimisation of resource use and dynamic pricing to manage demand	Behavioural Change - computer technologies are increasingly being used with persuasive intent. Optimization - ICT provides numerous opportunities for increasing efficiency and decreasing resource use effects. in existing systems	Data collection and communication - providing real-time data and analysis that allows for better decision-making identifies the need for change or encourages more efficient behaviours.	Smart buildings Smart appliances Smart grid (demand response) Intelligent transport	Big data - using information to capture massive efficiency and optimization opportunities
	All three	Various	Organisational / production process optimisation		??? Mass customisation – delivering just what is needed in particular context and no more		Process, activity & functional optimisation - intelligent simulation, automation, redesign, or control to optimise process, activity, function or service.	i-Optimisation (of production processes) Smart industry (design tools) Smart city planning	
Push (primarily)	All three	Various		??? Induction effect: ICT stimulates the consumption of another resource	Soft transformation – adapting existing building stock, public spaces and transportation infrastructure to meet new requirements		System integration - managing the use of resources and integrating lower-emissions intensive processes	Integrated renewable solutions (smart grid for renewable energy)	Catalysing cleantech - accelerating cleantech to gigatonne scale

Table 58 Comparing strategic conceptualisations of Sustainability by ICT (previous page).

9.4.2 ENABLERS

The analysis of the existing conceptualisations of Sustainability by ICT in Table 58 shows that although some of the five identified themes relate to individual Enablers, none clearly distinguish all Enablers. The model that distinguishes the greatest social variation in DDS is the LES Model that appears to divide automation from the remaining Enablers. No conceptualisation clearly distinguishes coordination except in the form of telepresence. Some conceptualisations make no clear distinction of social variation, notably the Three-Levels Model, and the Smarter 2020 change levers (2012).

Only the first two themes distinguish augmentation from coordination, and they are limited to what Zapico *et al.* call "dematerialisation" i.e. media substitution and telepresence. This distinction is replicated in Mitchell *et al.* (1999), Zapico *et al.* (2010), and Pamlin & Pahlman (2008). The fifth category, push systems, does not describe social variation at all.

The third and fourth categories distinguish production from consumption, but make only a weak distinction between the Enablers. The categories associated with the third theme of "behavioural / consumption process optimisation" emphasise behaviour rather than just "consumption", which does imply augmentation or coordination. It is not clear whether the fourth theme, "organisational / production process optimisation", relates to any specific Enablers.

The LES Model may distinguish automation from the remaining Enablers, as it distinguishes technological and human levels of process optimisation. *"Process optimisation can occur either at a level where people are involved (e.g. organisational changes in production, behavioural changes in consumption) or at a purely technological level by making physical changes"* (L. Hilty & Aebischer, 2015). The "technological level" of the LES Model appears equivalent to automation, because it is about technology acting without the involvement of people, through digital devices alone i.e. ICT hardware and software. By exclusion, the other forms of process optimisation might be presumed to involve the human interactions of augmentation.

There is a hint of the distinction between augmentation and coordination in the LES Model, but it appears at the macro-scale of structural effects. The networked economy appears in the LES model as a form of structural economic change. It is a new mode of production that has emerged with the appearance of the Internet and, in particular, Web 2.0 technologies. *"The fundamental unit of such an economy is not the corporation but the individual. Tasks aren't* *assigned and controlled through a stable chain of management but rather are carried by independent contractors"* (L. Hilty & Aebischer, 2014). However, the LES Model does not account for the key role of human networks at the micro-scale of enabling impact. As with dematerialisation, the networked economy emerges from the aggregation of micro-scale interactions, and these micro-scale interactions are mediated by the digital interactions of people, i.e. through coordination impacts.

9.4.3 DECOUPLING DIRECTNESS

The existing conceptualisations of Sustainability by ICT analysed in Table 58 are dominated by save systems that create resource efficiencies directly. Push systems appear as the fifth theme, but only the "Cleanweb Themes" [150] by Pure Energy Partners clearly distinguish push systems. Pamlin & Pahlman's (2008) "Integrated Renewable Solutions" specifically supports renewable energy. Smarter 2020's system integration is a mixture of push and save, that integrates lower-emissions intensive processes and manages the use of resources and soft transformation that adapts existing building stock, public spaces and transportation infrastructure to meet new requirements.

Although Smarter 2020 never fully distinguishes save and push, it does state that *"Although all proposed GHG abatement potentials are related to ICT, some of the mentioned abatement sublevers are much more strongly linked to ICT (e.g. telecommuting) while others play a more indirect role (e.g. integration of renewables)"* (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012).

Although Push systems enable the substitution of one product with a more sustainable one, they do not fit in the "substitution" category of the Three-Level model, as it appears to be limited to media substitution. In the SGM, media substitution is classified as save, because using an e-book rather than a paper book is primarily about saving resources directly, rather than encouraging the adoption of some other clean technology.

The effects of push systems work more like the Three-Levels category of "induction", as they stimulate the consumption of another resource. However, in the Three-Levels Model induction is part of the problem rather than part of the solution. As the aim of push systems is to be part of the solution, they cannot be placed on the Three-Levels model.

In the LES Model, all impacts of ICT are seen as special types of substitution – even process optimisation. This should cohere well with the concept of push, which enables substitution of

[150] The Cleanweb Themes were provided by personal correspondence during the action research of Chapter 3.

one resource with resource. Nevertheless, it is not clear how push systems should be placed within the LES Model enabling impacts. The LES Model makes no clear distinction between enabling impacts due to saving resources directly, and those due to pushing some form of cleantech. All the descriptions given seem to refer just to saving resources. For instance, in process optimisation uses information to reduce the use of another resource by the process, and externalisation of control "has the potential to lead to further optimizations (e.g., energy savings …"). The only mention of push systems is obscure, when Hilty & Aebischer associate a chapter called "Supporting Renewable Power Supply" within the technological level of the LES Model enabling impacts.

9.4.4 FUTURE WORK: SGM3 FRAMEWORK FOR INTERDISCIPLINARY ICT4S RESEARCH

This subsection argues that the five dimensions of the SGM3 can identify the industries relevant to particular Sustainability by ICT research problems, and those disciplines from which methods and results can be imported and integrated in order to address those problems. Developing the SGM into a framework for identifying fields, industries, theory and method relevant to particular research problems is an opportunity for future work.

ICT4S research problems must sit within the various combinations of the five final dimensions of the SGM as summarised in Table 60 (Section 10.3): enabler, submarket (i.e. production and consumption process), and sustainability application (i.e. resource type for DDS). These make around 2000 combinations, each of which will contain many specific research problems. Each category, along each dimension, can generally be associated with a major research field and industry, with their own publications and conferences. Relevant research problems for ICT4S can be found within these industries, and relevant research methods and results within each of these fields.

Much relevant research also lies within ICT4S. Considering where a research question sits in the five dimensions can help identify relevant ICT4S results and methods. Examples of ICT4S research are identified here using the SGM3 (Table 52).

This section selects one example to illustrate the wide range of relevant fields and industries: consider the website tool offered by Sungevity[151], which helps householders estimate the potential profit of installing solar panels on the roof of their home. A relevant research question would be:

How can online tools for designing and estimating domestic solar panel installations be made usable, persuasive and accurate?

151 http://www.sungevity.com/

What research within and beyond ICT4S is relevant to this question? This is **pushing domestic solar energy** through the **augmentation** of **design and marketing**. Results and methods from each of these five dimensions can be systematically sought within ICT4S and external disciplines to investigate this particular combination. Considering different combinations of these four components will suggest different literatures within and beyond ICT4S: 1) pushing domestic solar energy; 2) pushing design and marketing by augmentation; 3) employing augmentation; 4) using the other two Enablers to design and market solar energy.

Firstly consider how **domestic solar energy is pushed.** ,This combines decoupling directness (push) dimension and the resource type dimension (domestic solar energy). There is a research area relating to solar energy, with journals such as *Solar Energy* and conferences such as the *International Conference on Renewable Energy Technology.* Research into solar energy has been quite limited within ICT4S, although the role of the smart grid in supporting renewable energy generation has been investigated (Sonnenschein et al., 2015).

The action research of Section 3.4.4 found that the economy is often organised into sectors based on resource type. There is a coherent solar energy industry worth billions of dollars. Rooftop solar is a major component of the industry. Companies include *Solar City*[152] and *Sungevity*[153]. The solar industry has trade media such as *Solar Power World*[154] and conferences such as *Solar Power International*[155]. Here ICT4S researchers can identify research problems that might address the industry's latest challenges (Potts, 2017) e.g. How can online design tools increase the range of buildings upon which solar panels are installed? How can they be adapted for solar roof-tiles, which are now competing with panels? Could such measures be sufficient to offset falling consumer interest in rooftop solar?

Pushing design and marketing by augmentation has been researched by ICT4S with respect to retrofitting building stock (Massung et al., 2014; C Weeks et al., 2014; Christopher Weeks et al., 2015). *Computer-aided-design* and *digital marketing* are both research areas and major industries that address augmentation of design and of marketing. Scholarly journals include *CAD Computer Aided Design* and the *Journal of Direct, Data and Digital Marketing Practice.* Methods and results can be brought from broader marketing and design, such as design architecture and nudging (Thaler & Sunstein, 2009).

Sections 5.4 and 5.5 argued there is a coherent body of ideas within ICT4S and in wider digital research that relates to each Enabler. Relevant **augmentation** research within ICT4S

[152] http://www.solarcity.com/
[153] http://www.sungevity.com/
[154] http://www.solarpowerworldonline.com/
[155] http://www.solarpowerinternational.com/

includes persuasive technologies (Costanza et al., 2015; Jakobi & Stevens, 2015a; Katzeff & Wangel, 2015) and gamification (Huber & Hilty, 2015; Jia et al., 2015; Weiser et al., 2015). The main field researching augmentation is arguably *Human-Computer Interaction,* which publishes in journals such as the *International Journal of Human Computer Studies* and at the *Conference on Human Factors in Computing Systems (CHI)*. The *user experience design (UX)* is the industry equivalent developing augmentation systems, with magazines such as *UX Magazine*[156] and conferences such as *Interaction*[157].

Alternatively, the **other two Enablers** could push the design and marketing of domestic solar energy. Citizen-based design processes as explored by Gooch & Kortuem (2016) could **coordinate** the creation of community solar energy installations on blocks of flats. In contrast, design processes could be **automated** by incorporating Autodesk's "generative design" [158] with artificial intelligence?

Some Sustainability by ICT research questions are more **generic** than the example above, not specifying all five dimensions. For example, the question *"how can social computing support lean manufacturing practices?"* which does not identify resource type or the decoupling directness. For these questions, it may not be necessary to develop a literature within ICT4S, as existing sources of external literature may suffice. Nevertheless, there is value in interdisciplinary work to gather and summarise results from other fields into comprehendible summaries tailored to ICT4S researchers and cleanweb practitioners.

9.4.5 FUTURE WORK: TYPOLOGIES OF BROAD SUSTAINABILITY

Based on the climate change analysis of Berners-Lee & Clarke (M. Berners-Lee & Clark, 2013), Knowles argues that Sustainability by ICT has been too concerned with demand-side resource use efficiencies, and must instead address the supply side. The extraction of natural resources must be limited because once extracted, market forces and rebound effects lead to inevitable consumption. *"Any serious commitment to climate change… must involve a strategy for getting fossil fuel companies to leave as much as 80% of their assets in the ground"* (Knowles et al., 2014).

In the LES Model, efforts such as those reviewed in Section 2.3.6 are towards **institutional change** to the "rules of the game" such as laws, policies, social norms, in the language. These relate to the "broad sustainability" category identified in the classification development of Section 6.2.2. They are DSS but not the cleanweb systems (DDS) that focus on resource use,

[156] http://uxmag.com/events
[157] http://interaction17.ixda.org/
158 https://www.autodesk.com/solutions/generative-design

and are the purview of the SGM (Section 6.3.1). An example is email campaigning by climate change group 350.org. Whilst three of the five dimensions identified by this investigation will not be relevant to institutional change as they are resource-use focussed, the Enablers dimension is relevant to any application of ICT. Future work could form new typologies of institutional DSS with the Enablers.

CHAPTER 10 CONCLUSIONS

The contributions resulting from this investigation are described in each of the sections of this concluding chapter, addressing the research questions (Figure 3) that are **highlighted** in the relevant sections below. The first two contributions described are the Enablers and Decoupling Directness (DD), which are then combined to form the central contribution, the Smart Green Map (SGM).

10.1 FOUR ENABLERS: HOW DIGITAL SYSTEMS COMBINE PEOPLE AND DIGITAL TECHNOLOGY TO HAVE IMPACT

This investigation has found that there are four "Enabler" processes by which **cleanweb systems (DDS) combine people and digital technology to progress sustainability**: **automation, augmentation, coordination and autination.** This typology of digital systems distinguishes an important category of social "coordination" systems such as social networks, collaborative consumption and crowdfunding that are not acknowledged by existing conceptualisations of ICT4S. The Enablers classification was identified and validated by a mixture of methods, primarily qualitiative.

The possibility of the Enablers classification was first identified through action research with communities of Sustainability by ICT practitioners (Chapter 3), which encountered many cleanweb systems that are highly social, such as the collaborative consumption systems of the Sharing Economy (Section 3.4.3). These social systems in particular are not distinguished by existing conceptualisations of ICT4S such as the LES Model.

A qualitative analysis of 500 cleanweb company descriptions, primarily from the CrunchBase online database, effectively sampled the possibility space by "crowdsourcing" the ingenuity of digital entrepreneurs (Chapter 4, Chapter 5). Relevant characteristics of the companies were coded (Table 64 and Table 62 in the Appendix), and the codes were sorted to identify higher-level concepts (Figure 22, Figure 24, Table 23, Table 25) and two dimensions of top-level categories. The categories were then refined by classifying new samples and diagramming to develop conceptual models (Figure 26 - Figure 28). This resulted in the four-category Enablers of social variation: automation systems are purely technological and minimally social; augmentation systems involve one main user, and coordination systems involve multiple users that interact. For instance, smart thermostats[159] function automatically with little human involvement. In contrast, ridesharing apps offer a marketplace in which millions of users coordinate with each other, a form of social machine. Section 5.4 linked each enabler with a context of topics and disciplines, illustrating their contrasting characteristics (Figure 29 - Figure 31). This clear contrast between each enabler is simply because humans and human interactions are important, and so their presence or absence within a digital system is significant.

A fourth enabler was identified whilst classifying the new samples of ICT4S research and cleanweb startups in Chapter 8. The fourth enabler was named “autination” for “automated-coordination”, as such systems coordinate the interests of different actors autonomously. An example from Sustainability by ICT is aggregators of supply or demand-response associated with the smart grid.

By comparing various strategic conceptualisations of Sustainability by ICT, Chapter 9 showed that the Enablers Model distinguishes a level of social variation that is a not addressed by existing conceptualisations (Table 58). This suggests that the Enablers Model is an original contribution to ICT4S, although this has not been demonstrated for other disciplines. Whilst the enabling impacts of the LES Model already distinguish a technological level of process optimisation similar to automation, the Enablers provide a more general model of the social variation in digital systems that distinguishes the coordination of social systems, from the more established augmentation of individual users. Whilst the distinction between augmentation and coordination is not made explicit in the different conceptualisations, it is reflected in the distinction between media substitution (augmentation) and telepresence (coordination) identified by Mitchell (1999), Zapico (2013) and Pamlin & Pahlman (2008). A less clear distinction can also be drawn between categories of automation and augmentation in process optimisation in the same conceptualisations and in GeSI Smarter 2020 (2012).

Section 9.4.2 argued that the LES Model implicitly acknowledges the importance of coordination systems, by describing the “networked economy” at the Structural Level. However, this networked economy must emerge from the aggregation of micro-scale coordination effects - i.e. through the digital interactions of people – which are not presently acknowledged by the LES Model.

A **conceptual basis** for the three Enablers classification of social variation was developed during the qualitative analysis of Chapter 5: the Enabling Impact Chain (EIC) model of the causal chains of interactions between the digital and human components of the system that lead to the resulting enabling impact. The Enablers are distinguished by the number of

[159] E.g. Google Nest https://nest.com/uk/thermostat/meet-nest-thermostat/

human actors within a particular Enabling Impact Chain: zero for automation, one for augmentation, and many for coordination. The diagram in Figure 35 was developed to illustrate the relationship between the three Enablers, based on the EIC Model. To account for autination, the EIC will require refinement to distinguish which digital devices are working on behalf of which actors.

Evidence that the Enablers are a **useful and effective classification of DDS for research** resulted from Chapter 8 which successfully employed the Enablers to test a hypothesis that **social systems are more prevalent in cleanweb entrepreneurship than ICT4S research,** by classifying a sample of research papers and startups. The results are discussed in Section 10.4 below. Two key desiderata of any classification is that the categories are exhaustive and mutually exclusive. By defining the Enablers with the EIC model, Section 5.6.1 deducted that they are exhaustive with respect to all digital systems and enabling impacts, but they are only mutually exclusive if a “typical” EIC is identified for each digital system or enabling effect.

That the Enablers can be a **useful and effective classification of DDS for practitioners** has been shown by Chapter 7, which presented a case study of the adoption of the Enablers by a venture capital firm specialising in resource efficiency. The firm integrated the Enablers into their investment framework to distinguish the “fundamental methods through which technology can deliver resource efficiency and sustainability”, informing investment decisions, and communicating investment policies to existing and potential investors (Figure 39 - Figure 41). A limitation of this study is that the Enablers have not yet been employed over a period of time, to better assess their effectiveness.

As discussed in Section 10.3 below, the Smart Green Map (SGM) classification employs the Enablers to distinguish how **DDS benefit sustainability** by combining people and digital technology. By integrating with the LES Model, the SGM also addresses how **leading conceptualisations of ICT4S can better describe social systems**.

A potential critique of the resulting Enabler model is that it is reductionist, seeking to understand macro-scale behaviour of large and complex digital systems by modelling their micro-scale structure (Section 5.6.3). Two opportunities for future work on the Enablers classification were identified. Firstly, further investigating the fourth enabler, autination, by modelling with Enabling Impact Chains and reconsidering the Enabling Impact Model. Secondly, attempting to model Enabling Impact Chains as resource-use hierarchies in order to better integrate them with the LES Model. Further investigation might also explore whether this threefold model of enabling impacts could be useful to the many areas of digital research applying the transformational power of ICT to other goals than environmental sustainability.

10.2 DECOUPLING DIRECTNESS: DISTINGUISHING HOW DIGITAL SYSTEMS CONTRIBUTE TO RESOURCE DECOUPLING FOR SUSTAINABILITY

This investigation has found that **cleanweb systems (DDS) progress sustainability by either saving resources directly or "catalysing cleantech",** or both**.** This "Decoupling Directness" (DD) typology of DDS distinguishes an important category of **"push systems"** that support the adoption, construction and operation of more sustainable products (i.e. "cleantech"). Push systems may make up half of cleanweb entrepreneurship, and yet they are much less researched within ICT4S and have not been distinguished by existing conceptualisations of ICT4S. The DD classification of DDS and their enabling impacts into "save" and "push" systems was identified and validated by a mixture of mainly qualitative methods.

The potential for the DD classification was first identified through action research within communities of Sustainability by ICT practitioners (Chapter 3). Many of the startups that spoke at the Cleanweb UK meetups "catalyzed cleantech" i.e. their systems help design, manufacture, maintain and sell environmentally beneficial technologies (Section 3.4.1). For instance, certain websites encourage homeowners to install solar panels, by helping them plan and budget for the project[160]. This category of cleanweb systems had been identified by Pure Energy Partners (Figure 17) and Pascual (2013, 2014) (Figure 18), but are not clearly distinguished by existing conceptualisations of ICT4S such as the LES Model.

The qualitative analysis of Chapter 4 and Chapter 6 first coded the company descriptions (Table 64, Table 62), and sorted the codes to identify higher-level concepts (Table 23, Table 25, Table 36) and the two dimensions of top-level categories, which were refined by classifying new samples and diagramming to develop conceptual models (Figure 51 - Figure 61). The two-category Decoupling Directness classification of DDS was identified, forming the second dimension of the SGM1.

Save systems create resource efficiencies directly, most often by monitoring and optimising resource use. Both smart thermostats and ridesharing apps are save systems. On the other hand, push systems "catalyze cleantech" i.e. they enhance the adoption, construction and operation of other systems, which then use resources more sustainably. Whilst save systems work to directly minimise resource-use, push impacts work by actually increasing the consumption of certain products, easily aligning with commercial priorities. As such, Push

[160] E.g. www.sungevity.com

systems are even more open to critiques of modernism and consumerism in ICT4S such as Knowles (2014) and Brynjarsdottir *et al.* (2012) (Section 2.3.6). The qualities of the save and push categories are contrasted in Table 59. By analysing the distribution of cleanweb startups Chapter 8 has shown that this push category is important, as it constitutes fully half of the cleanweb startups analysed, and thus comprises considerable economic value.

Chapter 9 showed the originality of the Decoupling Directness classification within ICT4S by comparing it with major strategic conceptualisations of the area (Table 58). Push systems do not fit well within the enabling impacts of either the LES Model or the Three-Levels model, being neither "substitution" nor "induction". The other conceptualisations had focussed much more on save than push, with four out of five identified themes relating more to resource efficiencies. The only category equivalent to push systems was "Catalyzing Cleantech" in Pure Energy Partners "Cleanweb themes", whilst three studies had a category that was somewhat similar push systems: the WWF, Smarter 2020 and E-topia studies. (Global eSustainability Initiative (GeSI) & Boston Consulting Group, 2012; W. Mitchell, 1999; Pamlin & Pahlman, 2008).

Chapter 9 developed **the conceptual basis for the DD distinction** by developing Figure 54, a model of save and push as resource-use hierarchy substitutions, the theory that underlies the LES Model enabling impacts (Figure 9, Section 2.3.2). The model identifies a mechanism for push systems that is quite distinct from the established mechanisms of save systems. Figure 54 shows how push systems employ process optimisation to maximise product adoption, in contrast to most save systems which employ it optimise resource use to decrease environmental impact, or employ media substitution. Expressed in terms of Spreng's triangle (D Spreng, 2013) (Figure 8, Section 2.3.1), push systems use the enabling impacts of ICT to reduce production time rather than energy usage, which Spreng argues is equivalent to money. Achachlouei has used both LCA and systems dynamics to model the macro-scale dematerialisation impact of a number of save systems, and in principle, the same methods could also be used to model push impacts (Achachlouei, 2015, p39).

Evidence that the DD are a **useful and effective classification of DDS for research** resulted from Chapter 8, in which the DD dimension was able to classify a sample of research papers and startups and thus test the hypothesis that **push systems are more prevalent in cleanweb entrepreneurship than ICT4S research**. The results are discussed in Section 10.3 below. Chapter 9 also evaluated the properties of the DD as a classification. The model of save and push based on resource-use hierarchies (Figure 54) implies that it is exhaustive, and similarly all examples of a DDS encountered empirically could be classified as Save, Push or occasionally both (Chapter 6, Chapter 8). Although not conclusive, this is strong evidence of exhaustiveness of the DD for all DDS/cleanweb systems i.e. for all digital systems that contribute to dematerialisation. DD is not a mutually exclusive categorisation, as both enabling impacts or digital systems that saves resources can simultaneously push a sustainable product. Arguably, this lack of mutual exclusivity is valuable, as it reflects two different sustainability claims, which would be calculated differently, and can be targeted simultaneously. Save systems would be measured by how much resource they save, whilst push systems would be primarily be measured by how much of another green product they support, and thus indirectly how much resource they save.

One area for future investigation is to test how useful the Decoupling Directness classification of DDS is for practitioners. Another question is how externalisation of control, the third type of resource substitution identified by the LES Model, relates to the concepts of Save and Push impacts described by Figure 54.

SAVE	PUSH
Using digital systems per se to **directly** decouple resource use	Using digital systems **indirectly** to enhance the adoption, construction and operation of other systems that decouple resource use
Digital system **as cleantech**	Digital system **catalyzing cleantech**
Success metric: **resource saved** directly	Success metric: **amount of cleantech** adopted Or indirect resource gained / saved
Use a **product better**	Use a **better product**
Well described by the LES Model enabling impacts: **process optimisation, media substitution, and externalisation of control**	Not distinguished by the LES Model enabling impacts, but does also takes place by process optimisation.
Includes Substitution for ICT (Media substitution)	**ICT-enabled substitution** (Similar to Induction)
Discouraging the consumption of environmentally *harmful* resources	***Encouraging*** the consumption of environmentally ***beneficial*** resources
Spreng's triangle: reducing **energy use**	Spreng's triangle: reducing **production time**
Similar proportion in samples of ICT4S research and cleanweb entrepreneurship	Much more prominent in the sample of cleanweb entrepreneurship than ICT4S research

Table 59 Comparing save and push systems and enabling impacts of the DD dimension

10.3 THE SMART GREEN MAP: A NEW CLASSIFICATION OF DDS

This investigation has identified five **dimensions for classifying cleanweb systems (DDS) and their enabling impacts,** which have been combined to form the final version of the **Smart Green Map (SGM3)** (Table 60):

- The **Decoupling Directness (DD)** dimension.
- **Level of automation** and **level of social interaction** that distinguish the four **Enablers**.
- The **production and consumption processes** of the **Circular and Sharing Economies,** which had not been clearly described by existing conceptualisations of

ICT4S. These first emerged from the SGM "**submarkets**" identified empirically in the quantitative comparison of Sustainability by ICT research and startups in Chapter 8, which were then identified with Circular and Sharing Economy processes in Section 9.2.1.

- **Resource type.** The AR (Section 3.4.4) and the classification development of Phase 2 both found that resource type is a useful way of organising Sustainability by ICT systems just as it is for cleantech, the Sharing Economy and the whole economy.

Chapter 8 showed that six markets of the SGM can be a **useful and effective classification of DDS for research,** as it was successfully employed to investigate the distribution of recent literature from the field of ICT4S and compare it with the distribution of a sample of cleanweb startups, in order to test a hypothesis (Table 52). The results of this investigation are described below in Section 10.3.

Does the SGM have the properties required to be a useful and effective classification for research? The SGM benefits from exhaustiveness but does not achieve mutual exclusivity for either digital systems or enabling impacts. As the SGM markets are simply a combination of the Enabler and DD axes, they inherit those properties discussed above. The SGM markets are therefore likely to be exhaustive for all DDS/cleanweb, but not mutually exclusive on either dimension.

The SGM addresses the main research question, **how can Sustainability by ICT systems be classified effectively and usefully?** By combining the Enablers and DD dimension, the SGM describes **how DDS are combining people and digital technology in order to benefit sustainability, often by "catalysing cleantech"**. These questions arose from the action research within communities of Sustainability by ICT practitioners (Chapter 3), and early literature review, which identified the opportunity for a new classification of DDS that addresses limitations with leading strategic conceptualisations of Sustainability by ICT by distinguishing the wide social variation of cleanweb systems and their ability to catalyse cleantech (Section 3.7).

To address these limitations, Chapter 6 used the qualitative classification methods of Chapter 4 to develop the first version of the Smart Green Map[161] (Figure 37), with two initial dimensions: the Enablers, which distinguished the social variation in digital systems (Chapter 5); and Decoupling Directness (DD) that distinguishes digital systems that directly cause resource efficiency from those that "catalyze cleantech" (Chapter 6). By combining the Enablers and DD axes, the SGM1 identified six "markets" into which cleanweb systems could

[161] www.smartgreenmap.com

be organised: autoSave and autoPush (automation); iSave and iPush (augmentation); and weSave and wePush (coordination). This list must now be supplemented by the four Enabler, Autination.

Chapter 9 addressed how **leading conceptualisations of ICT4S can better describe the role of social systems, cleantech catalysts, the Circular Economy and the Sharing Economy,** by integrating the SGM with the LES Model to form the last version of the Smart Green Map (Figure 61, Table 52). The classification of startups and research in Chapter 8 identified a set of empirical subcategories within each of the six markets that were termed "submarkets" (SGM2, Table 44). Chapter 9 undertook a theoretical synthesis that compared and contrasted the SGM1 and LES Model enabling impacts to find areas of congruence from which a combined theory could be built. The key point of overlap identified was the processes of production and consumption within the LES Model that aligned with the SGM submarkets. A list of such processes was developed by integrating models of the Circular Economy, which also includes processes of sharing and reuse, to create the final version of the SGM. The importance of the Production/Consumption distinction was also shown by its similarity to the Impact Factors Axis of the Zouk SIAM (Section 7.5.3).

The **conceptual basis for the observed variation in DDS** was also developed through synthesis between the SGM, LES Model and Circular Economy Model. Figure 53 employed the resource-use hierarchy theory that underlies the LES Model to model the Decoupling Directness distinction, also integrating the Circular and Sharing Economy processes of production and consumption. The conceptual basis for the SGM is therefore this resource-use hierarchy definition of Save and Push impacts integrating Circular Economy processes (Figure 53), as well as the EIC model which defines the Enablers (Section 5.3).

There is some evidence that the SGM markets and submarkets are a **useful and effective classification of DDS for practitioners.** The action research of Chapter 3 first identified demand for a new and more granular classification of DDS amongst leading figures of the cleanweb startup community, through action research within a number of Sustainability by ICT practitioner communities to determine what further research might benefit the Sustainability by ICT communities. This suggested that a new classification would allow quantitative comparisons to be made, as well as raising awareness of the sector amongst stakeholders, helping them coordinate better.

Chapter 7 showed that one component of the SGM, the Enablers, have been useful to a significant practitioner in the cleanweb startup industry, a venture capital firm, employed to distinguish the "fundamental methods through which technology can deliver resource efficiency and sustainability", to inform investment decisions, and communicate investment policies to existing and potential investors. Furthermore, the metrics would be selected for each quantifiable component of the scope with guidance from the impact reporting and investment standards (IRIS) (Global Impact Investing Network, 2014). This shows that the investor has confidence in the ability of the classification to fulfil requirements identified during action research of helping stakeholders coordinate better, making quantitative comparisons, and possibly also to raising awareness of the sector.

As evidence of practitioner utility of the SGM is limited to the Enablers, future work could include a focus group to test the usefulness of the entire SGM classification including supporting category-specific insight and stakeholder awareness of the area.

Future work could develop a framework to use the five dimensions of the SGM3 to identify the industries relevant to particular ICT4S research problems, and those disciplines from which methods and results can be imported and integrated in order to address those problems.

<table>
<tr><td>Enablers</td><td colspan="3">
<table>
<tr><td></td><td></td><td colspan="2">Level of social interaction</td></tr>
<tr><td></td><td></td><td>Independent actors</td><td>Interacting actors</td></tr>
<tr><td rowspan="2">Level of digital automation</td><td>Substituting for human action</td><td>Automation</td><td>Autination</td></tr>
<tr><td>Shaping and supporting human action</td><td>Augmentation</td><td>Coordination</td></tr>
</table>
Typology of all digital systems and enabling impacts of ICT.
Derived from qualitative analysis of company descriptions (Chapter 6).
Modelled with Enabling Impact Chains (Section 5.3).
Exhaustive list for all digital systems, but requires interpretive prioritisation to be mutually exclusive.
Section 8.4.4 identified fourth Enabler, Autination, and split into two dichotomies.</td></tr>
<tr><td>Decoupling directness</td><td>Save
Push</td><td colspan="2">Typology of all DDS and their enabling impacts.
Derived from qualitative analysis of company descriptions (Chapter 6).
Modelled with resource-use hierarchies (Figure 54).
If model complete then exhaustive for DDS, but not mutually exclusive.
By integration with type of resource substitution
Save could further be divided into:Resource efficient process optimisation; Media substitution and Resource efficient externalisation of control.</td></tr>
<tr><td>Production and consumption processes</td><td>Generation
Extraction
Farming
Logistics
Analysis
Design
Manufacture
Marketing
Installation</td><td>Retail
Purchase
Medium
Use
Sharing
Reuse
Maintenance
Refurbishment
Collection
Disposal</td><td>Based on models of the Circular Economy (Figure 20, Figure 51) and empirical submarkets identified during comparison of startups and research papers (Chapter 8).
Not a fully empirical result.
Not exhaustive or mutually exclusive.
Based on qualitative analysis of cleanweb company descriptions (Chapter 6).</td></tr>
<tr><td>Resource type</td><td>Building efficiency
Renewable Energy
Carbon and fossil fuels
Electricity distribution and storage
Sustainability in ICT
Transport, logistics and electric vehicles
Cities</td><td>Water and waste water
Food, agriculture and fishing
Waste, materials and mineral extraction
Manufacturing and supply chains
Real estate, storage and construction
Consumer goods</td><td>Based on industrial taxonomies organised by resources, particularly of cleantech (Section 3.4.1), and on qualitative analysis of company descriptions (Chapter 6).
Not exhaustive or mutually exclusive.</td></tr>
</table>

Table 60 The complete Smart Green Map (SGM3): all five dimensions identified in this investigation for classifying cleanweb systems (DDS).

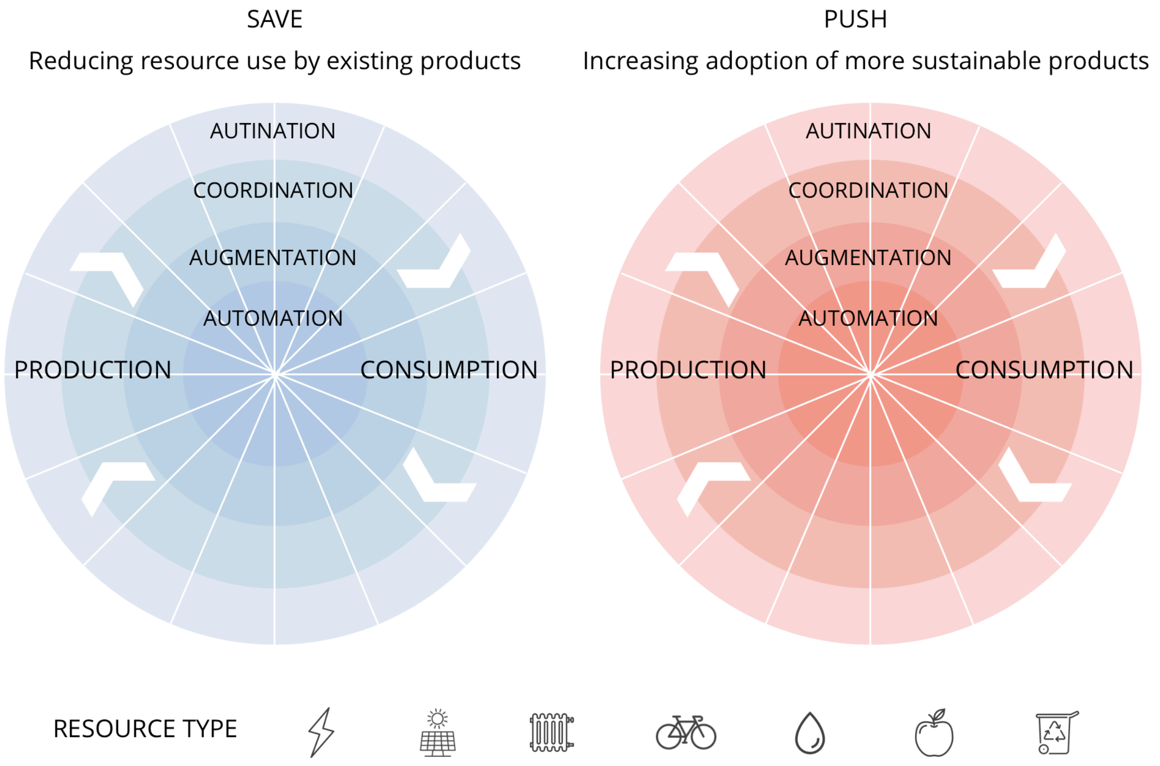

Figure 61 Diagram of the Smart Green Map, version 3 (SGM3). Mapping out all DDS (cleanweb systems) as the application of the four Enablers to circular processes of production and consumption that either save resources, push sustainable products or both (Section 8.4.6). Icons illustrate the resource type dimension[162]*.*

10.4 DISTRIBUTION OF RESEARCH AND ENTREPRENEURSHIP: PUSH SYSTEMS ARE MORE PREVALENT AMONGST STARTUPS

This thesis has tested whether **push systems and coordination systems are more prevalent in cleanweb entrepreneurship than ICT4S research,** a hypothesis that emerged from the action research **comparison of communities that address Sustainability by ICT** (Chapter 3)**.** The hypothesis was tested by classifying a fresh sample of ICT4S research papers and cleanweb startups in Chapter 8, and analysing the results in comparison with the literature in Chapter 9 (Table 58, Table 52).

Chapter 8 confirmed that **push systems are more prevalent in cleanweb entrepreneurship than ICT4S research**, finding that the ratio of Save to Push for the research papers was around 80:20, whilst for the startups it was 50:50 (Figure 46). Chapter 8 showed that although research into push systems is in the minority, several examples were

[162] Icons by Freepik, MadebyOliver, Made by Made, Zlatko Najdenovski and Chanut is Industries from www.flaticon.com.

identified such as supporting household retrofitting (Massung et al., 2014; Christopher Weeks et al., 2015), bicycles (Claes et al., 2015) and organic food (Bohne et al., 2015). Chapter 8 hypothesised that there may be less ICT4S research interest in push systems because they function similarly to other commercial ICT systems in supporting the growth of a product, rather than saving resources directly, and so the research problems they generate may be less specific to ICT4S. Moreover, ICT4S researchers may eschew the modernist and consumerist *modus operandi* of push systems, discussed in Knowles (2014) and Brynjarsdottir *et al.* (2012) (Section 2.3.6).

There were more ambiguous results as to whether **coordination systems are more prevalent in cleanweb entrepreneurship than ICT4S research.** Both research papers and startups were distributed similarly across the three Enablers in the approximate ratio automation 27% : augmentation 39% : coordination 34%. It is automation systems – the least social systems – rather than highly social coordination systems that are marginally less represented in both research and startups, particularly automation push systems (autoPush). The emphasis on augmentation agrees with Di Salvo *et al.* (2010) who found that 70% of SHCI papers were focused on the individual user. However, ICT4S research into coordination may have emerged more recently in 2015, and the range of coordination systems investigated is narrow, with a number of submarkets such as Sharing Economy systems receiving little attention. Instead, research into coordination was highly focussed on just one area, Social Behaviour Change. This interest in Social Behaviour Change follows over a decade of research into persuasive technologies (Fogg, 2003), corresponding to the Individual Behaviour Change category of augmentation (iSave), the most populated submarket of all due to the large number of research papers (Figure 45).

Chapter 9 found that **strategic conceptualisations of Sustainability by ICT have a similar emphasis to the distribution of research papers**. Save systems and augmentation systems, the most popular categories of ICT4S research papers (Figure 46), are also the most prominent categories in the various strategic conceptualisations of Sustainability by ICT (Table 58). The five shared themes identified across the conceptualisations included all three enablers but put more emphasis on augmentation systems than the other Enablers, and were more focussed on Save than Push.

Chapter 8 analysed comparative samples of startups and research from leading Sustainability by ICT conferences located in Europe. It is interesting to investigate these communities as they are, created through processes of marketing, self-identification and curation. However, generalisations to the whole of research and the whole of entrepreneurship must be drawn cautiously as they are convenience samples subject to sample bias (Section 8.4.7).

Future work could undertake a more complete meta-analysis, searching more exhaustive databases of scientific literature or startups. It could also avoid researcher bias by asking a sample of practitioners to classify a set of DDS, allowing effectiveness to be assessed with statistical methods.

10.5 IMPACT WITHIN SUSTAINABILITY BY ICT COMMUNITIES

The action research of Chapter 3 sought to make impacts within the communities of Sustainability by ICT practice encountered, as well as making observations that shaped the later research to make it more valuable. The main impacts on those communities are discussed and evaluated in Sections 3.5 and 3.6.

10.6 CONCLUSION

The Smart Green Map (SGM) is a new classification of the enabling effects of digital systems that can make resource use more sustainable (DDS, cleanweb or smart green systems). A variety of mainly qualitative research methods were used to develop, assess and refine the five dimensions of the SGM. Results suggest that the SGM is useful and effective as a conceptualisation and classification of DDS.

Digital systems were found to decouple resource use either by saving resources directly through efficiency, or otherwise indirectly by “pushing cleantech” i.e. enhancing the adoption, construction and operation of more sustainable products. This dichotomy forms a dimension of the SGM called “Decoupling Directness”. The contrasting mechanisms were modelled with the LES Model’s resource-use hierarchy theory. The Decoupling Directness dimension has distinguished a new “push” category of DDS enabling impacts, which is not clearly distinguished by established conceptualisations of ICT4S. Push impacts neither optimise resource efficiencies directly, nor substitute media with ICT. Counter to environmental intuition, these push impacts work by actually increasing consumption of certain products such as renewable energy, bicycles, or home insulation. This “cleantech” then substitutes for more harmful products and technologies. Push systems may constitute half of all commercial DDS.

Digital systems were found to combine people and digital technology in four contrasting ways, termed the "Enablers": "Automation" is purely technological with little human involvement; "Augmentation" supports and shapes the actions of one main user; "Coordination" supports the communication, interaction and collective action of many users; whilst "Autination" – a term proposed here for "automated coordination" - enables social interactions themselves to be automated. These four Enablers are defined by the matrix of two of the SGM dimensions: "level of automation" and "level of social interaction". A venture capital firm has used the Enablers as the basis for their investment framework, informing decisions and communicating policies to investors and the wider market, as described in a case study. The Enablers distinguish social systems, which have not been described by the LES Model of ICT4S, but which are basis of the macroeconomic "network economy" it does describe.

The processes of production and consumption by which resource use is decoupled were best described by the Circular Economy. This forms a further dimension of the SGM that situates recycling, reuse and maintenance within ICT4S, and Sharing Economy systems such as tool-sharing and ridesharing platforms. The remaining dimension of the SGM is the type of resource, such as heat energy, water or materials.

Integrating the five dimensions of the SGM with the Enabling Level of the LES Model offers a richer description of the range of DDS within ICT4S and their enabling impacts, acknowledging the important role of automation, cleantech push and social computing.

APPENDIXES

GROUNDED THEORY CODING TABLES

This appendix presents some tables generated during the qualitative classification development process of Phase 2.

Codes	Concept	Description Memos	Category
optimisationalgorithms	Data Analysis and Dissemination	Data Analysis and Dissemination	Gathering and analysis
scoringandcomparison			
datahostinganalysisandvisualization			
designingplanningororganising			
dataforothers			
simplespecificdatapoints			
dataasaserviceamassingandhosting			
transactionalsystem			
planningandorganising-decisionsupportsystems			
meterssensorsandcontrollermanagement	Sensors and Controllers	Sensorsandcontrollers	
demandresponse			
smartmeters			
telemetry			
fulfillingspecificcontentrequirements	Knowledge Dissemination	Knowledge Dissemination	"Gathering and analysis", but with more human involvement
creatingspecificonlinecontent			
behaviourfocussedadvice			
broadernewsintelligenceandopinion			
training			
games			
organisationalKM			
p2p			
promotingandmarketingonlinecontent			
knowledgedissemination			
choice engineering	Behaviour Change	Behaviour Change	
gamification and peer comparison			
behaviourchange			
impactfeedback			
trackingspendinghabits			
data gathering	Community	Community	

sharing knowledge and content	Sourcing	Sourcing	
fundraising			
collective innovation			
p2pmarketplace-trustscoring	Connecting People	Connecting People	Connecting actors
p2pmarketplace			
marketplaceofsustainablebusinesses			
Socialnetworkingforgreens			
telepresence	Telepresence	Telepresence	
accelerator	Related services	Relatedservices	Not DSS so out of scope
softwaredesignandordevelopment			
managementandrelatedconsulting			
seedfundingventurecapital			
itsupportservices			
miscrelatedservices			
internethosting			
sustainablecoding	Sustainability in ICT	Sustainability in ICT	
cleancloud-implementing			
cleancloud-hosting			
scoringbenchmarkingicts			
autoshutdownscripts			
movingservicestothecloud			
renewablespoweredict			
ictefficiencies			
ethicallysourcedmaterials			
volunteercomputing			

Table 62 Initial codes relating to "web approach" which were sorted and resorted to identify concepts. Not all these codes are within the scope of the final classification (DDS).

Codes	**Concept**
airqualityvsairpollutionandtoxins	airandwaterquality
waterquality	
biodiversity	biodiversity
cash-fundraisingdonations	cashfundraisingfinancing
disseminatedsustainabilityknowledge	disseminatedknowledgeandopinionsandcommunity
spreadingprosustainabilityopinions	
buildingsustainabilitycommunity	
moreeffectiveenviroindustries	effectiveenviroindustries
moreeffectiveenviroindustries-humanresources	
moreeffectiveenviroindustries-sales	
moreeffectiveenviroindustries-ict	
moreeffectiveenviroindustries-majorplanning	
moreeffectiveenviroindustries-	

regulatoryandlegal	
moreeffectiveenviroindustries-financing	
moreeffectiveenviroindustries-mentoring	
improveduserexperienceofgreenindustries-publictransport	
moreeffectiveenvironmentalscience-mapping	
energy	Energyandcarbon
energy-carbonghgs	
energy-energyefficiency	Energyefficiency
energy-energyefficiency-industrialprocesses	
energy-energyefficiency-buildingsandheating	
energy-energyefficiency-cities	
energy-energyefficiency-transportnetworks	
energy-energyefficiency-logistics	
energy-energyefficiency-icts	
energy-energyefficiency-icts-serverfarms	
energy-energyefficiency-homes	
energy-energyefficiency-electricitygrid	
energy-electricity	
energy-demandshifting	
energy-energyeffiicency-naturalgasandothernontransportfossilfuels	
innovationnewtechnologiesorpoliciesetc	innovation
newsustainabilityknowledge	
multiple-direct	multiple
muliple-indirectfundamentaltech	
multiple-indirect	
energy-carbonghgs-offsettingactivities	offsetting
energy-renewables	renewables
services	serviceslocaleconomyandselfsufficiency
services-localexperiences	
services-localevents	
localeconomy	
selfsufficiency-gardening	
space-storage	space
space-accomodation	
stuff	stuff
stuff-icts	
stuff-food-meals	
stuff-food-ingredientsandagriculture	
stuff-industrialorbuildingmaterials	
stuff-forkids	
stuff-lostandfound	
stuff-tools	
stuff-wastereduction	

stuff-vehicles	
moresustainablebehaviours	sustainabilitybehavioursandpersuasion
persuadingotheractorstoactmoresustainably	
sustainablepurchasingandprocurement	
transport-movingstuff-moreefficiently	transportandlogistics
transport-movingpeople-moreefficiently	
transport-movingpeople-avoidedthroughtelepresence	
transport-movingpeople-encouragingwalkingandcycling	
transport-vehiclenavigationandrouting	
transport-fleetmanagement	
transport-greenvehiclemanagement	
transport-movingstuff-replacingwithvirtualproductsdematerialisation	
waterquantity	waterquantity

Figure 63 Initial codes relating to "sustainability outcome" which were sorted and resorted to identify concepts. Not all these codes are within the scope of the final classification (DDS).

Company Tagline	**Description**	**Sustainability and ICT4S search terms found**	**Web search terms found**	**Web Approach Codes**	**Sustainability Outcome Codes**
Peer-to-Peer Identity for Sharing	(Company) is building a digital identity document that helps participants in the sharing economy trust one another by knowing who they are dealing with beforehands based on a peer-validated web of trust. Trust between strangers is a key issue in the sharing economy, all the more so as it is trying to become mainstream. The problem is that for years, we have been using identity paradigms based on avatars, online profiles and nicknames, and those were fine so long as we were only interacting online. But with the sharing economy, we start interacting online and we end up meeting offline, with potentially physical consequences to our behaviour towards one another. Facebook profiles, nicknames and paper document copies are simply not adapted to identifying us in these situations.	collaborativeconsumption airbnb sharingeconomy	web online collaborative mobile facebook digital information peertopeer sharing	peer-to-peer marketplace trustscoring	moreeffectiveeenviroindustries
Finding your way	(Company) provides a software solution for travel planning. Unlike other solutions that consider only one means of transport at a time, (company) addresses the entire travel route by integrating rail, road and air connections. In a single search, (company) patent-pending technology finds and ranks the best possible travel routes, allowing users to sort them according to their priorities such as price, travel time and CO2 emissions.	CO2 emissions UN Environment Program	web software twitter facebook website	simplespecificdatapoints	transport-movingpeople-moreefficiently improveduserexperienceofgreenindustries-publictransport
Collaborative transport marketplace	(Company) creates technology that makes transport more efficient. At the core of our business is a belief that there are disconnects between demand and supply between transport users and providers, and if this can be	environmental carbon cleantech sustainability collaborativec	collaborative computing marketplace	optimisationalgorithms	transport-movingpeople-moreefficiently improveduserexp

	improved, then significant savings can be generated. Transport networks (both passenger and freight) are both highly inefficient with dead mileage of 30%; combined with rising fuel costs, this creates significant burdens on transport providers and increased costs for transport users. The environmental impacts and congestion associated with transport create additional costs for both users and providers (one US senator suggested that the cost in the US for congestion was $200 billion per year), and Transport for London thinks that congestion creates an annual cost of £2-4 billion per annum). It is anticipated that the cost of congestion to the UK market will be over £20 billion per annum if left unchecked by 2025.	onsumption			erienceofgreenind ustries- publictransport
(empty)	(Company) brings the essence of all social communication media in one easy to use system. (Company) helps you more successfully network with your business associates, customers, peers, and family. The (Company) Platform: Video and Social Communication Center Media Center White Boarding Voice Over IP Social Networking Internet File Storage Mobile Message Posting Communication Center	videochat voip	internet socialmedia online cloud mobile twitter facebook blog email social	telepresence	transport- movingpeople- avoidedthroughtel epresence

Table 64 The first four companies coded, examples of the initial coding process that identified "web approach" and "sustainability outcome".

VERSIONS OF TERMINOLOGY

Automation As it acts autonomously	**Augmentation** As it can increase the ability of an individual to act effectively. From augmented reality, cybernetics	**Coordination** As it enables people to interact and act together effectively
auto- standard suffix for automation	i- first person singular pronoun	we- first person plural pronoun
Device-led Internet of Things Robot Artificial - from artificial intelligence Device - from device learning, robotics, device-to-device Providing - as it does the work for the user Gathering and Analysis	Human-led User experience – as occurs due to interaction between humans and computers Companion / Attendant / Aide – as accompanies, influences, supports and guides the user Guiding/Guidance – as influences the user's action Intersection of "Gathering and Analysis" and "Connecting Actors"	Group-led Networks – as form networks of interrelationships between people Social networks – as both social and networks of relationships. More than just social networking, per se however. Collective – from collective intelligence Connecting – as actors generally communicate to act together Connecting Actors

Digital system	**Enablers**	**Decoupling Directness**	**Save**	**Push**
Digital solution Digital product Web system ICT Digital technology Internet system Social machine IT system Application	Sociodigital Mode Digital Mode Sociality The Smart Axis Ways of being smart Digital powers Digital capabilities Driving processes Doing Web approach	Green Axis Sustainable resource use	Efficiency (Sustainable) resource efficiencies	(Cleantech) enablers (Cleantech) catalysts

Table 65 Previous versions of terminology used, or considered for use, to describe the components of the SGM.

ENABLING IMPACT CHAINS (EIC) EXAMPLES

This appendix illustrates the concept of EICs with hypothetical examples that have been constructed by consulting company websites and manuals.

AUTOMATION

Automation is the first enabler. In automation, there are no human actors interacting within the enabling impact chain (N = 0). The following is a rudimentary EIC from a typical automation DDS: the MSS optical sorter[163] and industrial device used in the recycling industry that uses light sensors and "intelligent" digital control to separate waste into different streams. Once activated, MMS sorters operate autonomously, undertaking high numbers of sorting actions with minimal human involvement.

The following enabling impact chain was developed by using the MSS site and brochures[164]. The typical enabling impact chain involves just one digital device (the MSS sorter apparatus and digital control system), and no human actors so N = 0 and it is an automation system. The MSS industrial apparatus is controlled by an embedded computer system that does not appear to be connected to the Internet.

1. Digital device (MSS sorter apparatus and control system)
    a. MSS Sorter moves the high speed conveyor belt upon which the waste enters the apparatus
    b. MSS Sorter uses light sensor to detect the optical profile of each waste piece
    c. MSS Sorter processes the information from the sensor to determine the composition of the waste piece
    d. MSS Sorter operates an air valve block to blow the waste piece into the "eject" fraction if it is determined to not have the correct composition. Otherwise the waste piece falls into the "pass" fraction.
    e. MSS Sorter conveyor belts take the pass and eject waste fractions onto the relevant next stage in the process.

Extended periods of such autonomous operation (N = 0) is the typical mode of operation of MSS. However, the MSS sorter has a screen through which it can be controlled by industrial staff. At these points it is in augmentation mode, when its enabling impact chains involve interaction with a single human actor (N = 1).

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[163] MSS http://www.magsep.com/

[164] MSS eWaste sorting device brochure http://www.magsep.com/wp-content/uploads/2014/05/MSS-Optical-Sorter-Brochure-Cirrus-bookmark.pdf

AUGMENTATION

Augmentation is the second enabler, when a single human actor interacts with the enabling impact chain (N = 1) The following is a hypothetical EIC from a typical automation DDS, Safaira[165], a design environment that helps engineers increase the resource efficiency of the buildings they create.

Safaira is an add-in to the Sketchup design environment. The Sketchup application is hosted on the user's computer, but accesses resources (such as maps and design libraries) from the Internet i.e. from software running in remote data centres. The typical enabling impact chain involves one digital device (a personal computer running Sketchup), and one human actor so N = 1 and it is an augmentation system. To simplify this example Sefaira is considered as one, including the user's digital hardware (personal computer or mobile) and software (operating system, Sketchup and Sefaira), and the Internet infrastructure.

1. Human actor (Engineer)
    a. Wants to design a building with high environmental performance
2. Human actor - digital device interaction (Engineer - Sketchup with Sefaira Add-in)
    a. Engineer opens Sketchup
    b. Computer generates Sketchup environment.
    c. Engineer undertakes design action.
    d. Computer responds to design action.
    e. …

COORDINATION

Coordination is the third enabler when there are at least two people interacting in the enabling impact chain (N ≥ 2). The following is a coordination enabling impact chain from a coordination DDS within the Sharing Economy. BlaBlaCar[166], a ridesharing platform founded in France in 2006. BlaBlaCar enables drivers with spare spaces in their cars to find passengers willing to pay for the ride. BlaBlaCar coordinates drivers and riders so they can act together to fulfil their goals, such as making a journey, money, meeting new people, avoiding boredom on long journeys, and being able to use lanes reserved for cars with passengers.

The following enabling impact chain was developed by using the BlaBlaCar site and consulting step-by-step guides to using the service[167]. The enabling impact chain involves one device (the BlaBlaCar platform), and two human actors (Driver and Rider), so N = 2 and it is a

[165] http://sefaira.com/
[166] BlaBlaCar https://www.blablacar.com/
[167] Based upon https://www.blablacar.co.uk/faq/question/how-do-i-offer-a-ride

coordination system. The BlaBlaCar application is a remote web application hosted in one or more data centres and accessed over the Internet. To simplify this example all the intervening components are included as part of the digital device of the BlaBlaCar platform, including the digital hardware (personal computer or mobile) and software (operating system, internet browser) used by the driver and rider, and the internet infrastructure.

1. Human actor (Car owner)
    a. Driver wants to offer a ride
2. Human actor - digital device interaction (Driver - BlaBlaCar application)
    a. Driver arrives at BlaBlaCar website
    b. BlaBlaCar presents initial options
    c. Driver selects option to offer a ride
    d. BlaBlaCar requests itinerary information (Departure and arrival cities, stopovers, date and time)
    e. Driver specifies the itinerary information
    f. BlaBlaCar requests offer details (price and luggage space)
    g. Driver specifies the offer
    h. BlaBlaCar requests login details
    i. Driver specifies login details
3. Human actor (Rider)
    a. Rider needs a ride
4. Human actor - digital device interaction (Rider - BlaBlaCar application)
    a. Rider arrives at BlaBlaCar website
    b. BlaBlaCar asks the rider for required departure location and destination
    c. Rider provides departure location and destination
    d. BlaBlaCar presents list of offers with drivers and itineraries
    e. Rider examines and selects offer
    f. BlaBlaCar presents list of offers with drivers, itineraries, price and other details
    g. Rider clicks on offers of interest
    h. BlaBlaCar shows detailed information about each offer and requests further details from the driver
    i. Rider specifies further details, accepts terms and conditions and requests to book
    j. BlaBlaCar requests Rider login details
    k. Rider provides login details
    l. BlaBlaCar requests payment details
    m. Rider provides payment details
5. Human actor - digital device interaction (Driver - BlaBlaCar application)
    a. BlaBlaCar informs Driver of Rider's request
    b. Driver accepts Riders request
    c. BlaBlaCar sends confirmation of the trip to the Driver, and processes payment
6. Human actor - digital device interaction (Rider - BlaBlaCar application)
    a. BlaBlaCar informs Rider that Driver has accepted request and provides confirmation of the trip to the Driver
    b. Rider receives confirmation
7. Human actor - human actor interaction (Rider - Driver)

a. Driver picks up rider at agreed time and place and fulfils the agreed itinerary

This is a typical action chain of BlaBlaCar, enabling a transaction between two human actors (N = 2) leading to the realisation of the journey. Achieving this transaction is the ultimate purpose of this online marketplace system. The BlaBlaCar web application can also undertake the other enablers, being used for other EICs for which N≤1. For instance, a user can consult the frequently asked questions (FAQs) for advice on using the system.

As discussed in Section 5.6.2, subsets of a coordination enabling impact chain such as this have N≤1. Taken on their own, sections 2, 4, 5 and 6 are all augmentation (N=1). Whilst sub-sections 2(b, d, f. h), 3(b, d, f, h, j, l), 5(a, c), and 6a are all automation (N=0)

SEARCH TERMS

This appendix shows the search terms that were developed in order to identify companies likely to be operating digital sustainability systems (DSS) within the Crunchbase database. *Regex* terms were developed to find variations in usage, as shown in the second column. See Chapter 2 for more details, including how these terms were derived.

SUSTAINABILITY SEARCH TERMS

Search term	**Regex search string**
environmental	environmental
renewable	renewable
alternativeenergy	alternative\\W?energy\\W
climatechange	climate\\W?change\\W
biodiversity	biodivers\\w
cradle-to-	cradle\\W?to\\W
CO2	co2\\W
carbon	carbon
emissions	emission
rainforest	rainforest
coral	coral\\W
pollution	pollut
landfill	landfill\\W
LCA	lca\\W
freshwater	freshwater\\W
particulate	particulate
recycling	recycl\\w
energyefficiency	energy\\W?efficien\\w
solarenergy	solar\\W?energy\\W
solarenergy	solar\\W?panel
solarenergy	photovoltaic
windenergy	wind\\W?energy\\W
windenergy	wind\\W?power\\W
conservation	conservation\\W
hazardouswaste	hazardous\\W?waste
publictransport	public\\W?trans\\w
bus	bus\\W
railway	railway
railway	railroad
water	water\\W
river	river
forest	forest
glacier	glacier
ocean	ocean

sea	seas?\\W
catchment	catchment\\W
woodland	woodland
countryside	countryside\\W
hydrology	hydrology\\W
agriculture	agriculture\\W
farm	farm
energy	energy\\W
marine	marine\\W
rural	rural\\W
atmosphere	atmospher
naturalresource	natural\\W?resources?\\W
fishing	fishing\\W
fishing	fishery\\W
fishing	over\\W?fishing\\W
trawler	trawler
deforest	deforest
species	species\\W
contamination	contamination\\W
ecoregion	ecoregion
groundwater	groundwater\\W
mass transit	mass\\W?transit\\W
geothermal	geothermal\\W
fossil fuel	fossil\\Wfuel
electricity	electricity\\W
tram	tram\\W
EuropeanTradingScheme	european\\W?trading\\W?scheme
mountain	mountains\\W
UN Environment Program	unep\\W
planet	planet\\W
reef	reef
arctic	arctic\\W
antarctic	antarctic\\W
cleantech	clean\\W?tech\\W
supplychain	supply\\W?chain
toxin	toxins?\\W
toxic	toxics?\\W
sustainability	sustainability\\W
reuse	reuse\\W
circulareconomy	circular\\W?econ
lake	lakes?\\W
localcommunity	local\\W?communit
decarbonisation	decarbon\\W
peakoil	peak\\W?oil\\W
resourceefficiency	resource\\W?efficien\\w
carbontrading	carbon\\W?trad\\w
emissionstrading	emissions\\W?trad\\w
retrofit	retrofit\\W

fuelcell	fuel\\W?cell
powerstorage	power\\W?storage\\W
energystorage	energy\\W?storage\\W
corporatesocialresponsbility	csr\\W
corporatesocialresponsbility	corporate\\W?social\\W?responsbility\\W
distributedenergy	distributed\\W?energy\\W
microgeneration	microgeneration\\W
electricvehicle	electric\\Wvehicl
localism	localism\\W
electriccar	electric\\W?car\\W
electrification	electrificat
energysaving	energy\\W?sav\\w
lowcarbon	low\\W?carbon

ICT4S SEARCH TERMS

Search term	**Regex search string**
buildingmanagementsystem	building\\W?management
buildingmanagementsystem	bms\\W
energymonitoring	energy\\W?monitor
powermonitor	power\\W?monitor
intelligentbuildings	intelligent\\W?building
smartgrid	smart\\W?grid
ridesharing	ride\\W?shar
ridesharing	car\\W?shar
recommerce	recommerce
energydashboard	energy\\W?dashboard
internetofthings	iot\\W
telepresence	telepresence\\W
teleconferencing	telecon
videochat	video\\W?chat\\W
dematerialisation	dematerial
ict4s	ict4s
voip	voip
videocalling	video\\W?call
teleworking	telework
airbnb	airbnb\\W
hyperlocal	hyperlocal\\W
sharingeconomy	sharing\\W?economy\\W
carbonmanagement	carbon\\W?manag
emissionsmanagement	emissions\\W?manag\\W
carbonaccounting	carbon\\W?account
carpooling	car\\W?pool

DIGITAL SYSTEM SEARCH TERMS

Search term	Regex search string
web	web\\W
internet	internet\\W
socialmedia	social\\W?media
socialnetworking	social\\W?network
online	online\\W
new media	new\\Wmedia\\W
cloud	cloud\\W
SaaS	saas\\W
collaborative	collaborat
software	software\\W
computing	comput
ICT	ict\\W
artificialintelligence	artificial\\W?intelligence\\W
ICT	information\\W?technolog
mobile	mobile\\W
opendata	open\\W?data\\W
openaccess	open\\W?access\\W
opensource	open\\W?source\\W
openknowledge	open\\W?knowledge\\W
communities	communit
virtual	virtual
collectiveintelligence	collective\\W?intelligence
wiki	wikis?\\W
twitter	twitter\\W
facebook	facebook\\W
google	google\\W
yahoo	yahoo\\W
creativecommons	creative\\W?commons\\W
microsoft	microsoft\\W
amazon	amazon\\W
ebay	ebay\\W
marketplace	marketplace
wikipedia	wikipedia\\W
website	website
digital	digital\\W
rating	rating
apps	apps?\\W
userinterface	ui\\W
UX	ux\\W
humancomputerinteraction	hci\\W
humancomputerinteraction	human\\W?computer\\W?interaction\\W
humancomputerinteraction	chi\\W

algorithm	algorithm
aggregator	aggregator
recommendation	recommendation
knowledge	knowledge\\W
data	data\\W
information	information\\W
blog	blog\\W
open	open\\W
socialplatform	social\\W?platform\\W
email	email\\W
ubiquitouscomputing	ubiquitous\\W?comput
pervasivecomputing	pervasive\\W?comput
internetofthings	home\\W?automation
behaviourchange	behaviour\\W?chang
nudging	nudg
mmorpg	mmorpg
gaming	gaming
mmo	mmo\\W
games	games?\\W
raspberrypi	raspberry\\W?pi\\W
distributed	distributed\\W
sensor	sensor\\W
automation	automation\\W
socialcommerce	social\\W?commerce\\W
m2m	m2m\\W
zigbee	zigbee\\W
peertopeer	peer\\W?to\\W?peer
private cloud	private\\W?cloud
crowdsourcing	crowd\\W?sourc
crowdfunding	crowd\\W?fund
social	social\\W
gamification	gamif\\w
peertopeer	p2p\\W
sharing	sharing\\W
Industrial internet	industrial\\W?internet\\W
bigdata	big\\W?data
datascience	data\\W?science

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