UNIVERSITÀ DEGLI STUDI DI MILANO

DIPARTIMENTO DI INFORMATICA

SCUOLA DI DOTTORATO DI INFORMATICA

CORSO DI DOTTORATO INFORMATICA, XXVI CICLO

TESI DI DOTTORATO DI RICERCA

From micro behaviors to macro effects - Agent Based Modeling of environmental awareness spread and its effects on the consumption of a limited resource

SETTORE DISCIPLINARE INF/01

GIOVANNA SISSA

SUPERVISOR: PROF. ERNESTO DAMIANI
Università degli Studi di Milano, Italy

CO-SUPERVISOR: PROF. LORENZ HILTY
University of Zurich, Switzerland

Direttore della Scuola di Dottorato: Prof. ERNESTO DAMIANI

A.A. 2012/13

Abstract

This research starts from an overview of the many aspects that link ICT - and related activities - to the environment, with particular reference to software development.

We introduce an interdisciplinary framework to delineate boundaries, overlaps, and relations between different areas of science that underlie the interactions outlined.

We then identified some conceptual tools that allow us to introduce the key concept of the research, namely environmental awareness and the mechanisms of its spread.

The concepts that are derived from this interdisciplinary and intersectorial excursus are mainly those of social influence in the spread of ideas, the formation of social norms, agent based modeling, the emergence of collective phenomena from individual behavior, and of the socio-technical systems.

The methodological approach followed here is based on the observation that while most people generally agree that environmental sustainability is a general objective worth achieving, at the specific level the consumption of finite resources is not sustainable. This leads to the conclusion that any behavioral change towards sustainability must be based on environmental awareness at the individual, collective, and institutional level. The research objectives consisted in identifying the underlying mechanisms of human behaviours in limited resource consumption, in order to define a conceptual model able not only to describe them but also to analyze if and when scenarios of sustainable behavior may be emerging.

The operating result is an agent-based model (ABM) that simulates how environmental awareness spreads in a system whose unsustainable consumption should be reduced and how both social influence and empowering technology play a role in determining social norms of sustainability. The examples given relate mainly to the use of energy, but the conceptual model is not limited to that resource.

SAM4SN (Spread of Awareness Model for Social Norm) is an ABM that may allow other researchers to conduct experiments in socio-technical innovation for environmental goals and to understand the responsibilities and consequences of human behavior on environmental sustainability in various institutions, including informal ones.

One of the main findings of the research is the ability of the model to provide some monitoring indicators able to foresee if the system will achieve the goal of reducing the limited resource, i.e. if it will reach sustainability. Such indicators, with the SAM4SN model, can be usefull tools in energy policy making.

Keywords

Awareness spread mechanisms, Agent Based Model, ABM, sustainability, tipping point, household energy consumption, smart metering functions, behavioral changes, collective behaviors, social influence, social norm, social reinforcement, ICT and sustainability, interdisciplinary framework, socio-technical system, modeling for policy making.

Sommario

La ricerca descritta in questa tesi parte da una panoramica relativa ai molteplici aspetti che legano l'ICT - e le attività connesse - all'ambiente, con particolare riferimento allo sviluppo del software.
Viene introdotto un framework interdisciplinare per delineare confini, sovrapposizioni ed relazioni fra diverse aree scientifiche che soggiacciono alle interazioni delineate.
Sono identificati così alcuni strumenti concettuali che consentono di introdurre il concetto chiave della ricerca, che è quello della consapevolezza ambientale, e dei meccanismi della sua diffusione.
I concetti che si derivano da tale excursus interdisciplinare ed intersettoriale sono principalmente quelli di influenza sociale nella diffusione di idee, di formazione di norme sociali, di modellistica ad agenti, di emergenza di fenomeni collettivi a partire da comportamenti individuali, di sistemi socio-tecnici.
L'approccio metodologico seguito parte dalla constatazione che mentre viene sostenuto genericamente da più parti che la sostenibilità ambientale sia un obiettivo generale da raggiungere, a livello specifico invece il consumo di risorse limitate non è sostenibile. Questo porta alla conclusione che qualsiasi mutamento nei comportamenti verso una maggior sostenibilità debba basarsi su una consapevolezza ambientale individuale, collettiva ed istituzionale.
Gli obiettivi di ricerca sono stati identificare i meccanismi soggiacenti ai comportamenti umani nei consumi di una risorsa limitata, per definire un modello concettuale che li descriva e consenta poi di analizzare se e quando emergano scenari sostenibili.
Il risultato operativo è un modello di simulazione ad agenti (ABM) che descrive come si diffonde la consapevolezza ambientale in un sistema i cui consumi non sostenibili vanno ridotti e di come sia l'influenza sociale che l'empowering tecnologico giochino un ruolo nel determinare norme sociali di sostenibilità. Gli esempi presentati si riferiscono principalmente all'utilizzo di energia, ma il modello concettuale non si limita a tale risorsa.
SAM4SN (Spread of Awareness Model for Social Norm) è un ABM che potrà consentire ad altri ricercatori di fare esperimenti di innovazione socio-tecnica a fini ambientali e di approfondire, in varie istituzioni anche informali, le responsabilità dei comportamenti umani ed i loro effetti sulla sostenibilità ambientale.
Fra i principali risultati che della ricerca vi è quello relativo alla capacità del modello di fornire alcuni indicatori di monitoraggio che consentono di prevedere se il sistema raggiungerà di obiettivi prefissati di riduzione della risorsa limitata, ovvero se raggiungerà la sostenibilità. Tali indicatori, con il modello di simulazione SAM4SN, possono costituire dei validi strumenti a supporto dei decisori di politiche energetiche.

Preface

This doctorate research is the result of multiple turning points in my life-long engagement with the study of science, ecology, and individual agency. Among the many crucial moments two stand above all the others: the Club of Rome's publication of *The Limits to Growth*, with its insistence on the limited natural resources of the planet; and the production of the *Brundtland Report* by the United Nations World Commission on Environment and Development, with its argument that sustainability should be predicated on both individual and collective responsibility. The first one, published some years before my graduation in Physics, has deeply affected my academic and professional decisions. The second publication, on the other hand, has provided me the benchmark for judging the environmental impact of all activities, including mine.

My professional life experienced many twist and turns but also maintained some fixed points. The first is a belief in approaching the analysis of phenomena in a systematic, rigorous way—a belief that follows from my basic scientific training in Physics. The second is my trust in the potentially positive role for Computer Science (and more generally ICT) in the development of innovation, which has made me more aware of socially productive trends in the industry and more proactive in applying these trends to the social and economic progress. The third is the awareness that the planet on which we live belongs to everyone, so that what each of us has an effect on it. Direct individual and collective responsibility, therefore, must be assumed by all.

My career often took me to wonder what I could do in my institutional role to contribute to a sustainable future. As a physicist and computer scientist, but also as a teacher and an innovator in different contexts and stages of my life, I have reached the conclusion that my individual responsibility was to bring together my different skills and experiences to explore many of the interdisciplinary routes I have encountered in my professional life. After many professional experiences I became clearly aware of my need to deepen and systematize my knowledge in this field. I realized that only academic research would have allowed me to give my life-long project an effective and transmissible form that could be understood, criticized, maybe refuted, but eventually developed and improved.

As a result, my research is inherently interdisciplinary and, as such, presents multiple singularities in the topics covered and developed. Thus, I have to apologize to the scholars of the various disciplines I have drawn upon. Sociologists and economists may find inevitable but unavoidable simplifications in my treatment of some concepts related to their disciplines. Environmental scientists should be aware that many limitations in my discussion have been a conscious decision to limit the range or not diverge into peripheral topics in order to achieve a more concise work. In particular, in order to engage the greatest amount of stakeholders, I have focussed on the complexity of the interrelation among ICT and the environment. As for what concerns scholars in Computer Science, my intention has been to open lines of communication between them and the scholars of the disciplines mentioned above. Finally, I hope that the final result of my research, SAM4SN (Spread of Awareness Model for Social Norm), will be useful to other researchers to conduct experiments in socio-technical innovation and to explore its sustainability.

Prefazione

Il percorso di ricerca che mi ha condotto a questo dottorato ed a questa tesi nasce da alcuni momenti cruciali che hanno marcato la mia visione del rapporto fra scienza, ecologia e responsabilità individuale. Sono identificabili nella pubblicazione de "*I Limiti dello sviluppo*" (The Limits to Growth) del Club di Roma - che introduce il concetto di limitazione delle risorse naturali su scala planetaria - e del *rapporto Brundtland*, da parte della United Nations World Commission on Environment and Development - che declina il concetto di sostenibilità in termini di responsabilità individuale e collettiva. Il primo, pubblicato pochi anni prima della mia laurea in Fisica, ha segnato profondamente il mio percorso di studi istituzionale. Il secondo mi ha fornito un termine di paragone cui rapportare gli effetti delle attività di ogni tipo e dunque anche delle mie.

La mia vita professionale si è articolata in fasi e percorsi variegati, ma ha avuto alcuni punti fissi. Il primo è un approccio sistematico all'analisi dei fenomeni, approccio che consegue dalla formazione scientifica di base in Fisica. Il secondo consiste nella fiducia del possibile ruolo positivo dell'Informatica (e più in generale l'ICT – Information Communication Technology) nello sviluppo innovativo, che mi ha reso sempre attenta alle tendenze del settore e propositiva nelle applicazioni per l'evoluzione sociale ed economica. Il terzo è la consapevolezza che il pianeta su cui viviamo è patrimonio di tutti, che dunque quello che ognuno di noi fa ha degli effetti su di esso. L'assunzione di responsabilità diretta individuale e collettiva dunque, poiché ognuno dunque deve fare la sua parte.

Proprio il percorso professionale mi ha portato spesso a chiedermi che cosa potevo fare ogni volta nel ruolo istituzionale specifico in cui mi trovavo per contribuire a un futuro sostenibile. Da fisica in origine, informatica per elezione ed innovatrice nei fatti, che è stata docente, ricercatrice ed innovatrice in diversi contesti e fasi della vita, ho concluso che la mia responsabilità individuale consisteva nel mettere insieme le competenze diverse e le esperienze molteplici per esplorare i percorsi interdisciplinari che proprio l'intreccio professionale mi aveva fatto intravvedere. A valle dunque di questo intreccio esperienziale ho avvertito con chiarezza la necessità di approfondimento e sistematizzazione. Solo il contesto della ricerca accademica poteva consentirmi di dare a questo lavoro una forma efficace, trasmissibile agli altri per poter così essere compresa, criticata, confutata, eventualmente ripresa e sviluppata.

La ricerca che propongo è dunque intrinsecamente interdisciplinare e, in quanto tale, presenta delle alternanze nei temi trattati e nei livelli di approfondimento. Devo quindi delle scuse agli studiosi delle varie discipline cui ho attinto. Ai sociologi e agli economisti, se troveranno nella trattazione di alcuni aspetti ineludibili ed afferenti alle loro discipline semplificazioni inevitabili. Agli scienziati ambientali, per le limitazioni che ho dovuto impormi per finalizzare la ricerca e non divergere nei mille risvolti di tali scienze.

Ho cercato di far emergere la complessità della interrelazione fra ICT e ambiente, al fine di renderne consapevole tutti gli stakeholder del settore.

Rivolgendomi alla comunità scientifica della mia disciplina, l'Informatica, ho cercato di aprire dei canali di comunicazione scientifica fra tale comunità e gli scienziati delle discipline citate sopra. Mi auguro anche che il risultato operativo della ricerca, SAM4SN (Spread of Awareness Model for Social Norm) sarà utile ad altri ricercatori per condurre esperimenti di innovazione socio-tecnica e per esplorarne la sostenibilità.

Acknowledgments

Corrado Ratto, my first Physics professor, made me understand the nature of a limited resources system and the meaning of renewable resources, at a time when all these themes were not universally accepted by the scientific community.

My father, who with half a century of advance had figured out that informatics would be "the future."

The team of research and development at Ansaldo Trasporti in the 1980s, which allowed me to experience concretely how an industrial idea was born, how it was realized, and what was the life cycle of a software product.

Antoni Zotti, to whom for nearly forty years I went with my scientific questions, sure that his Physics background will provide me with answers reliable as well as concrete.

Giovanni Franza enlightened me about the underlying mechanisms of the community of Open Source developers.

Giulio Occhini and Franco Filippazzi, for their efforts in the diffusion of computer science.

Anna Carola Freschi and Vittorio Mete encouraged me to address the sociological aspects of my research.

Marielle Berra, Marco Jacquemet, Mauro Lombardi, and the many others who supported me in undertaking this adventure at an advanced stage of my professional life.

Pietro Terna showed me a vision of the potential of agent-based models.

Ernesto Damiani for the trust placed in choosing a research topic is highly interdisciplinary and for being the scientific point of reference.
Lorenz Hilty gave me a solid benchmark on issues of environmental sustainability and ICT.
Pillo, my faithful and inseparable ally in this period of intense work, confirmed for me that animals, in addition to affection and patience, can give us lessons of balance and harmony with the environment and that there is always something to learn from them.

Ringraziamenti

Corrado Ratto, che mi ha fatto di capire nel mio percorso di studi in Fisica cosa sia un sistema a risorse limitate e quale senso abbiano le risorse rinnovabili, quando tutto ciò non era universalmente accettato dalla comunità scientifica.
Mio padre, che con mezzo secolo di anticipo aveva capito come l'informatica sarebbe stata "il futuro".
Il team di ricerca e sviluppo di Ansaldo Trasporti di quasi trent'anni fa, che mi ha consentito di sperimentare sul campo come nasce un'idea industriale, come si realizza e cosa sia il ciclo di vita di un prodotto software.
Antoni Zotti, a cui da quasi quaranta anni rivolgo domande scientifiche, sicura che il suo senso fisico mi darà risposte tanto attendibili quanto concrete.
Giovanni Franza, che mi ha illuminato sui meccanismi profondi del funzionamento delle comunità di sviluppatori Open Source.
Giulio Occhini e Franco Filippazzi, per il loro impegno nella divulgazione scientifica del settore informatico.
Anna Carola Freschi e Vittorio Mete, che mi hanno incoraggiato ad affrontare anche gli aspetti sociologici della mia ricerca.
Marielle Berra, Marco Jacquemet, Mauro Lombardi e quanti mi sostenuto nell'intraprendere questa avventura in fase avanzata della mia vita.
Pietro Terna che mi ha aperto una visione sulle potenzialità dei modelli ad agenti.
Ernesto Damiani per la fiducia accordatami nella scelta di un tema di ricerca fortemente interdisciplinare e per essere stato il punto di riferimento scientifico.
Lorenz Hilty che mi ha dato un punto di riferimento rigoroso sui temi della sostenibilità ambientale e dell'ICT.
Pillo, mio fedele e inseparabile alleato in questo periodo d'intenso lavoro che, oltre all'affetto ed alla pazienza, mi ha confermato come dal comportamento degli animali si traggano sempre lezioni di equilibrio ed armonia con l'ambiente e che ci sia sempre qualcosa da imparare da loro.

TABLE OF CONTENTS

Table of Contents

INTRODUCTION: SUSTAINABILITY, RESOURCE USE AND BEHAVIOURAL PATTERNS

This thesis describes a model of social interaction mechanisms and their effects on environmental collective behavior. The overall goal of the presented research is reducing (or optimizing) the consumption of a critical or limited resource, leveraging on social norms and environmental awareness.

We look at the individual behavior from a perspective that goes beyond the traditional “homo oeconomicus” paradigm by including psychological and societal influential mechanisms which may lead to more sustainable consumption patterns.

We have to introduce some landmarks in the history of environmental sustainability and the relation of Information Communication Technology with sustainability. We will highlight some basic definitions and concepts. An interdisciplinary research framework emerges, where technological, social and political dimensions can cope with sustainability issues in a sociotechnical dimension.

This challenging interdisciplinary approach lead to some research questions that this thesis aims to answer. As overall research contribution we will present an agent-based model to explore mechanisms of social influence and energy consumption as well as the role that smart metering functions can play in facilitating households behavioral changes.

Some historical definitions

The present research is focused on the socio-technical aspects of environmental awareness diffusion in the consumption of people of a limited resource.

Before mentioning which resource we refer to and before defining what we mean for limited resource, we have to introduce three landmarks in the history of environmental sustainability.

A **resource**[1] is a source or supply from which benefit is produced. Typically, resources are materials, services, staff, money, or other assets that are transformed to produce benefit and in the process may be consumed or made unavailable. Benefits of resource utilization may include increased wealth, meeting needs or wants, proper functioning of a system, or enhanced well-being. From a human perspective a natural resource is anything obtained from the environment to satisfy human needs and wants. Resources have three main characteristics: utility, limited availability, and potential for depletion or consumption.

The report to the Club of Rome entitled "The Limits to Growth"- published in 1972 and regarded as one of the most influential books of the twentieth century – states, as core message for the whole scientific community, that in a finite world, material consumption and pollution cannot continue to grow forever (Meadows, Meadows, Randers, Behrens III, 1972).

The limitation of natural resource at a worldwide level is at the basis of definition of **limited resource**. The gradual depletion of non-renewable resources leads directly to the idea of an unsustainable resource consumption.

The second landmark is represented by the report "Our Common Future" in 1987, usually known as Brundtland Report, named after the former Norwegian Prime Minister Gro-Harlem Brundtland, who chaired the United Nations World Commission on Environment and Development in the 1980s. This report contained the most cited **definition of sustainable development**: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

During the last decades, sustainability research has emerged as an interdisciplinary research field.

Sustainability is studied and managed over many **scales** (levels or frames of reference) of time and space and in many contexts of environmental, social and economic organization (Conceptual Framework Working Group of the Millennium Ecosystem Assessment, 2003). The focus ranges from the total carrying capacity (sustainability) of planet Earth to the sustainability of economic sectors, ecosystems, countries, municipalities, neighborhoods, home gardens, individual lives, individual goods and services, occupations, lifestyles, behavior patterns and so on.

Although the Brundtland Report did not technically invent the term sustainability, it was the first credible and widely-disseminated study that probed its meaning in the context of the global impacts of humans on the environment (Theis & Tomkin, 2012). The report uses the terms "sustainable development", "sustainable", and "sustainability" interchangeably, emphasizing the connections among social equity, economic productivity, and environmental quality. Thus there are three dimensions that sustainability seeks to integrate: economic, environmental, and social (including socio-political).

Economic interests define the framework for making decisions, the flow of financial capital, and the facilitation of commerce, including the knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity (Theis & Tomkin, 2012).

Environmental aspects recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human wastes.

The socio-political aspect refers to interactions between institutions/firms and people, functions expressive of human values, aspirations and well-being, ethical issues, and decision making that depends upon collective action. The report sees these three elements as part of a highly integrated and cohesively interacting, if perhaps poorly understood, system.

Quite recently, almost a quarter of a century after the Brundtland report, the International Resource Panel of the United Nations Environmental Programme (UNEP) published the Report "Decoupling Natural Resource Use and Environmental Impacts from Economic Growth" (UNEP, 2011). This report is today the most comprehensive document explaining on scientific grounds what has to be done to make sustainable development possible.

---

[1] http://en.wikipedia.org/wiki/Resource

[2] 1tonne (or metric ton) is equal to 1,000 kilograms

The report focuses on the issue of **decoupling**, namely resource decoupling and impact decoupling.

- *Resource decoupling* is defined as "reducing the rate of use of (primary) resources per unit of economic activity." Resource decoupling leads to a gradual dematerialization of the economy, because it becomes possible to use "less material, energy, water and land resources for the same economic output" (UNEP, 2011, p. 4).
- *Impact decoupling,* by contrast, means reducing negative environmental impacts per unit of economic activity. "Such impacts arise from the extraction of required resources (such as groundwater pollution due to mining or agriculture), production (such as land degradation, wastes and emissions), the use phase of commodities (for example, transport resulting in CO_2 emissions), and in the post-consumption phase (again wastes and emissions)" (UNEP, 2011, p. 4).

The so-called Stern Review on the Economics of Climate Change (Stern, 2006), after a long period scientific controversial debate, triggered political awareness of the problem of global warming as an impact of greenhouse gas emissions, which mainly consist of CO_2. **Because the main source of CO_2 emissions is the combustion of fossil fuels, impact decoupling is roughly congruent with resource decoupling in this case.**

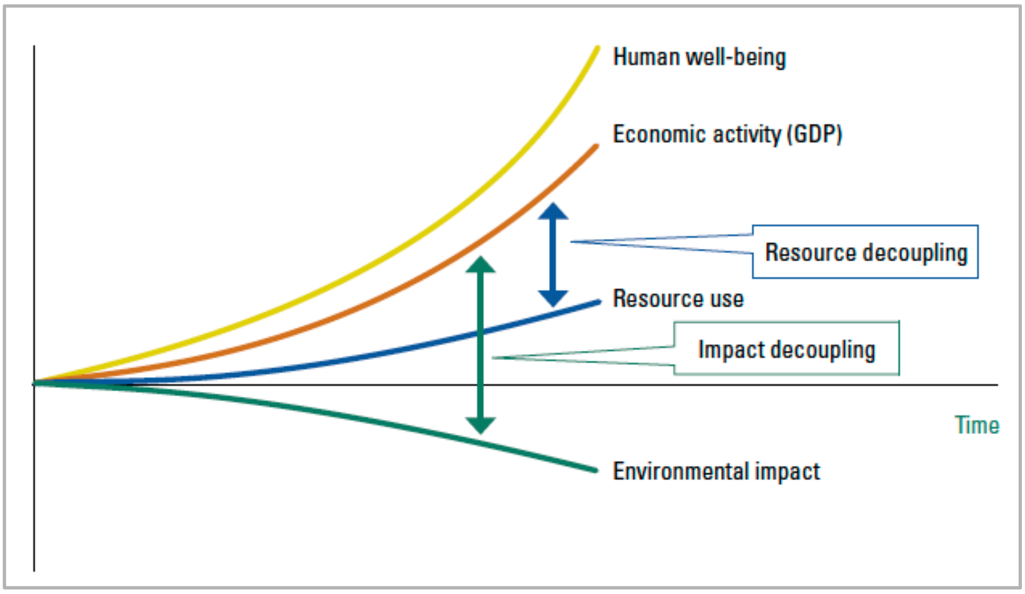


Figure 1 - Stylized representation of resource decoupling and impact decoupling

In Figure 1 the trajectories of human well-being, economic activity, use of natural resources, and environmental impact are normalized to an initial value (100%); the vertical axis is therefore dimensionless. Resource decoupling makes it possible to have more economic growth than the growth in the use of natural resources. Impact decoupling does the same for environmental impact (UNEP, 2011, p. 5).

Because issues of resource decoupling are equally important for sustainable development, the UNEP report on decoupling can therefore be considered a milestone in bringing sustainability issues beyond climate change onto the political agenda.

The idea of resource decoupling is based on the difference between material and immaterial resources.

One strategy of decoupling (also called **dematerialization**) is to shift the focus of economic activity from material to immaterial resources. There is intrinsic relation between dematerialization and Information Communication Technology (ICT).

Immaterial resources can be multiplied infinitely. "Using immaterial resources does not change the qualities that make them useful, or reduce the range of available applications. The same song of the bird may be used by still another composer or give highly-valued pleasure to a birdwatcher, and the same starlight can provide information for hundreds of captains and later provide information to astronomers about the creation of the universe." (UNEP, 2011, p.1).

For the material resources we use, there must be a second strategy of decoupling, aiming to slow down their decline. "Material resources do not disappear through transformation (basic physics does not allow for the disappearance of energy/matter), but their potential usefulness for the same purpose is no longer available. How much of a resource declines as it is used (or converted from one state to another) depends largely on how much the resource is modified through use." (UNEP, 2011, p. 2).

A number of initiatives, at all levels of policy-making, reflect the desire to promote sustainable economic development (Egger, 2006) and ensure that it does not "jeopardise" the well-being of the planet and of future generations (Som, Hilty, & Köhler, 2009). In the public debate as well as the scientific debate about the role of ICT on the environment, there is often a schism between a *pro-growth* party (outlining opportunities for ICT innovations to drive green growth and foster sustainable consumption) and a *beyond growth* party which outlines criticalities and risks of ICT for sustainability.

An increasing set of buzzwords, such as "green growth", "sustainable growth", "green for growth", is evolving. We witnessed several rhetoric attempts to reconcile innovation and growth oriented views with environment-oriented approaches. For example in the hype about *smart cities* the emphasis is put on the enabling green potential of ICT, but this statement often stays wishful thinking.

A general awareness, in the private as in the public sectors, about how ICT can help in the transition to a low-carbon society, needs to start from a scientific approach on which arguments can be based. Given that decoupling is a basic condition for sustainable development, an analysis of the relationship between Information and Communication Technology (ICT) and sustainable development should then focus on the potential contribution of ICT to implement decoupling strategies.

ICT and sustainability

The end of last century has been characterized by a positive societal view of ICT as a driver for innovation. The diffusion of ICT hardware goes along with increased energy consumption in production and consumption and induces flows of hazardous and scarce materials. Because for decades the electronic devices, which have pervaded our everyday lives, have been regarded as being "clean" technologies, the spread of awareness for this ambivalence was limited, especially in the computer science communities.

An in-depth understanding of the "ICT and environmental sustainability" issue requires paying attention also to the software features. For example the energy consumption in the computer's use phase does not depend only on hardware, but also on the software configuration. Software is also responsible for induced hardware obsolescence, making the service life of devices shorter than necessary. These considerations are part of what is called "Green Computing" (or "Green ICT"). Specific conferences and research activities are mushrooming, but usually their scope is restricted to technical aspects of ICT and focused on energy consumption.

Understanding the relationship between ICT and the environment requires the analysis of complex systems. Environmental effects of ICT are classified into first-, second- and third-order effects (OECD, 2010a).

First-order effects consist of direct impacts of the physical ICT life cycle.

Second-order effects refer to the effects of ICT in other sectors, mainly through optimization, substitution and induction effects. The SMARTer 2020 (Gesi, 2012) study estimates that ICT could cut 9.1 billion tonnes [2] (Gt) carbon dioxide equivalent (CO_2e) of global greenhouse emissions.

Third-order (or systemic) effects are related to the societal changes that ICT brings along (Hilty et al., 2006b) and are explained by new habits, social structures and consumption patterns arising through the use of information and communication services. An important kind of third-order effect is the rebound effect.

There are scientific voices pointing out the crucial role that ICT could play for sustainable development in the future, as for example the International conference ICT4S[3] – ICT for Sustainability.

The basic idea is that the hardware/software distinction in ICT, which is essentially the difference between material and immaterial resources, and the way in which value is created with software could become a paradigm for the decoupled economy of the future. The long-term availability of ICT services may enable and foster a transition to a "less material-intensive economy" (Hilty et al., 2006a).

In Chapter 1 we will approach systematically the complex relation between ICT and environmental sustainability, in order to supply a **reference framework**.

---

[2] 1tonne (or metric ton) is equal to 1,000 kilograms

[3] http://ict4s.org

Technological efficiency alone will not produce sustainability: the rebound effect

In 1865 the British economist William S. Jevons (1835-1882) wrote a book entitled "The Coal Question"[4], in which he presented data on the depletion of coal and observed an increase in the consumption of coal in England throughout most of the 19th century.

He theorized that significant improvements in the efficiency of the steam engine had increased the utility of energy from coal and, in effect, lowered the price of energy, thereby increasing consumption. This is known as the *Jevons paradox*, the principle that as technological progress increases the efficiency of resource utilization, consumption of such a resource will increase. Increased consumption that negates part of the efficiency gains is referred to as "**rebound**", while overconsumption is called "**backfire**" (Theis & Tomkin, 2012). Such a counter-intuitive theory has not been met with universal acceptance, even among economists as for example in "The Efficiency Dilemma" (Owen, 2010). Many environmentalists, who see improvements in efficiency as a cornerstone of sustainability, openly question the validity of this theory.

William S. Jevons was proven right, although no shortage of coal ever occurred, because coal as a source of energy was later replaced by oil. The hypothesis of the counter-intuitive effect of efficiency progress was later generalized to what is now called the Jevons paradox or the rebound effect, and has been underpinned with much empirical evidence (Polimeni, Mayumi, Giampietro, &Alcott, 2009).

Saving resources such as energy by improving the efficiency with which a resource is used is therefore not an approach that is as straightforward as it might appear from a technical perspective. From an economic and behavioral perspective, the situation is more complex, because the dynamics of markets has to be taken into account to predict the outcome, as well the dynamics of people behaviours.

This implies that decoupling – as defined in UNEP (2011) report – is not a sufficient condition for saving resources.

In particular, resource decoupling may result in a growth rate higher than the decoupling rate, therefore counteracting the resource-saving effects of decoupling.

This applies not only to steam machines, but to ICT or many "smart" technologies as well (Boulanger et al., 2013; Hilty, Lohmann, & Huang, 2011). Software too can be responsible of rebound effects (Hilty et al., 2006b).

Chapter 2 will be focused on the rebound effects, and in particular in ICT, and on how to avoid them by playing on the concept of "limiting factor".

In synthesis we can say that environmental problems are unprecedented in their **complexity** and their spatial and temporal reach. These problems involve interconnected ecological and social systems, operating on **multiple scales**.

Social and political dimensions to cope with environmental issues

To face environmental problems governments have to motivate people to change behaviors (e.g., reducing material consumption or recycling). There are two forces that can have impact on behavior. One is linked to **government actions** and a second one is linked to **social pressure**.

Solutions to the sustainability problem can only be found in a combination of technological and social developments. For example, energy saving has emerged as a new kind of social norm, but there are many steps to take until it becomes a **social practice**, supported by **accepted technologies**. The role of technology may be to increase energy efficiency or to give energy feedback, both of which have to become part of social practice to be effective.

Some have argued that progress on these problems can be made only through a concerted effort to change personal and social norms. A **social norm** can be defined (Ellickson, 2001) as "a rule governing an individual's behavior that third parties other than state agents diffusely enforce by means of social sanctions".

There is a complex interaction of behaviors, values, and policy (Kinzig et al, 2013). Environmental friendly behaviors, to be effective, have to be adopted by the majority of the population. Recent researches focus on social consensus through the influence of committed minorities (Xie et al., 2011).

Decision makers have several instruments to push towards a behavior change, from financial interventions or regulations to active norms management. Each of these policy instruments potentially influences personal

---

[4] http://www.econlib.org/library/YPDBooks/Jevons/jvnCQ.html

behaviors in different ways. All these instruments can be more or less effective, but all of them require funds and new expenses, and sometimes, despite great efforts, results are poor. We want to look instead at a second kind of force that can have impact on behavior, those linked to social pressure.

Voluntary behavioral changes are usually driven by some kind of rewards, not necessary an economic benefit. If the adoption of a voluntary behavior is driven by awareness and such awareness shifts from an individual dimension to a shared collective one, this turns a social appraisal into the most effective reward. Such mechanism is the trigger for a social norm.

When a behavior becomes a social norm it will be carried on without any need for controls, fines or law enforcement. "Effective policies are ones that induce both short-term changes in behavior and longer-term changes in social norm" (Kinzig et al., 2013). Social norms are persistent and, once adopted, will be followed even after the state intervention ceases.

Sociotechnical ICT-based systems, as for example smart metering advanced functions, can be pivotal for effectiveness of social norms (OECD, 2011).

An Interdisciplinary Research Framework

ICT as a field of research is not a single scientific discipline but is itself based on various disciplines and sub-disciplines: Computer Science, Telecommunications/Telematics, Informatics, Electrical Engineering, Network Science, Social Network Analysis, and Human Computer Interaction. In a similar way, sustainability research cannot be based on one scientific discipline, but concerns a broad spectrum of disciplines, e.g. Environmental Sciences, Energy Science, Economics, and Social Sciences.

The strong multidisciplinary and interdisciplinary feature of our research represents an important scientific issue.

While in Part one we will address the relationship between ICT and sustainability, in Part two we will approach the interdisciplinary aspects of the social dimension of people behavior. We will focus on the basic insight from social psychology that individuals are influenced by the decisions, actions, and advice of other individuals, both consciously and unconsciously. Understanding how and when "social influence" arises should therefore be considered as a central component in any theory of collective social behavior.

Furthermore, *social organization has more or less discrete levels*, such as the household, community, and nation, which correspond broadly to particular scale domains in time and space. Many environmental problems originate from *the mismatch between the scale at which ecological processes occur* and the **scale** at which decisions on them are made (Conceptual Framework Working Group of the Millennium Ecosystem Assessment, 2003). Outcomes at a given scale are often critically influenced by interactions of ecological, socioeconomic, and political factors from other scales.

Resource consumption reduction and sustainability at a local scale

Environmental sustainability addresses the issue of limited resources and is intended to avoid their overuse. When the limitation in the availability of a resource is directly perceived from its users such perception can lead to competition among users. For example the market is a mechanism traditionally representing this competition.

Our attention will focus on an urban district or a geographically limited area of a Global North[5] country, where the prevailing life style is not sustainable in terms of energy consumption, carbon dioxide emission, and depletion of scarce resources. At such a scale a resource, such as energy or water, is supplied by utilities companies, and **is not perceived as limited** in itself by final users. The range of the consumption implies that the resource availability has no limitations from the supplier, nor its price is affected by a possible overuse. Competition mechanisms are out of the scope of this thesis because of that.

Nevertheless the resource usage has to be reduced (or optimized) for environmental related issues and such a need can trigger an emerging social norm. An environmentally aware behavior will take into account such a resource as "environmentally significant" or "critical", and can lead to reduce the consumption.

---

[5] The economically developed societies of Europe, North America, Australia, and others.

A resource can be defined as "environmentally critical" if its consumption has to be reduced, regulated or optimized (in case of agents that are *prosumers* instead of consumers) for reasons related to environmental issues. Such reasons can be, for example:

- Availability is different depending on time (of the day in the case of energy, of the season in the case of water).
- Availability depends on external uncontrolled factors (e.g. energy supply from foreign countries or from dirty sources).
- Consumption increases GHG (Greenhouse Gas) emissions.
- If uncontrolled, the consumption trend leads to an overuse.
- There are mechanisms leading to rebound effects and nullifying efficiency improvements.
- Availability and optimal use depend on peak hours. Consumption patterns have to match such constraints to avoid losses or overuses.

The limiting factor

As before mentioned, the generic need to reduce energy consumption leads to maximize efficiency, but technology efficiency alone will not produce sustainability. There are risks to counter potential gains with rebound effects (Hilty et al., 2006b) and **only a combination of efficiency with sufficiency** (Hilty et al., 2011) can be effective.

The sufficiency constraint is strictly linked with the concept of **limiting factors**. Traditionally policy interventions are playing at a general level to give limiting factors in terms of laws or economic measures. Without going in details about the effectiveness of tax policies or incentives, as already mentioned, the proposed model plays at a different scale: the individual one.

In such a dimension it is a matter of social norms and of **personal reputation** in a **social institution**. Social norms are able to penalize someone who tends to an overuse. Such limiting factor is more effective than, for example, market prices mechanisms that are not strong enough to modify behaviors only for economic motivations.

The scope of our research is to explain and better understand the mechanisms leading a group of households to perceive a resource as "critical" for environmental sustainability and to try and reduce its consumption, playing on the social dimension as limiting factor.

Often environmentally motivated reduction programs are launched by local government or by utilities companies, like in Western Australia where a behavioral change program for water reduction has been launched in 2011 (Anda, Le Grey Brereton, Breman, & Paskett, 2013).

The need of modeling to make social experiment on environmental sustainability

International organizations, like OECD, suggest to further research into the systemic impacts – intended and unintended – of the diffusion of ICTs. Systemic impacts of ICTs on the environment are relatively unexplored, mainly because of the complexity of assessing future directions of production and consumption (OECD 2010a). Measures taken to protect the environment often have other, unintended effects on society.

This recommendation leads to the opportunity of making social experiments.

An innovative way to deal with experimental methodologies is represented by computational social science (Conte et al., 2012) approach. Simulation, and in particular agent based simulation (Janssen & Ostrom) is a way of make experiments (Epstein, 2008) and in particular to make an explicit model of behaviors in a limited resource.

In explicit models, assumptions are laid out in detail, so we can study exactly what they entail (Epstein, 2008). This is a kind of virtual laboratory to make experiments focused on sustainability issues allowing a better understanding the effects of every assumption.

The OECD recommends[6] encouraging measurement: "Members should encourage development of comparable measures of the environmental impacts of ICT goods and services and ICT-enabled applications and among similar products. They should also increase understanding of the effects of government policies (information, incentives, regulations) on improving measurement tools and increasing public awareness." In

---

[6] See the OECD (2010) Recommendation of the Council on Information and Communication Technologies and the Environment

addition, the OECD recommends setting policy targets and increasing evaluation: "Members should set transparent policy objectives and targets to measure and improve government green ICT strategies, including ICT-enabled applications across the economy. They should be monitoring compliance with policies on a regular basis to set clear responsibilities and improve accountability."

Since several studies recommend to include behavioral patterns in environmental sustainability researches, so that circumstances can be introduced whereby beneficial impacts are promoted and the detrimental impacts are prevented as much as possible (OECD, 2010b), the thesis focuses on the role that users, consumers or citizens can play in spreading and adopting beneficial behavioral changes. We propose a conceptual model to explore awareness spread and the role of smart metering[7] functions to turn such extended awareness into more sustainable behaviors.

The idea is to pivot on **social norms** *instead of prescriptive norms* and look at voluntary individual behavioral changes as a turning point[8] to reach the sustainability goals.

Our assumption is that behavioral changes toward a more environmentally oriented consumption style cannot be explained by the classical economic theory, but we need a new approach.

We will focus on energy as limited resource and, as said before, our attention will focus on an urban district or a geographically limited area of a Global North country, where energy - as well as water - is not immediately perceived as a limited resource, because everybody can buy as much as he wants. No competition - in traditional terms - for the limited resource is triggered among households because the resource is available such a scale and is possible to buy it without a direct perception of its price modification.

While a "common good" - as modeled y Janssen, Radtke & Lee (2009) in their experiments about Common Pool Resource dilemma - is a resource shared by multiple users that can consume it without limitation because it's collectively owned by everybody, in the presented case energy is not a common good because such resource is traded on the market.

The need to reduce the consumption of energy can be triggered not by its direct perceived limited availability, but by social norm, playing the role of limiting factor, in terms of collective rewards and punishments.

In Part three we will implement an Agent Based Model (ABM) to explore mechanisms of social influence in resource consumption, as well as the smart metering functions that can be provided to households can facilitate their behavioral changes. An overall scope of our model is to support decision makers in local sustainability programs or campaigns.

Research contribution and research questions

The aims of the thesis are to contribute to the definition of an interdisciplinary conceptual framework on ICT and Sustainability (ICT&S) and to answer to some research questions.

The interdisciplinary reference framework will:

- Improve the knowledge sharing among related different disciplines and the mutual understanding among the involved scientific research communities in ICT&S issues;
- Enable a better and more effective cross-discipline research activity in these areas;
- Contribute to reach a common language allowing scientists and researchers to easier relate each others in the ICT&S field;
- Promote environment-related ICT skills and curricula.

Such a framework could also be used in political debates about the role of ICTs to reach environmental sustainability.

The novelty of the proposed research approach consists of looking at social norms as limiting factors to avoid resource overuse and to focus on the role of ICT-based services.

According to such approach the **first research question** is **if Agent Based Models are suitable to simulate behavior of people in consumption of a limited resource**.

---

[7] Smart metering is an umbrella term used to indicate different kinds of hardware or software tools, ranging from elementary devices to sophisticated web-based systems. We refer to advanced smart metering functions, as described in Chapter 6.

[8] We will return on this concept in Part two and in Part three.

The **second research question** is **when a system of agents that consume a limited resource reaches environmental sustainability**. From what does it depend whether this system reaches sustainability is a question that needs to perform different and multiple experiments to find an answer. The methodological approach consists of playing experiments to increase understanding of the limited resource consumption mechanisms. An agent-based computational model is the tool to explore such processes systematically.

The specific **research contribution** of this thesis consists of an analysis of the environmental awareness spread and its effects on the consumption of a limited resource.

The **outcome** of such an analysis is the implementation of an ABM to simulate the awareness diffusion and its role in household energy consumption and to supply decision-maker with new tools and indicators toward sustainability.

Thesis organization

The thesis is organized in three parts.

In Part one, we introduce the complex relation between ICT and environmental sustainability.

A conceptual framework of ICT effects is supplied in Chapter 1, providing examples of environmental risks and green potentials. In particular in Chapter 2 the rebound effect is introduce in general and in ICT sector in particular. After a state of art about rebound effects classification, an alternative approach to classic energy-economics-based assumptions is proposed, introducing the key concept of awareness. We will then introduce the idea to consider the social influence as a limiting factor to avoid the rebound effects. This approach needs crossing disciplinary borders between ICTs, energy and environment disciplines as well as social and behavioral sciences.

The second part presents the conceptual building blocks to model human behavior from the environmental sustainability point of view, in a scenario of consumption of a limited-resource. We will focus on the background social mechanisms in Chapter 3 and we will introduce in Chapter 4 the potential of Agent-Based Modeling to describe at the micro level individual behaviors and to observe at the macro level the emerging general effects of such behaviors.

In particular in Chapter 5 and in Chapter 6, we propose a conceptual model to explore environmental awareness spread mechanisms, highlighting the importance of facilities, provided by advanced smart metering functions, in empowering users to turn such extended awareness into more sustainable behaviors.

We will describe the implementation of this model in Part three, using the standard protocol ODD (Objective, Design, Details) (Grimm et al., 2010) for ABM. Some explorative simulation experiments leading to sustainable or no sustainable scenarios are supplied in Chapter 8, while Chapter 9 deals with the choice of stakeholder validation as validation strategy.

A set of SAM4SN (Spread of Awareness Model for Social Norm) sensitivity analysis experiments in Chapter 10 allow us to consider a new indicator of sustainability as a main findings: the sustainability tipping point.

In the conclusion we highlight that although the presented ABM refers to energy use, the overall conceptual model behind it can apply to other types of limited resources, according to the definition given in this Introduction.

REFERENCES

Anda, M., Le Grey Brereton, F., Breman, J., & Paskett, E. (2013). Smart metering infrastructure for residential water efficiency: results of a trial in a Behavioral Change program in Perth, Western Australia. In: L. Hilty, B. Aebischer, G. Andersson and W. Lohmann (Eds.), *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich, February 14-16, 2013* (pp. 116-122). DOI 10.3929/ethz-a-007337628.

Boulanger P., Couder, J., Marenne, Y., Nemoz, S., Vanhaverbeke, J., Verbruggen A., & Wallenborn, G. (2013). *Household Energy Consumption and Rebound Effect* HECoRE (Final Report). Brussels: Belgian Science Policy.

Conceptual Framework Working Group of the Millennium Ecosystem Assessment. (2003). *Ecosystems and Human Well-being*. Chapter 5. *Dealing with Scale*. 107–124. ISBN 155634030. London: Island Press.

Conte R., Gilbert, N., Bonelli, G., Cioffi-Revilla, C., Deffuant, G., Kertesz, J., Loreto, V., Moat, S., Nadal, J. P, Sanchez, A., Nowak, A., Flache, A., San Miguel, M., & Helbing, D.(2012). Manifesto of computational social science. *The European Physical Journal Special Topics, 214*(1), 325-34.

Egger, S. (2006). Determining a sustainable city model. *Environmental Modelling & Software 21*(9), 1235-1246.

Ellickson, R.C. (2001). The market for social norms. *American Law and Economic Review 3* (1), 1- 49.

Epstein, J.M. (2008). 'Why Model?'. *Journal of Artificial Societies and Social Simulation, 11*(4), 12. http://jasss.soc.surrey.ac.uk/11/4/12.html.

Gesi. (2012). *Smarter2020: the role of ICT in driving a sustainable future*. http://gesi.org/SMARTer2020

Grimm, V., Berger, U., DeAngelis, D., Polhill, J. G., Giske, J., & Railsback, S. (2010). The ODD protocol: A review and first update. *Ecological Modelling, 221*(23), 2760-2768.

Hilty, L.M., Lohmann, W., & Huang, E.M. (2011). Sustainability and ICT - an overview of the field. *Notizie di POLITEIA, 104*, 13-28.

Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., & Wäger, P.A. (2006a). The relevance of information and communication technologies for environmental sustainability - A prospective simulation study. *Environmental Modelling & Software, 21*, 1618-1629.

Hilty, L.M., Köhler, A., Schéele, F., Zah, R., & Ruddy, T.F. (2006b). Rebound effects of progress in information technology. *Poiesis & Praxis: International Journal of Technology Assessment and Ethics of Science, 4*(1) 19-38.

Janssen, M. A., Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society, 11*(2), 37.

Janssen, N.A., Radtke, N.P., & Lee, A. (2009). Pattern oriented modelling of Commons Dilemma Experiments. *Adaptive Behaviour, 17*(6), 508–523. DOI:10.1177/1059712309342488.

Jevons, W.S. (1865). *The Coal Question, can Britain survive?*. First published 1865, Republished Macmillan, London, 1906.

Kinzig, A.P., Ehrlich, P.R., Alston L.J., Arrow, K., Barrett, S., Buchman, T.G., Daily, G. C., Levin, B., Oppenheimer, M., Ostrom, E., & Sahari, D. (2013). Social Norms and Global Environmental Challenges: the Complex Interaction of Behaviors, Values, and Policy. *Bioscience, 63* (3), 164-175.

Meadows, D., Meadows D.L., Randers, J., & Behrens III, W.W. (1972). *The Limits to growth: A report for the Club of Rome's*. New York: Universe Books.

OECD [Organisation for Economic Co-operation and Development]. (2011). *Greening household behavior: the role of public policy*. Paris: OECD Publishing.

OECD. (2010a). *Greener and smarter - ICTs the environment and Climate Change*. Paris: OECD Publishing.

OECD. (2010b). *Recommendation of the Council on Information and Communication Technologies and the Environment*. Paris: OECD Publishing.

OECD. (2009a). *Toward green ICT Strategies: Accessing Policies and programmes on ICT and the Environment.* Paris: OECD Publishing.

OECD. (2009b). *Measuring the relationship between ICT and the Environment*. Paris: OECD Publishing.

Owen, D. (2010). Annals of Environmentalism. The Efficiency Dilemma. *The New Yorker*, December 20, 2010, p. 78.

Polimeni, J. M., Mayumi, K., Giampietro, M., & Alcott, B. (2009). *The Myth of Resource Efficiency. The Jevons Paradox*. London: Earthscan.

Som, C., Hilty, L. M., & Köhler, A. R. (2009). The Precautionary Principle as a Framework for a Sustainable Information Society. *Journal of Business Ethics 85* (3), 493-505. DOI 10.1007/s10551-009-0214-x

Stern N. (2007). *The Economics of Climate Change. The Stern Review.* Cambridge University Press

Stern N. (2006). *Stern Review on the Economics of Climate Change* (prepublication edition of Stern, 2007). London: HM Treasury.

Theis, T.,& Tomkin, T.(Eds.).(2012). *Sustainability: A Comprehensive Foundation*. Huston: Rice University.

UNEP [United Nation Environmental Program](Fischer-Kowalski, M., Swilling, M., von Weizsäcker, E.U., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Romero Lankao, P., Siriban Manalang, A.). (2011). *Decoupling natural resource use and environmental impacts from economic growth.* A Report of the Working Group on Decoupling to the International Resource Panel. Paris: UNEP.

WCED [World Commission on Environment and Development]. (1987). *Our Common Future*. Oxford: Oxford University Press.

Xie, J., Sreenivasan, S., Korniss, G., Zhang, W., Lim, C., & Syzmanski, BK. (2011). Social consensus through the influence of committed minorities. *Physical Review E* 84, 01130, 1-8.

PART ONE: ICT AND SUSTAINABILITY

There is an important connection between ICT-based innovation and environmental issues. ICTs have a direct impact on the environment, consuming energy, materials and producing e-waste. But ICTs are also a major enabling technology for mitigation of environmental impacts across all economic sectors. ICTs can contribute in achieving more sustainable lifestyles, consumption and production, because ICT applications can help limit energy use and material consumption. In other words ICTs can be the driver for an emission reduction policy.

In Chapter 1 we introduce a reference framework about ICT and environmental sustainability, highlighting some methodological issues that lead to a new approach to avoid some risks.

We supply also two examples of such risks: the first example is related to great opportunity and the equally great environmental risks of cloud computing, while the second example is related to the role of software in inducing hardware obsolescence, a rebound effect that can be avoided.

In particular in Chapter 2 the rebound effect is introduce in general and in ICT sector in particular. After a state of art about rebound effects classification, an alternative approach to classic energy-economics-based assumptions is proposed, introducing the key concept of awareness. We will then introduce the idea to consider the social influence as a limiting factor to avoid the rebound effects. This approach needs crossing disciplinary borders between ICTs, energy and environment disciplines as well as social and behavioral sciences

1. OVERALL SCENARIO ON ICT AND SUSTAINABILITY

1.1 Introduction

ICTs can be environmentally oriented, toward a CO_2 emissions reduction (Masanet & Matthews, 2010). While there are many positive benefits of ICTs, such as an improved productivity and quality of life (GeSi, 2008), their negative impacts on the environment have to be taken into account. There has been a consistent questioning of the overall net benefit of ICTs.

The nuclear accident at Fukushima opened a global debate not only on the energy resource types but also on the consumption styles. This is positive, because more attention to energy resources leads to more attention to energy consumption reduction. The role of ICTs as a key factor will become much more important than in the past decades.

The interest in the use of ICTs for environmental sustainability is increasing. There are concerns about ICTs direct environmental impact, such as energy use and e-waste. The positive effects of using ICTs for sustainability, however, are argued to be bigger and the corpus of research in this area is growing (Hilty & Lohmann, 2013). There is a risk, however, of rebound effects, whereby unexpected usage and changes in behavior can cancel out the gained efficiency (Hilty, Köhler, Schéele, Zah, & Ruddy 2006).

Governments and institutions can stimulate further research into the impacts – intended and unintended – of the diffusion of ICTs, in order to assess how ICTs, and mainly the Internet, contribute to long-term environmental policy goals. Public policies can be instrumental in promoting a sustainable ICT-based approach and increase public awareness. Government policies can encourage improvement of environmental performance along the entire ICT life cycle and promote ICT applications to make non-ICT sectors more resource efficient.

Overall, much more needs to be done to develop measurable policies to improve environmental performance of ICTs (OECD, 2009a). However, the true net impacts of ICT can only be understood when we consider its negative impacts alongside its many possible benefits (OECD, 2010a).

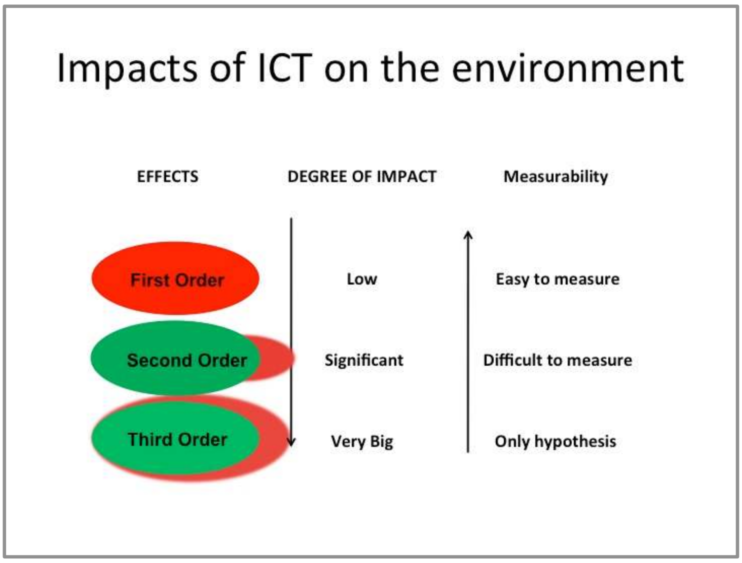
I will try to highlight the open issues related to the definition of a methodology to evaluate the "net environmental impact" of ICTs.

1.2 ICT effects on CO2 emission and their assessment: an overview

An environmentally oriented ICT strategy needs transparent policy objectives and targets to be measured. Clear responsibilities must be set out and compliance with policies has to be monitored on a regular basis to improve accountability (OECD 2010b). Increasing public awareness allows users to monitor and verify the effect of adopted policies. Stakeholder-driven monitoring increases understanding of ongoing policies, but needs measurement tools.

An increased understanding of the effects of government policies (whether information, incentives or regulations), improving measurement tools, and increasing public awareness has to be developed (OECD 2010b).

The effects of ICT on the environment are commonly considered in terms of first, second and third order effects (Berkhout & Hertin, 2001). This framework that is seminal in literature and has been reused and reinterpreted many times (Hilty & Lohmann, 2013), highlights the importance of analyzing impacts on all three levels to assess the net environmental impact of green ICT. For the sake of simplicity, we will start from a short overview on assessment issues of each effect type separately, whereas they are **conceptually and in fact nested** (Hilty, 2007).



Impacts of ICT on the environment

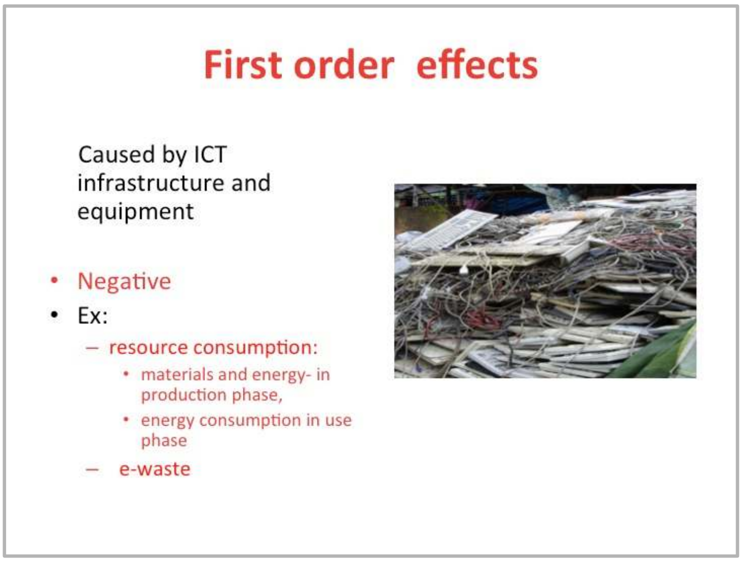
EFFECTS	DEGREE OF IMPACT	Measurability
First Order	Low	Easy to measure
Second Order	Significant	Difficult to measure
Third Order	Very Big	Only hypothesis

Figure 2 - ICT and sustainability

1.2.1 First order effects

In 2007 Garner Group published - for the first time at worldwide level - astonishing data[9] about the environmental impact of ICTs. In 2007 the total footprint of the ICT sector was 830 $MtCO_2e$ (Mega tonnes of CO_2 equivalent) emissions, about 2% of the estimated total emissions from human activity released that year. The Smart2020 (Gesi, 2008) report makes forecasts, under different scenarios, for 2020. Despite the huge amount foreseen for the ICT sector's footprint, further adjustments to the figures are suggested by environmental organizations (Greenpeace, 2011), highlighting the scale of ICTs' estimated energy consumption, and providing new analysis on the *projected growth in energy consumption of the Internet and cloud computing* for the coming decade, particularly as driven by data centers.

Each stage of a computer's life cycle, from its production, throughout its use, and to its disposal, increases carbon dioxide emissions and impact on the environment. Computers are continually making astonishing progress in energy efficiency (Murugesan, 2008), measured in performance per watt, due to innovative design techniques ranging from technological aspects to the processing architecture and dynamic management.



First order effects

Caused by ICT infrastructure and equipment

- Negative
- Ex:
  - resource consumption:
    - materials and energy- in production phase,
    - energy consumption in use phase
  - e-waste

Figure 3 – First order effects

---

[9] http://www.gartner.com/newsroom/id/503867

The power density is also increasing. But the demand for ICT is increasing even faster than the energy efficiency of ICT devices (Hilty, 2008).

New-generation information technology (IT) systems provide more computing power per unit of energy but, despite this, they are actually responsible for an overall increase in energy consumption. This is because users are taking and using the increased computing power offered by modern systems regardless of its implication for environmental sustainability (Lopez, Natvig, & Sissa, 2011). Although the per unit consumption is relatively straightforward and the total number of end-users of a given service in a given geographical area is known, assumptions have to be made for the usage patterns of the equipment, the intensity of use and the service life of the equipment (Coroama & Hilty, 2009).

Moreover, cloud computing (Buyya, Yeo, Venugopal, Broberg, & Brandic, 2009) is changing how to quantify the ICT direct effects (Sissa, 2011a), as more detailed in section 1.3. To formulate even a rough estimate, the entire **life cycle** of the whole system providing a given **service** should be studied in order to assess the environmental impact of producing one *functional unit of the service*. But quantifications would be not comparable because of the different features of cloud computing services and incompatible starting assumptions. More cloud computing companies are pursuing design and siting strategies that can reduce the energy consumption of their data centers, but primarily as a cost containment measure. For most companies, the environmental benefits are generally secondary concerns. The *emission factor* - the rate to convert kilowatt-hours into units of carbon dioxide emissions - is the basis for any ICTs direct impact evaluation. But this rate is different country by country or region by region[10], because it depends on the source from which electric power is produced.

An example of the extent of such geographical dependency of the emission factor is given by the Australian Computer Society that, in a report about the Carbon Footprint of ICT usage (Australian Computer Society/Connection Research, 2010), supplies the emissions factor by each Australian State, showing as there is no unique simple formula for converting kWh to CO_2e (Carbon Dioxide equivalent), because the formula varies depending upon how the power that is being used is generated. Victoria state, for example, generates most of its power from brown coal, which emits significantly more CO_2 than other regions. Tasmania, which uses a lot of hydroelectric power, is much cleaner. Differences are significant. This is just an example of the need of sharing a scientific baseline for ICTs environmental effects assessment.

Within the framework of environmental sustainability the necessity to develop concrete and common methodologies is well recognized, including a unified metric to describe and estimate objectively and transparently the present and future energy consumption of ICTs over their entire life cycles. Initiatives are emerging to help the ICT industry to measure its carbon footprint[11], such as those for the traditional high carbon industrial sectors[12].

Within the International Telecommunications Union's Telecommunication Standardization Sector (ITU-T), Study Group 5 is the Lead Study Group on ICT and Climate Change. It has developed Recommendation L.1400, "Overview and general principles of methodologies for assessing the environmental impact of ICT". This is one of a number of new initiatives to help the ICT industry to measure its carbon footprint.

- ITU-T Recommendation L.1400 "Overview and general principles of methodologies for assessing the environmental impact of ICT"[13];
- The European Telecommunications Standards Institute (ETSI) activities;
- The Greenhouse Gas (GHG) Protocol ICT supplement[14].

---

[10] For examples on regional emission factors, see the report: *Carbon and Computers in Australia. The Energy Consumption and Carbon Footprint of ICT Usage in Australia in* 2010 (Australian Computer Society, 2010).

[11] The second draft of the ICT Sector Guidance, a global guidance to provide common approaches for calculating carbon emissions of ICT products and services, was made available for public comment on January 31, 2013 to March 4, 2013.

[12] http://www.ghgprotocol.org

[13] The Recommendation ITU-T L.1400 (*Overview and general principles of methodologies for assessing the environmental impact of ICT*) was approved on 22 February 2011. The recommendation presents the general principles on how to assess the environmental impact of ICTs, provides examples of opportunities to reduce the environmental load thanks to ICT, and outlines methodologies for:

Assessing the environmental impact of ICT goods, networks, and services;
Assessing the environmental impact of ICT projects;
Assessing the environmental impact of ICT in organizations;
Assessing the environmental impact of ICT in cities;
Assessing the environmental impact of ICT in countries or group of countries

In short we can say that first order effects are (relatively) known and in principle measurable. The degree of uncertainty depends on the maturity of the assessment model.

Public sector policy can play a significant role with policies toward sustainable ICTs. For policy accountability is important to monitor programs and evaluate their outcomes. This links policy objectives to measurable output targets and leads to define indicators to monitor inputs and to assess outputs (Munck, 2010). The UK Cabinet Office Greening Government ICT[15] described how changes, like extending the life of PCs, making double-sided printing the default option, and making sure computers are turned off at night, have helped cut the carbon footprint of central government computers.

1.2.1.1 Green ICT and sustainability

As far as resource consumption and sustainability impact of the ICT sector itself is concerned ("Green in IT/ICT"), an energy and CO_2 perspective seems too narrow, because many scarce resources are used in electronics products (Wäger et al., 2011).

The most comprehensive methodology to be used here is **Life Cycle Assessment (LCA),** the standard practice for detecting the overall environmental impact of providing a functional unit by following products from cradle to grave. Life-cycle thinking and methodology can be applied to any function provided by any product, including ICT products or products affected by ICT.

Balin and colleagues (2012) present an approach starting from LCA applied to ICT hardware, which is then extended by the introduction of four additional factors:

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

The last stage of the ICT hardware life cycle, electronic waste (e-waste or WEEE, Waste Electrical and Electronic Equipment) and its worldwide impact has stimulated highly specialized activities and publications (Manhart, 2011; Schluep et al., 2013)

The variety of materials contained in ICT hardware makes recycling difficult and less efficient. Digital ICT is the first technology claiming the use of more than half of the periodic table of the elements. **For example, 57-60 chemical elements are used to build a microprocessor today; in the 1980s, a microprocessor contained only 12 elements** (National Research Council, 2008; Behrendt et al., 2007). Memory components, peripheral devices and external storage media are also increasing in material complexity.

Miniaturization and integration work against efforts to close material loops by recycling electronic waste. Some metals are contained in very small concentrations (such as indium in flat screens) and could therefore only be recovered in centralized industrial processes – as far as recovery is profitable at all, both in economic and energy terms. If not recovered, these resources are dissipated and therefore irreversibly lost. The combination of highly toxic and highly valuable materials in digital electronics adds other challenges of recycling, which are not only of a technical nature, but also involve trade-offs among environmental, occupational health and economic objectives.

By focusing on the reduction of CO_2 emissions caused by power generation from fossil fuels, the Green ICT debate tends to underestimate the supply risks and resulting geopolitical and ecological problems following on from ever increasing hardware churn rates combined with miniaturization and integration.

The demand for rare metals is growing fast. For the elements gallium, indium, iridium, palladium, rhenium, rhodium and ruthenium, over 80 percent of the quantities extracted since 1900 were mined in the past 30 years (Wäger et al., 2010). There will be no really Green ICT until society learns to reverse the trends towards higher material complexity and shorter service lives of ICT hardware.

Not all ICT products are the same in terms of production, use and end-of-life treatment. For some ICT products (such as servers or set-top boxes) it is essential to reduce the power consumption during use, because the use phase comprises the largest share in their total life cycle impact; for others it is more important to optimize their design for recyclability or to avoid negative effects during end-of-life treatment.

---

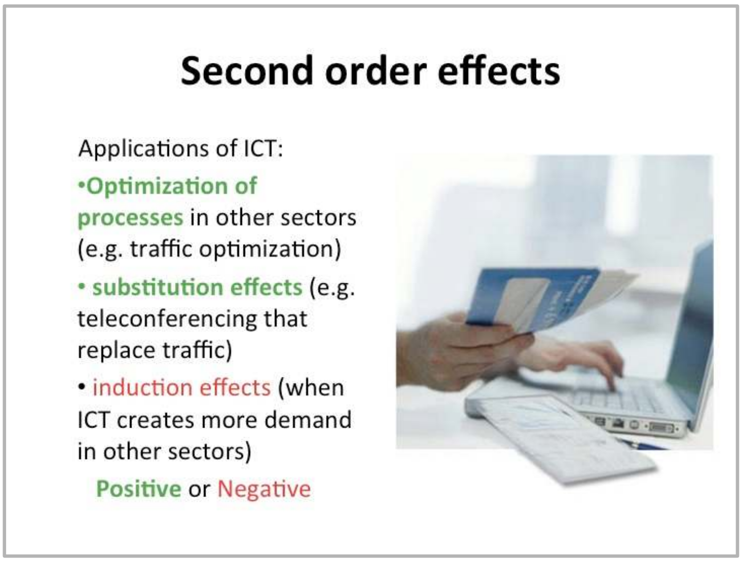
[14] http://www.ghgprotocol.org/feature/ghg-protocol-product-life-cycle-accounting-and-reporting-standard-ict-sector-guidance

[15] http://www.cabinetoffice.gov.uk/resource-library/greening-government-ict

For example, Radio-Frequency Identification (RFID) chips and small embedded ICT products entering the waste stream can affect established recycling processes, such as paper, metals, glass or plastics recycling or textile recycling (Köhler, Hilty, & Bakker, 2011).

1.2.2 Second order effects

ICTs are the essential driver for productivity improvements and innovation (for instance, the virtualization of government and business services), as well as for more efficient management, control, and visualization of all kind of network (buildings, energy production and use, mobility, water and sewage, open spaces, public health, and safety). The American Consumer Institute (Fuhr & Pociask, 2007) several years ago added to the discussion of how to reduce greenhouse gas emissions, documenting the reductions that can be realized by the widespread delivery of broadband services in the U.S. This study finds that wide adoption and use of broadband applications can achieve a net reduction of 1 billion tons of greenhouse gas over 10 years.



Second order effects

Applications of ICT:

- Optimization of processes in other sectors (e.g. traffic optimization)
- substitution effects (e.g. teleconferencing that replace traffic)
- induction effects (when ICT creates more demand in other sectors)

Positive or Negative

Figure 4 – Second order effects

Some ICT services are potentially able to decrease emissions by replacing material intensive physical products and services with virtual alternatives, i.e. by **dematerialization**.

It is critical to be able to quantify the potential benefit, for planning a policy and for quantifying the targets. *Unlike for the first order effects of ICTs, direct measures are impossible. An ex-ante analysis can be just an estimate* (Coroama & Hilty, 2009). But also if it is at a rough estimate level, a scientific baseline has to be clearly defined and shared by stakeholders. The goal is to be able to estimate the potential benefit, in terms of potential emission reduction, for quantifying the targets.

The basis for any quantification is the calculus of an “emission equivalent” for any activity (Pamlin, 2008). There are a lot of tools to derive these figures[16]. The annual “greenhouse gas emissions per passenger vehicle” is the basis of a lot of ICT services related to traffic[17]. Government agencies, non-governmental organizations, and private companies, to increase awareness and trigger behavioral changes of individual users, often provide individual carbon footprint calculators (Starkey, 2012). They allow users to learn and quantify each activity in terms of green house gas (GHG) emission equivalent. However, research on the comparison between several GHG calculators (Padgett et al., 2008) shows inconsistencies in output values for a given input.

---

[16] A Greenhouse Gas Equivalencies Calculator is available at http://www.epa.gov/cleanenergy/energy-resources/calculator.html. A visual, simple and effective tool is http://www.carbon.to to understand the magnitude of the numbers told.

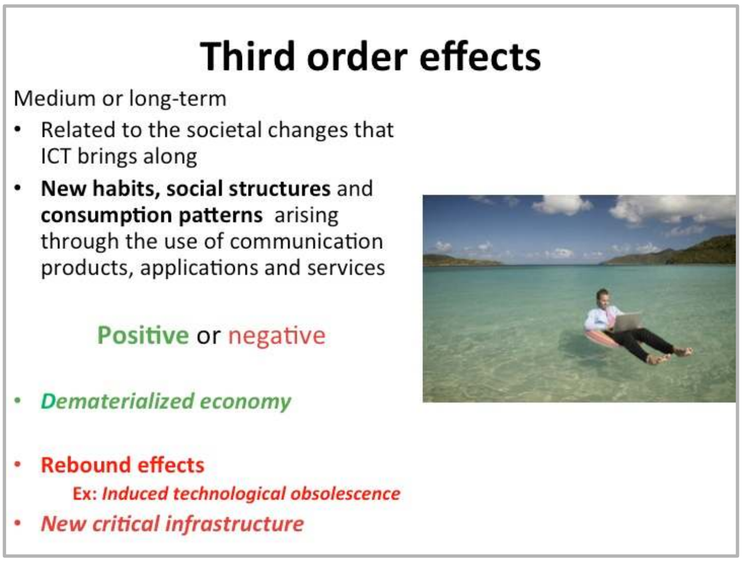
[17] http://www.epa.gov/cleanenergy/energy-resources/refs.html#vehicles

Calculator outputs could affect the public pressure on policy makers regarding emissions reduction efforts. The above mentioned comparison report shows as, although similar approaches to CO_2 estimation, the results can vary, even when using uniform inputs. Differences in calculating methodologies, behavioral estimates, conversion factors, can lead to variations. A lack of transparency makes it difficult to assess the accuracy and relevance of the calculations. When compounded in calculations, such small differences can produce considerable variation in results.

The need for transparent and clearly defined criteria is mandatory for institutions engaged in the policy of dematerialization. Criteria need transparent, friendly and easy-to-use tools to try and quantify potential emission reductions arising from ICT services. The GeSi group released an assessment methodology to evaluate the carbon-reducing impacts of ICT (GeSi, 2010). Existing tools allow only a rough assessment just *by giving an idea* of the *magnitude order of potential benefits* rising from the adoption of an ICT service for dematerialization.

1.2.3 Third order effects

Systemic impacts of ICTs on the environment are relatively unexplored, mainly because of the complexity of assessing future directions of production and consumption (OECD, 2010a). Measures taken to protect the environment often have other, unintended effects on society. One concern is that negative rebound effects may offset the benefits of changed behaviors.



Third order effects

Medium or long-term

- Related to the societal changes that ICT brings along
- **New habits, social structures** and **consumption patterns** arising through the use of communication products, applications and services

Positive or negative

- *Dematerialized economy*
- **Rebound effects**
  Ex: *Induced technological obsolescence*
- *New critical infrastructure*

Figure 5 – Third order effects

The unwanted rebound effects are a reaction to growing efficiency, change of economic and institutional structures and change of life-styles (Hilty et al., 2006).

Koomey, Berard, Sanchez, & Wong (2011a; 2011b) showed that the energy efficiency in computing, expressed in computations per energy input, has doubled every 1.57 years between 1947 and 2009. The substantial increases in efficiency that are being demonstrated in the ICT sector itself through application of ICT to optimize processes, to substitute information services for products or telecommunications for travel, do not automatically cause any resources to be saved. This is due to the so-called rebound effect, according to which a transition to more efficient technologies causes an expansion of activities given constant costs and time budgets.

Technological measures alone do not assure a reduction in the use of natural resources for production and consumption (Göhring, 2004); instead politicians have to create framework conditions to incentives for a more economical use of material and energy.

Trying to make a synthesis: there is a gap in the analysis quality of first, second and third order effects of ICTs on GHG emissions in general (Erdmann & Hilty, 2010) and in particular on ICT-based dematerialization services.

First order effects are relatively well known, complex but possible to quantify, and there are ongoing activities to improve the quality of the assessment methodology. The second order effects are difficult to foresee exactly, but can be estimated at a magnitude order level, and some first tentative methodologies have been proposed. Third order effects are really hard to assess.

In short, sustainability is a matter of policy and technological progress may be only a prerequisite for implementing certain types of policies. The main challenge is *how individual and collective behaviors can transform themselves to shape a more sustainable society*. The emerging concept of collective awareness is meant to create an extended consciousness of the environment and of the consequences of our actions, and to encourage us to take informed and sustainability-aware decisions. It is a key step in improving the role of citizenship and enabling a bottom-up approach to policy assessment.

1.3 Dematerialization and stakeholder involvement

We focus now on “ICT services for dematerialization” and their assessment. We assume the citizen point of view, because such individual and collective behavioral changes can lead to a society of an increasing number of dematerialized services (Sissa, 2011). An active citizen involvement is a key issue, and such involvement plays a twofold role: both in the policy implementation and in the policy assessment.

1.3.1 Collective situational awareness

Collective awareness is the subject of several European research projects[18], as for example BeAware[19] that is aimed at boosting energy awareness.

ICT systems must help us to progress towards sustainability (a beyond-GDP, low carbon economy), to use collective or individual self-regulation, in a lightly coordinated bottom-up approach, without being commercially driven. Examples range from informing consumer decisions to encouraging behavioral changes towards more sustainable lifestyles, enabling communities of peers to access real-time information about the environment, and anticipating social changes and social innovations. A big challenge is how to transform individual and collective behaviors to shape a more sustainable society, using networks (Nuttall, Zhang, Hamilton, & Roques, 2009), which are capable of creating and supporting an appropriate level of situational awareness in both centralized and grassroots approaches.

ICTs can help to build resilience[20] through user empowerment, for instance, in energy, mobility, government services, technology design, quality of care, education and working patterns. The principles are about **making “more from less”, and making sense of data**. The key is enabling access to trusted knowledge about the state of the environment, and the impact of people’s own actions.

1.3.2 Environmental collective awareness and bottom-up policy assessment

Basic steps for the building of a collective environmental situational awareness are accessing real-time and easily understandable information on resource consumption, and comparing individual lifestyles against some **environmental benchmark**. Aggregated data can be used to evaluate the performances of larger entities (communities), i.e. *the scale of city neighborhoods* as in the *Urban ecomap*[21] of San Francisco in the United States of America or of Amsterdam in the Netherlands.

Measuring and understanding are the first steps to being able to act smart (Spagnolli et al., 2011). Smart meters can reduce household energy consumption (OECD, 2011). Better access to information about the use and about the price of electricity can help reduce energy consumption. Personal carbon accounting is necessary for citizens to be able to understand and manage their carbon footprint. It is essential to empower individuals and organisations with information that will help them to reduce their own carbon footprint.

Further energy savings can be achieved when **smart meters** are integrated into home automation systems and connected to the Internet (the Internet of Things). This allows the user to control electrical devices over the Internet. Smart meters and related services can reduce household energy consumption, but their success largely depends on behavioral changes by individuals and groups of individuals. A mix of basic needs, personal desires and social images drives consumers[22]. Therefore it is important to share sustainability goals.

Some important questions arise. How can the impact of ICTs evolve from fancy gadgets to tangible lifestyle changes towards sustainability? How can we identify and involve the most relevant stakeholders who can act as credible "agents of change" and reach the required massive scale of citizen trust and participation? To try and answer these questions, it is important to seize the opportunity offered by a mix of mobile devices, Internet of Things and crowdsourcing.

---

[18] Collective Awareness Platforms for Social Innovation and Sustainable Social Changes are ICT systems leveraging the emerging "network effect" by combining open online social media, distributed knowledge creation and data from real environments (Internet of Things) in order to create new forms of social innovation. See:
http://ec.europa.eu/information_society/activities/collectiveawareness/links/index_en.htm

[19] http://www.energyawareness.eu/beaware/

[20] First dialogue on "Platforms For Collective Awareness And Action", Brussels, 9 September 2011, European Commission

[21] http://urbanecomap.org/

[22] For details, see the European Community Report *Consumer 2020: From Digital agenda to Digital action*, May 2011

1.3.3 Location-Based Data as crowd-sourced data

New opportunities arise from social networks for the involvement of citizens in distributed sensing experiments (Lane et al., 2010).

Geo-referencing allows the user to share Location Based Data. A new breed of social networking services, from *Location Based Social Networks,* and *Participatory sensing* (Kanhere, 2011) has emerged. An example is user-generated maps of environmental quantities such as the shared maps of noise, a physical quantity easy to measure by smartphone (e.g. noisetube.net).

The Internet of Things and geo-referenced mobile devices allow an environmental situational awareness by gathering real-time, user-generated, location-based data and shared mapping of some environmental quantities (Lane et al., 2010). In Fukushima, Japan, after the nuclear accident in March 2011, citizens built a collective mapping of the radiation level in the area using radiation sensors[23] connected to mobile devices (Saenz, 2011; Kamel Boulos et al., 2011).

Global Positioning System (GPS) chipsets are being embedded in all kinds of moving objects (such as cars, shipments, and smart phones), allowing for the large-scale collection of movement data. Such data play an essential role in a variety of well-established application areas (e.g., tracking, urban planning, traffic management, and geo-social networks) (Kamel Boulos et al., 2011). Mobile applications in a Location-Based Social Network (Eaglea, Pentlandb, & Lazerc, 2009) could allow tracking personal footprints, sharing goals with friends, colleagues or neighbors to decrease personal CO_2 emissions and to make green behavior easier.

The increasing availability of people traces – collected by portable devices – poses new possibilities and challenges for the study of people's mobile behavior (Yan, Chakraborty, Parent, Spaccapietra, & Aberer, 2011; Cagnacci, Boitani, Powell, & Boyce, 2010; Jia-Ching Ying et al., 2010; Xie, Deng & Zhou, 2009; Spintasanti, Celli, & Renso, 2010).

For example the availability of a new Location-Based Service, such as a real-time transportation system to optimize routing or transport modality, is potentially positive for the environment (to reduce CO_2 emissions), and could lead to a green behavior, i.e. reducing a person's CO_2 footprint.

New opportunities arising from the mix of social networks, social metering systems and geo-referenced social media facilitate a bottom-up gathering of data that can be shared, allowing comparison of consumption, to compare environmental footprints and to increase collective and individual awareness. A new opportunity for stakeholders addressed by the policy is to verify directly the effect of such a policy (or of a new service or product) by measuring its outcomes.

---

[23] http://singularityhub.com/2011/03/24/japans-nuclear-woes-give-rise-to-crowd-sourced-radiation-maps-in-asia-and-us/

1.4 Conclusion

1.4.1 International institutions' policy recommendations

Systemic impacts of ICTs and their environmental repercussions are relatively unexplored, mainly because of the complexity of assessing future directions of production and consumption (OECD, 2010a).

Measuring and accounting can help in decision-making, to achieve the goal of optimizing, leading to behavior change, and avoiding rebound effects. An ICT-enabled environmental metric will gain a relevant position in the policy framework definition. International organizations have made a set of recommendations about the subject of ICT and sustainability.

The OECD recommends[24] encouraging measurement: "Members should encourage development of comparable measures of the environmental impacts of ICT goods and services and ICT-enabled applications and among similar products. They should also increase understanding of the effects of government policies (information, incentives, regulations) on improving measurement tools and increasing public awareness." In addition, the OECD recommends Setting Policy Targets and Increasing Evaluation: "Members should set transparent policy objectives and targets to measure and improve government green ICT strategies, including ICT-enabled applications across the economy. They should be monitoring compliance with policies on a regular basis to set clear responsibilities and improve accountability."

The European Commission (2010), in its Digital Agenda for Europe[25], recommends that the ICT sector should lead the way by reporting its own environmental performance through adopting a common measurement framework as a basis for setting targets to reduce energy use and greenhouse gas emissions of all processes involved in production, distribution, use and disposal of ICT products and delivery of ICT services.

1.4.2 The data issue

At a macroeconomic level OECD ICT statistics (OECD, 2008a) and OECD environment statistics (OECD, 2008b) are the key references. OECD has selected the more reliable indicators and provides comments on measurability, including data quality, availability and gaps (OECD, 2008a). While the relationship between ICT and the environment is not a recognized field of statistics, individually **ICT statistics** and **environment statistics** are recognized fields. A brief description of the conceptual frameworks for these fields is presented in the OECD report "Measuring the relationship between ICT and the Environment"(OECD, 2009b).

As far as statistical indicators linking ICT and the environment are concerned, the field **ICT and the environment** is a new one. Consequently, statistics directed to the policy questions related to this field are scarce. In respect of official statistics, it is necessary to look for data that throw light on relevant aspects of the field, though were not necessarily collected with a view to answer policy questions about the relationship between ICT and the environment (OECD, 2009b).

OECD database and other international institutions sources of information are key references, but only at a global, macro level. At a finer granularity level, the availability and accessibility of open public data is a key factor.

1.4.3 User generated data

Stakeholders of the ICT and sustainability area could supply datasets related to individual user behavior. Qualitative data sources can help to understand the specific contexts in which ICT products are applied and the ways in which they are used. For example, just to stay in the transportation field, surveys and interviews can indicate whether teleworkers really reduce commuting distances travelled by car; or whether total travelled road miles are reoriented, and maybe increased, through driving for other purposes, e.g. leisure, children and elderly care, shopping. The *development of such datasets* needs *cooperation among different scientific disciplines*, like ICT engineering, energy and environmental sciences, and social sciences.

---

[24] See the OECD (2010b) Recommendation of the Council on Information and Communication Technologies and the Environment

[25] http://ec.europa.eu/information_society/digital-agenda/index_en.htm

It can be interesting also to look at new potential kind of data, like user-generated data (Kanhere, 2011). Citizen participation can supply user-generated, location-based data about the environment. **Open data** and **linked data** are pivotal for a smart dematerialization policy (Budhathoki & Haythornthwaite, 2013). An example comes from the Massachusetts Bay Transit Authority, which decided to open up data[26] for software developers for the first time in September 2009. Within two months, developers had built six trip-planning applications including websites, a desktop widget, and smart phone apps, thereby enabling real-time route information for passengers in the area.

Social networks, social metering systems and geo-referenced social media allow the user to share information, to compare consumes, to increase collective and individual awareness, playing a key role to promote low-carbon lifestyle. Web and mobile applications (Kiukkonen, Blom, Dousse, Gatica-Perez, & Laurila, 2010) allow tracking personal footprints, sharing goals and making green behavior easy. Different kind of data could be supplied from stakeholder collaboration on the subject, using mixed methods, an approach that in social science research combines the collection and analysis of quantitative and qualitative data.

1.4.4 Participatory processes as empowerment processes

An extended awareness can be enabled by ICTs, for instance by decentralized and federated social networks, interfaced in real-time to the environment through networks of sensors, available to all citizens, both in terms of access and content creation.

Environmentally aware, grassroots processes and practices to share knowledge, to achieve changes in lifestyle, production and consumption patterns, will set up more participatory processes. Such participatory processes are enabled by the mechanisms of "motivating social environments", "psychological ownership" and "social proof", which will be introduced in Part two – Chapter 3.

1.4.5 Open issues

In this chapter we highlighted a number of open issues.

Firstly, a methodological approach for the net environmental impact evaluation of new ICT applications and services is a foundation for ICT-based green policy accountability. This approach leads to cross the disciplinary borders between ICTs, energy and environment disciplines, as well as social and behavioral sciences.

The chapter tried also to highlight some methodological issues, like **the scale** that makes the net environmental impact evaluation feasible and practically useful. Local scale looks to be the most suitable for a methodological in-depth approach. This issue is strictly related to the **data availability, their extent, quality and completeness**. It is really difficult to identify an available dataset documenting people behaviors at the right scale and level of detail.

Incomplete data, the difficulty of covering incoming effects and changing general framework conditions are complex issues to deal with (Hilty et al., 2006).

In the second part, we will introduce the need of modeling human behavior to cope with environmental issues and rebound effect.

---

[26] See "Where's my bus? Open data enables real-time route info for Boston riders" http://opensource.com/government/10/6/wheres-my-bus-open-data-enables-real-time-route-info-boston-riders

APPENDIX 1: Green opportunity and risks of cloud computing

A visionary idea of computing since early 60s has been that of *utility*. Cloud computing finally looks to be the implementation of this idea. While this paradigm is providing many opportunities for the development of the software sector, concerns about its environmental impact are also being raised. This Appendix focuses on the green potentials of clouds and how they have to be deployed for different user levels, highlighting the related environmental risks. The trend shows clearly as cloud computing is turning computing in a pay-per-use model, one in which Quality of Service requirements will need to be expanded to include green requirements.

Green computing has to take into consideration new opportunities and new issues for the environment not only focusing on the energy use phase but also on all phases of the Life Cycle for any service provided in the cloud. **The awareness of users and developers is the first step to realizing the green potential of the cloud**.

Back to the future: computing as utility

In the 60s' computers were as big and expensive as difficult to use and to maintain. Computational centers had to have human operators as an interface between users and the computer. User wrote his program on a set of punch cards and to run it he had to contact the computer center operator, to give him the packaged cards and pay for time of computation. The model was pay-per-use of the computing resource.

One of the stronger ideas underlying the development of the computing has always been that computing should be a utility, like water, electricity, gas, and telephony. To become true, this dream would have needed the availability of computing everywhere. At that time, there was no possibility of computing joining the ranks of other kind of utilities, because of the lack of a "pipeline" for computing resources.

But computing model evolved in the opposite direction: towards individual availability, at home or at office, of the computer itself, i.e. the personal computer. In the PC paradigm the user has become the owner of the computing capability, which he or she manages.

With Internet it was clear soon that something was changing. As early as 1969, Leonard Kleinrock (Kleinrock, 2005), one of the chief scientists of ARPANET, said "As of now, computer networks are still in their infancy, but as they grow up and become sophisticated, we will probably see the spread of *computer utilities* which, like present electric and telephone utilities, will service individual homes and offices across the country". The pipeline issue could be solved.

The vision of computing utilities based on a "service provisioning model" anticipated the cloud computing era, in which computing services are readily available on demand, just like other utilities, and users need to pay providers only when they access them.

Cloud computing opportunities

In the ICT sector, *Cloud Computing* is one of the most popular "search term". There are a great many definitions, but none is fully accepted by the scientific community as a whole.

The NIST[27] definition is very broad: "*Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model promotes availability and is composed of five essential characteristics, three service models, and four deployment models*" (NIST, 2011).

Cloud computing is the delivery of computing as a service rather than a product, whereby shared resources, software and information are provided to computers and other devices as a utility (like the electricity grid) over a network (typically the Internet).

Cloud computing delivers infrastructure, platform and software applications" as a services", which are made available to consumers as subscription-based services under the pay-per-use model.

Within each layer of abstraction there are myriad opportunities for defining services that can be offered (Sun, 2009). Users can access and deploy applications from anywhere in the world, on demand, and at competitive costs depending on their Quality of Service requirements. Users via Service Level Agreements (SLA) specify QoS requirements.

---

[27] National Institute of Standards and Technology (NIST)

The need to manage multiple applications in a data center creates the challenge of **on-demand** resource provisioning and allocation in response **to time-varying workloads**. This feature, called elasticity, is one of the five cited by NIST**:** *"*Capabilities can be rapidly and elastically provisioned, in some cases automatically, to quickly scale out, and rapidly released to quickly scale in. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be purchased in any quantity at any time"(NIST, 2011).

In other words, cloud computing refers to both the applications, delivered as services over the Internet, and the hardware and systems software in the datacenters that provide those services. The datacenter hardware and software is what we will call a Cloud. When a Cloud is made available in a pay-per-use to the general public, we call it a Public Cloud; the service being sold is also called "Utility Computing"(Ambrust et al., 2009).

If cloud computing is finally the implementation of the old idea of "computing as utility" (Buyya et al., 2009), what are the implications arising from it? The answer depends on whoever is posing the question.

The actual meaning of cloud computing is different for different people, depending on their use of the cloud. For application user it is the delivery of computing, storage and application over the Internet from centralized data centers. For Internet application developers it is an Internet-scale software development platform and runtime environment. For infrastructure providers it is the massive distributed datacenter infrastructure connected by IP network (Lin, Fu, Zhu, & Dasmalchi, 2009).

The cloud has been a boon for the companies hosting it. Developers no longer need to invest heavily or go to the trouble of building and maintaining complex IT infrastructures. Developers with innovative ideas for new Internet services no longer require large capital outlays in hardware to deploy their service.

Thus the computing world is rapidly transforming towards the development of software for millions to be consumed as a service, rather than to run over individual computers (Buyya et al., 2009). The network is the platform for all computing, where everything we thought as a computer yesterday is just a device that connects to the Internet (O'Reilly, 2005).

If cloud represents plenty of opportunities for different kind of users, what opportunity does it represent for the environment? What does the implementation of utility computing mean from an environmental point of view? Are there some risks, concerning environmental sustainability?

A query on Google Trend, made in April 2011, about "green it " and "cloud computing" showed a growth of interest in both terms, but stronger in cloud computing.

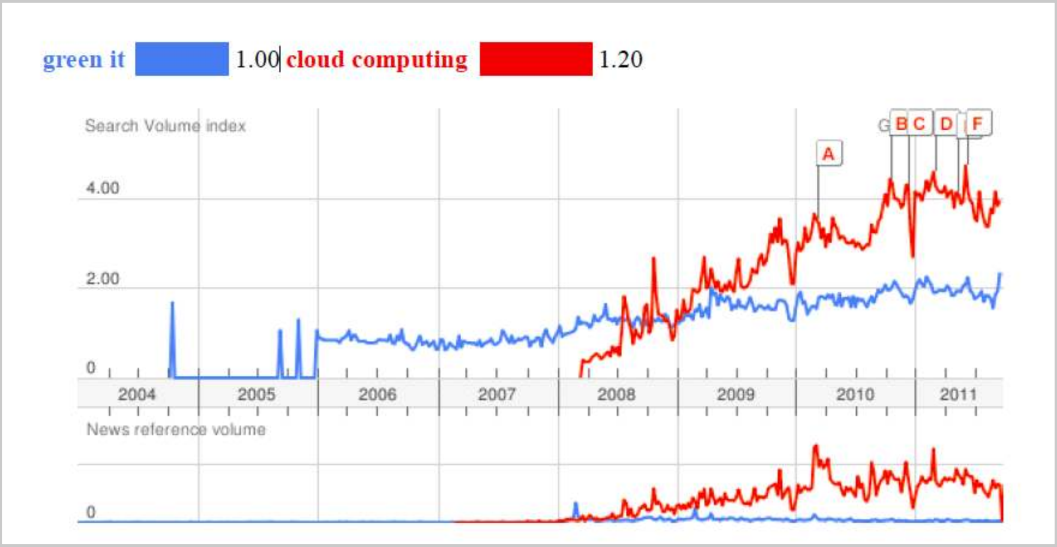


Figure A1.1 - green IT and cloud computing on Google Trends in 2011

The same query at October 2013 shows that the relative interest of green IT is increased.

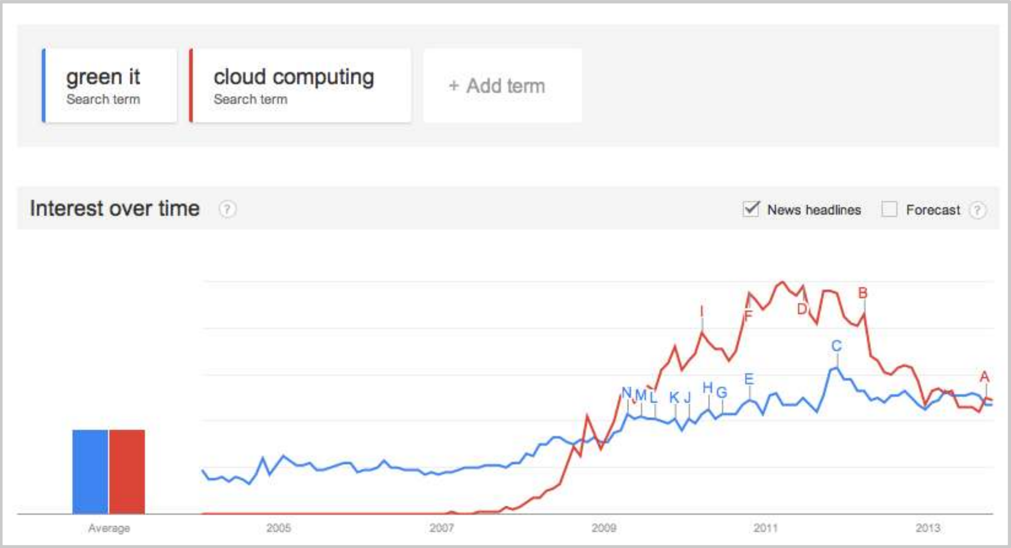


Figure A1.2 - Comparison between green IT and cloud computing on Google Trends in 2013

Given the importance of cloud computing, the question is not whether it is green as it is, but how it can became really green (Buyya, Belograzov, & Abawajy, 2012). The focus will be on the potential green role played by cloud computing, as implementation of computing as utility.

Strongly driven by the hardware producers, green computing supplies a huge offer of green ICT devices and products. But, since the computing paradigm has shifted towards cloud computing, i.e. utility computing, the green challenge of ICT will be played out more and more on such a paradigm.

Before going more in depth in the green aptitude of cloud, we have to remember some basic environmental sustainability principia related to the ICT sector that have been introduced in the last chapter and then to try and apply them to cloud computing.

Cloud computing first order effects

The total electrical energy consumption by servers, computers, monitors, data communications equipment, and cooling systems for data centers is steadily increasing. Data Centers now drive more in carbon emissions than both Argentina and the Netherland (Greenpeace, 2011). Google, Microsoft and Yahoo are building their data center near the Columbia River, to exploit cheap and reliable hydroelectric power. There is a trend emerging to build data farms in cold region, like Island, to decrease cooling power needs and price. In other words, there are a lot of nested relationships between ICT and the environment.

ICT devices are becoming more and more compact and energy efficient and green computing is the responsible of such improvements. New generation IT systems provide more computing power per unit of energy but, despite this, they are actually responsible for an overall increase in energy consumption. The demand for ICT is increasing even faster than the energy efficiency of ICT devices (Hilty et al., 2006). This is because users are taking and using the increased computing power offered regardless its effects on environmental sustainability.

Moreover cloud computing is changing the way we quantify the ICT direct effects, adding some additional **issues** about its **measurability**. The shift toward cloud computing looks, in line of principle, to be more environmentally friendly, compared to traditional data center operational/deployment models. The rule of thumb says that a higher consolidation/optimization of the infrastructure will make it possible to conserve energy. But, if cloud computing can *enable green*, and it could be a great way to reduce the carbon footprint, we have to be able to demonstrate it. And to demonstrate something you have to quantify it.

The emission factor, the rate to convert kilowatt-hours into units of carbon dioxide emissions, is the base for any evaluation of the direct impact of ICTs. This rate varies from country to country and from region to region, because it depends on the source from which electric power is produced, as already mentioned in last section. Different power sources can have dramatically different CO_2 footprints.

The industry adopted metrics like Power Usage Effectiveness (PUE) or Data center infrastructure efficiency (DCIE) take into consideration the efficiency of data center infrastructure relative to energy demand, but not to the overall resource impact or even the amount of energy needed for a particular computing activity. Metrics like PUE are valuable in helping data center operators to benchmark the design and efficiency of their facilities by providing an objective metric that drives effort to improve facility efficiency. Recent efforts have been made to develop additional resource-based metrics that speak to the Carbon intensity (CUE) and water utilization (WUE) of a data center.

All ICT-based services will increasingly be delivered on the clouds. When an ICT-based service is provided, it is responsible for a given amount of CO_2 emissions. The challenge, from a green perspective, is to be able to quantify the per-unit energy consumption, and more generally, the per-unit carbon emissions. In particular the challenge is to quantify a service when is delivered by the cloud.

Even in a rough estimate, the entire life cycle of the whole system providing a given service should be studied, in order to assess the environmental impact of producing one *functional unit* of the service. While it's quite straightforward to compare the CO_2 emissions of a new generation tablet with those of a desktop computer, it is far from straightforward to compare the emission equivalence of a computing activity delivered traditionally or by the cloud.

In other, words we have to be able to quantify the impact in terms of **CO_2 emission equivalent of an ICT-based service when is delivered on the cloud**.

By definition clouds are promising to provide services to users without reference to the infrastructure on which these are hosted. As consumers rely on cloud providers for their computing needs, they have to require that a specific QoS (Quality of Service) will be maintained by their providers, in order to meet their objectives and sustain their operations (Buyya et al., 2009). While it is clear that there are critical parameters such as time, cost, reliability and trust/security, equally important are parameters linked with the green performance of the cloud.

If we measure software quality with **software quality factors** that describe how software behaves in its system, from a green perspective we need new **green quality factors**. In particular we need **green cloud computing factors**, allowing a uniform way to measure the supposed gain in efficiency allowed by the cloud.

Environmental issues and challenges

Cloud computing with increasingly pervasive front-end client devices interacting with back-end data centers will cause an enormous escalation of energy usage. To address this problem, data center resources need to be managed in an energy-efficient manner to drive Green Cloud computing. In particular, Cloud resources need to be allocated not only to satisfy QoS, but also to reduce energy usage (Buyya, Beloglazov & Abawajy, 2010).

In order to test the green performance of the cloud we have to be able to answer such questions as: What is the hypothetical footprint of a start-up that may have chosen to built his own data center versus using cloud computing?

Running the numbers about how green a particular usage scenario actually is becomes more complicated than showing the green credentials. Moving from the *why* in cloud computing to the *how*, claims about the green credential of cloud computing need to be clearly answered, motivated and calculated in order to substantiate those claims.

Common sense says that reducing the number of hardware components and replacing them with remote cloud computing systems reduces energy costs for running hardware and cooling, as well as reducing carbon footprint, while higher DC consolidation / optimization will conserve energy.

IT industry points to cloud computing as the new, green model for our IT infrastructure needs, but few companies provide data that would allow us to objectively evaluate these claims. And **quantifications may not be comparable**, because **different cloud computing provides** different services features and has **incompatible starting assumptions**.

Some concerns are also emerging within the cloud computing community (Coven, 2009; Munro, 2010). We now have the ability to run our applications on thousands of servers, whereas previously this wasn't even possible. Then we can potentially use several years worth of energy in literary a few hours, where previously this was not even possible. So in direct contrast, hypothetically we are using more resources, not less.

Reuven Cohen, a longtime cloud evangelist, in one post titled "Is cloud computing actually environmentally friendly"[28], points to one of the most perplexing aspects of the claim that cloud computing is green. Relating

---

[28] http://www.elasticvapor.com/2009/12/is-cloud-computing-actually.html

to efficiency he says: "…On the flip side, if we bought those thousand servers and had them running (underutilized), the power usage would be significantly higher. You may use 80% less energy per unit, but have 1000% more capacity, which at the end of the day means you are using more energy, not less".

A part from a lack of transparency in the quantifications of energy consumption by cloud providers, some other environmental risks can be envisaged. That is because cloud computing encourages behavior that may not be very green (Colgan, 2010).

The availability of cheap resources may encourage poor optimization.

The ability and ease of access to a massively abundant cloud computing resource will drive that behavior on the server. It will be cheaper to add 10 more web servers than to profile, optimize, regression test and deploy the code base.

Cloud computing allows things that may never have been processed before to be processed without an impact on performance, for example selecting a very large set of data for analysis (because you can literally process the data in an hour where previously it could take days).

If cloud lowers the cost of providing services, it is possible to provide services that only generate a few pennies per transaction. While generally considered a benefit of the cloud, one has to question where the value of the end product is worth its environment cost. Another risk then is providing low value product and services.

Another important issue to take into consideration is how the spread of mobile ICT is changing how we communicate, relate and manage our daily lives at astounding speeds. In 2011 the world created a staggering 1.8 zettabytes [29] (1 zettabyte[30] = 1 trillion gigabyte) of digital information. Think about the rate of increase in the number of people performing some sort of computation (for example, the hundred million members of Facebook all uploading photographs) and the rate of increase in the amount of data to be manipulated (consider a five megapixel camera built into everyone's phone). All the while, in the cloud, processors will be running algorithms while constantly making adjustments as they **dynamically navigate** the trade-off between data size, connection speed, and client performance (as, for example, processor and screen resolution).

The question is: are we more environmentally friendly doing all of this in a shared cloud or on our own datacenters? Since the cloud allows our digital consumption to be largely invisible (and sometime free of charge), we may fall to recognize that the information we receive actually devours more and more electricity. The more computer cycles available, the more will be used.

Awareness from developers is a precondition for a **green behavior** (Sissa, 2010).

If cloud computing represents an extraordinary opportunity for developers, never seen before, able to decrease or fully eliminate the entry level in the applications or services delivering on the Net, for the final user it is a new way of using the computer. Power-users, as well as simple-users are shifting from a computer-centered to an Internet-centered style. Consumers now need nothing but a personal computer and Internet access to fulfill most of their computing needs. Personal applications are becoming available via Web, accessible anywhere, from any computer with a net connection and a decent browser. It's no longer mandatory to install applications on the personal computer.

Public awareness of climate change is increasing (Bechtel & Scheve, 2013) and the Cloud can be a good opportunity to achieve a greener ICT, in a broader sense, just by starting from end-user behavior. For example a sustainable recombination strategy can help in mitigating the obsolescence rate of end user devices, which are responsible for the major environmental first order effects, called e-waste, as described in the next chapter (Sissa, 2008a).

In our opinion Cloud computing is inherently green. To move to cloud computing appears to be more environmentally friendly compared with traditional data center operational/deployment models. Many companies have been able to do away with the need for physical infrastructure and thus reduce their energy footprint. Thus, in some ways cloud computing can *enable green*, and could be a great way to reduce the carbon footprint. There are many advantages to this approach for both customers (lower cost, less complexity) and service providers (economies of scale). But there is also some risk, for the environment, as well. Awareness and responsible behaviors are a background condition to achieve a sustainable green cloud computing.

---

[29] http://www.emc.com/leadership/programs/digital-universe.htm

[30] 1zettabytes=10^{21} bytes

2. THE REBOUND EFFECT

2.1 Introduction

Rebound effects are generally expressed as a ratio of the lost environmental benefit to the potential environmental benefit. **In economic theory is defined as the potential** created by **efficiency** gain that is **balanced off** (or even overcompensated) by **quantitative growth.** When a technological innovation makes a process more efficient (i.e. makes it possible to provide the same output with less input), this can lead to an increase in total consumption for that type of process instead of the expected decrease (Theis & Tomkin, 2012).

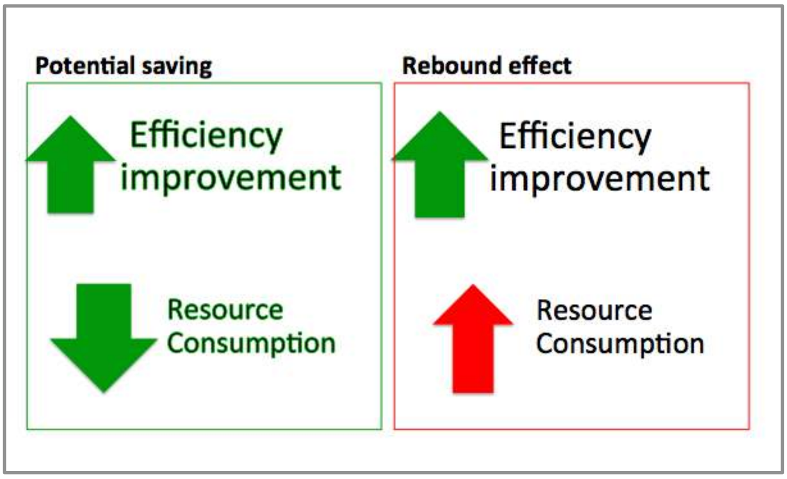


Figure 6 - Rebound Effects

The nature and magnitude of rebound effects is the focus of long-running dispute within energy economics (Sorrell & Dimitropolous, 2008) and even the definition and the scope of rebound effects have been the subject of heated debate. The discussion addresses both the magnitude and the mechanisms of the rebound effects.

With regard to the magnitude, analysts distinguish a weak rebound effect (efficiency measures are not as effective as expected), a strong rebound effect (most of the expected savings do not materialize), and a backfire effect (the efficiency measure leads to increased demand) (Hertwich, 2005).

With regards to the economics mechanism, literature in energy economics distinguishes between different types of rebound effect (Greening, Greene, & Difiglio, 2000):

1. The substitution effect
2. The income effect
3. Secondary effects (input-output effects, indirect effects)
4. General equilibrium or economy-wide effects
5. Transformational effects

The first two effects, sometimes also called direct rebound effects, are micro effects while the last three effects are macro effects.

Reduction of energy use and reduction of pollution are goals of energy and environmental economics, but an increase in production units may compensate the eco-efficiency improvements. These effects are often called backfire, take-back, offsetting behavior (Hofstetter, Madjar, & Ozawa 2006). We can say that rebound effect is not a well-defined term. In a nutshell, the phenomenon is always considered as an adverse effect of an improvement. In economics and technology, rebound effects designate the unexpected consumption of resource that follows a resource efficiency improvement (Girod et al., 2011).

Rebound effect does not occur only within energy consumption, but with **any technology** that makes a **significantly use of a natural resource**. It can be water, metal or any precious material, or any limited resource.

In general, rebound effects are defined as not realized savings in the use of resources, relative to expected savings in the use of these resources.

From these different definitions, we can summarize the rebound effect as being a **counterproductive consequence of what was conceived as an improvement**. The concept challenges a **certain technological determinism and its belief that improving the efficiency of resource use will necessarily lead to lower consumption**.

2.2 The rebound effect in energy economics: classical economic assumptions

Rebound effects are located (Berkhout, Muskens, &Velthuijsen, 2000) inside the framework of neo-classical economic principles. The neo-classical paradigm continues to enjoy a huge popularity among economists, despite continuous attacks. The economic principles have their limitations in terms of the underlying hypotheses.

The first and foremost principle is *rationality*. The economic agent obeys neat preferences. Preferences are for instance assumed to be *transitive* (if A->B and B->C then A->C), and they are *insatiable* (more is always preferred). A more disputed aspect of rationality is that the agent *optimizes*. The consumer maximizes utility while the producer maximizes profits or minimizes costs per unit of production (Sorrell, 2007).

The second principle concerns *certainty* and *complete information*. The agent is aware of all relevant information to behave rationally. There is no uncertainty. This complete information principle is relevant to the rebound effect. The costs of energy consumption of equipment disappear from the sight of the consumer as a part of the monthly bill. Therefore, he has no clue to the price of energy services of equipment.

Based on rationality and complete information the agent chooses an *optimum*. An improvement in the energy efficiency of the system leads to a reduction in the energy cost of useful work and hence the effective price of useful work (Sorrell, 2007). As a result, the consumption of useful work may be expected to increase. The response to this price reduction may be illustrated graphically, using *indifference curves*, which represent different combinations of goods/services to which a consumer is *indifferent.* At each point on an indifference curve, a consumer has no preference for one combination of goods over another, so that each point provides the same level of *utility,* or satisfaction (UKERC, 2007).

The analysis rests upon a number of standard *simplifying assumptions* regarding indifference curves and consumer behavior, including completeness, transitivity, non-satiation, continuity and strict convexity (Gravelle & Rees, 2004).

2.3 Household energy consumption in traditional consumer theory

One of the most important sectors where rebound effects are studied is the household energy consumption.

The commonly used theoretical framework for micro-level analysis of the rebound effects is the neoclassical model of consumer behavior or rational choice theory.

This theory considers four basic elements: the consumer's available income, the prices of goods or services on the market, the consumer's preferences and the behavioral assumption of "utility maximization". Given a limited income, a specific range of commodities to choose from, and a potentially infinite set of preferences, the consumer chooses commodities from those available in such a way as to maximize his or her subjective utility within the constraints of his or her available income (Jackson, 2005).

The assumptions of traditional consumer theory may seem unable to explaining long-term change processes (Linscheidt, 2001; Boulanger et al., 2013):

- Preference orderings rely on formal axioms which are ad hoc and do not conform to real-world situations;
- Preferences are assumed to be "not satiable", i.e. an individual wants or needs are essentially unlimited;
- Consumers' preferences are assumed as not affected by their consumption in the past (preferences are specified as time-separable functions). This effectively excludes "habit formation";
- Consumers' preferences are assumed as not affected by the actions of other consumers (there is no preference-interdependence), therefore excluding "social factors";
- A consumer is a "homo oeconomicus", a hyper-rational person capable of processing massive amounts of information to make optimal decisions in his or her own interest. The implicit assumption that a consumer never makes mistakes in computation and choices excludes cognitive and affective limitations;

- Consumers (only) differ because of income and not because of skills, decision making routines, etc. A representative consumer represents different micro-agents (all sharing identical average preferences) of the same (average income) class. A change in price would change the budget sets of all consumers, thus changing the behavior of all consumers. In other words, there is no (or very limited) heterogeneity of consumers.

2.4 Rebound effect in ICTs

While the rebound effect literature is generally focused on energy consumption (Sorrell, 2007) the theory can be generalized to any natural resource or externality that is embodied in final consumption (Maxwell, Owen, McAndrew, Muehmel, & Neubauer, 2011). We can see the effects on the environment as externalities.

If rebound effects are a complex issue to deal with, their definition, identification and quantification becomes even more complex in ICTs field (Sissa, 2013a). When an ICT-based service is enabling an environmental benefit, the efficiency improvement in energy (Binswanger, 2000) or in other limited or critical resource, can be overcompensated by rebound effects (Hofstetter et al., 2006). Despite their importance and their extent, the ICT-related rebound effects are relatively unexplored because of the complexity of assessing future directions of production and consumption (Hilty et al., 2006; Lepochat, 2011).

Because rebound effects are long-term effects, their actual manifestation and related data are available only a longtime after the phenomenon that generated them. That is the reason why data about rebound effects on ICTs are difficult to acquire and, when available, are delayed of one (or more) technology generation.

Because different ICTs generations lead to **different user behavioral patterns**, such **delay between the cause and the manifestation of these effects makes really difficult or impossible any concrete measure against negative rebound effects.**

A theoretical in-depth analysis of rebound effects in general, and in particular in ICTs, is out of the reach of our research, while its **research contribution aims to avoiding negative rebound effect**.

Some general remarks before exploring an alternative approach have to be done. As mentioned in 2.2, rebound effects are traditionally located inside the framework of the neo-classical economic principles under the assumptions of full rationality, certainty and completeness of information, and that the agents are insatiable ("more is always preferred").

On the other side we have to remember that an overall sustainability goal is to reduce the consumption of limited or critical resources. Although the traditional vision of innovation is based on the assumption that efficiency will lead to reduction of consumption of a limited resource, this is in contradiction with the "more is always preferred" principle. Inside the framework of classical economics is intrinsically impossible to avoid rebound effects.

The proposed approach to deal with rebound effects is to focus on behavioral patterns relevant to sustainability and to look at rebound effects from within this framework.

Concepts as new sociological institutionalism and unintended consequences can be useful for an alternative approach, where rebound effects can be dealt with and avoided by focusing on behavioral patterns relevant to sustainability. Looking at rebound effects within this point of view, environmental sustainability awareness and its spreading inside people and communities become key elements.

2.5 Rationale for models of limited resource consumer behavior

We can imagine that a better knowledge of (energy) consumption behavior could also help in avoid rebound effects. This points to the need for a more complete model of (energy) consumption behavior of households.

The key problem is that it is not possible to run historical "control" experiments on society to see whether total energy use is higher or lower than if there had been no energy efficiency improvements. It is difficult or even impossible to conduct economic experiments on individual households, let alone the entire society.

This impossibility leads to the need of sophisticated **models of (energy) consumption behavior**. The value of such models would not be so much the degree of realism of their assumptions, but rather the usefulness of the conclusions that can be derived from them (Boulanger et al., 2013). Computational models of consumer behavior would allow conducting various simulations of household behaviors, which can be tested for the accuracy in representing reality.

In order to fully understand the rebound effects at the micro-level of households, it is necessary to understand how and why the various households consume.

Since the mid-1970s, a succession of established disciplines has sought to develop theoretical models of human energy-related behavior grounded in the perspective of each particular discipline (Parnell & Larsen, 2005). Although existing models (rational choice model, attitude-behavior model, folk model, categorization of energy users, diffusion of innovations) have been found to work in some though, "*…no overarching model to predict, influence, or categorize human behavior on energy efficiency has emerged*" (Egan, 2001).

Literature has seen the emergence of a **multidisciplinary approach to energy-use behavior** as part of the wider study of Environmentally Responsible Behavior (ERB) (Parnell & Larsen, 2005). As stated by Ehrhardt-Martinez (2009), research on energy-efficient technologies and practices would benefit greatly from the adoption of a behavioral toolkit. "Such a toolkit would include the use of insights from a variety of social and behavioral fields including sociology, psychology, anthropology, demography, public policy, behavioral economics, marketing, and communications" (Ehrhardt-Martinez, 2009).

In economic literature, the development of "sustainable" consumer demand models includes the integration of psychological as well as sociological aspects and a detailed treatment of **consumption as a complex process** (Kletzan, Köppl, Kratena, Schleicher, & Wüger, 2002).

2.6 Alternative assumptions

The shortcomings described in section 2.3, as well as the above considerations on rebound effects, suggest an alternative approach, based on different assumption.

According to interdisciplinary approach of the research we can try and consider alternative assumptions, like for example bounded rationality – taken from decision-making theory – and other concepts, like unintended consequences or Neoinstitutionalism - deriving from other disciplines, as sociology.

2.6.1 Bounded rationality

Bounded rationality (Simon, 1957) consists of the idea that in decision-making, rationality of individuals is limited by the information they have, the cognitive limitations of their minds, and the finite amount of time they have to make decisions. It was proposed by Herbert Simon as an alternative basis for the mathematical modeling of decision making, as used in classical economics and related disciplines. It complements *rationality as optimization*, which views decision making as a fully rational process of finding an optimal choice given the information available.

In decision making **rationality** of individuals is **limited** by the information they have, the cognitive limitations of their minds, and the finite amount of time they have to make decisions.

A decision-maker has neither the time and space nor the ability to arrive at an optimal solution and many individuals may not seek to optimize at all. The idea of bounded rationality is that individuals strive to be rational having first greatly simplified the choices available. Thus, instead of choosing from every option, the decision-maker chooses between a small numbers. Because decision-makers lack the ability and resources to arrive at the optimal solution, they instead apply their rationality only after having greatly simplified the choices available. Thus the decision-maker is seeking a satisfactory solution rather than the optimal one.

The result may be that decision-makers become "*satisfacers" (*combining satisfy with suffice*)*; they accept a satisfactory solution, which is good enough for their purposes rather than finding the optimum answer.

2.6.2 Unintended consequences and relevance perception

In the social sciences, *unintended consequences* (sometimes called *unanticipated consequences* or *unforeseen consequences*) (Merton, 1996) are outcomes that are not the outcomes intended by a purposeful action. The concept has long existed but was named and popularized in the 20th century by the American sociologist, Robert K. Merton. Unintended consequences can be roughly grouped into three types:

- A positive, unexpected benefit (usually referred to as serendipity or a windfall);
- A negative, unexpected drawback;

- A *perverse effect* contrary to what was originally intended (when an intended solution makes a problem worse).

There may be information (in its widest sense, data, perspectives, general truths, etc.) that is not perceived as relevant because the information-seeker does not already have it and its relevance only becomes apparent after he or she has acquired it. Perverse effects are explained by the *relevance paradox*. The relevance paradox occurs because people and organizations seek only information that they perceive is relevant to them. However, there may be information (in its widest sense, data, perspectives, general truths, etc.) that is not perceived as relevant because the information-seeker does not already have it and its relevance only becomes apparent after he or she has acquired it.

Effects on the environment of people behavior are perceived as relevant only after they happened. The rebound effects can be seen as perverse effects of efficiency gain.

2.6.3 Neoinstitutionalism

Neoinstitutionalism describes social theory that focuses on developing a sociological view of institutions, the way they interact and the way they affect society.

It provides a way of viewing institutions outside of the traditional views of economics by explaining why so many businesses end up having the same organizational structure (isomorphism), even though they evolved in different ways, and how institutions shape the behavior of individuals: *"Institutions consist of cognitive, normative, and regulative structures and activities that provide stability and* ***meaning of social behavior****. Institutions are transported by various carriers - culture, structures, and routines - and they operate at multiple levels of jurisdiction*"(Smelser & Swdberg, 2005).

An institution is based on three "pillars":

- a regulative pillar (formal and informal rules that constrain and regularize behavior)
- a normative pillar (values and norms that prescribe and evaluate action)
- a cognitive pillar (common frames of meaning and interpretation that define situations in which action is taken)

Institutions consist of:

1. Formal elements (laws, constitutions, property rights, etc.)
2. Informal elements: code of conducts, taboos, sanction, customs, habits, etc.)

An example of informal institution is the Open Source software community.

This way of understanding individual choice is also relevant to economics. New institutionalists in economics recognize that institutions have at least as much influence on the economy as individual's choices.

We can try to summarize something about the effect of ICTs on the environment**:**

- Can become relevant for a group of people (for example, green consumers of ICTs services, or open source software developers);
- Such group of people can be see as a new institution (aware of ICTs effects on the environment);
- In such an institution there are some *social norms;*
- They will rely on **awareness level about the** of ICTs effects on the environment.

2.7 New perspectives for a model of energy consumption behaviors

Purchasing and consuming a product is supposed to add to the actual satisfaction of a weighted combination of wants, whereas the actual satisfaction of those wants may also depend on the consumption of (many) other commodities. The desired satisfaction in turn depends on personal characteristics of the household, including socio-demographic variables (such as household size, age, gender, education level, etc. of the households constituent members) and psychological factors (for instance personal motives or beliefs). The latter can and will also be influenced by the environment in which the household operates, in particular the sociocultural framework (Boulanger et al., 2013). We call such a framework an institutional framework. It includes social networks (interactions with family, friends, colleagues), social norms, etc. This is important, because it means that society not only influence consumer behavior through market and regulatory instruments (prices, taxes, subsidies, technological standards, etc.) but also through soft policy instruments like sensitization campaigns, energy education, etc.

Social psychologists have two concepts for reporting the way people refer to social norms: **descriptive** norms and **injunctive** ones. The first one refers to what people consider the most frequent (modal) behavior. **Injunctive** norms, on the other hand, refer to what people perceive as being socially approved or disapproved. Both kinds of norms motivate human action.

A new conceptual model should allow simulating consumption and reduction in consumption at the level of households. Such a model will contribute to a better understanding of rebound effect mechanisms and counter measures against them. From a scientific viewpoint, it is particularly obvious that there is a lack of studies investigating the matter of rebound from the perspective of the people concerned, focusing on their energy practices, conditions of action, and coping strategies. Policy measures should be socially fair and environmentally sound. From a sustainability point of view, economy is a mean to increase wellbeing while reducing environmental impacts. Sustainable consumption can be reached through **changing our** consumption patterns by a combination of the three strategies of consuming more efficiently, *consuming differently* and *consuming less* (Boulanger, 2010). **The consistent objective is an overall reduction of consumption** that can only be achieved through changing the activities and practices that people prefer.

2.7.1 Efficiency and sufficiency

The difference between **efficiency** and **sufficiency** strategies lies notably in their relative or absolute approach of energy consumption. **Energy efficiency** considers **the relative level of consumption**: it is measured as the relative gain obtained through a technological improvement. **Energy sufficiency** is translated in **absolute indicators**: a service should not use more than a given quantity (Hilty et al., 2011). For instance, the energy consumption of a TV can be measured as the energy/square inch or by its total consumption. In the former case, the energy consumption can increase, as the screen size gets bigger. A first step is therefore to use absolute indicators in general and at levels where the responsibility is. As van den Bergh (2011) argues: “When households or firms undertake energy conservation activities these may cause additional energy use within their own subsystem, even without them being aware of it. One policy response could therefore be **to make agents conscious or aware of rebound effects** occurring within their own realm”.

2.7.2 Potential limiting factors

As far as energy is concerned experimental results show how the energy bill represents a relatively small part of the overall household budget. The decrease in the energy share in the overall budget is largely due to the fact that household incomes have increased, it remains around 5% in the last 50 years - and decreasing share of the total household expenditures, there is no economic reason for citizens to try to mitigate their energy consumption.

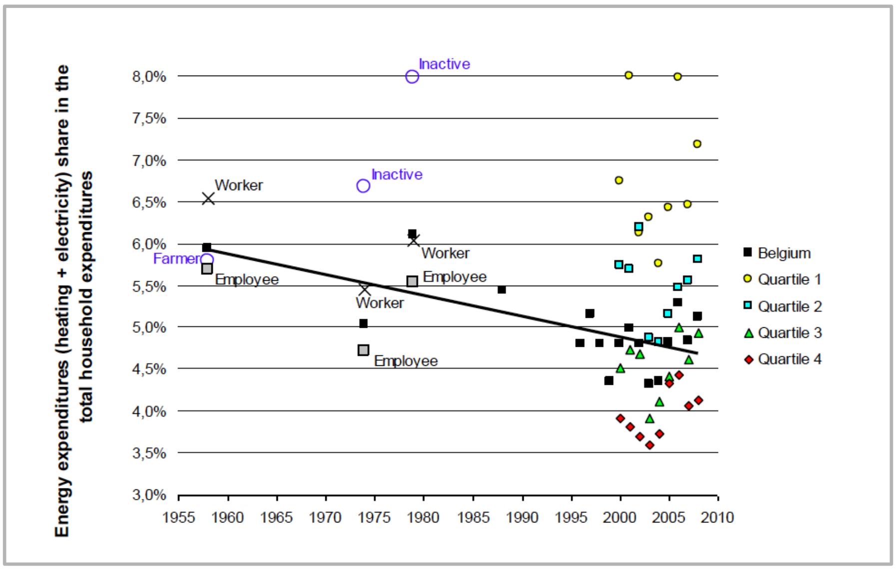


Figure 7 - Energy expenditure share in belgian household total budget (source Boulanger et al., 2013)

2.8 Conclusion: a model on energy consumption behaviour as a tool to study social mechanisms in a limited resource consumption

In ICTs a rebound effect can appears in terms on energy consumption (more efficient devices that does not lead to a net energy gain) or in terms of materials (strong miniaturization of devices that does not lead to a decrease in e-waste).

To **foresee rebound effects is difficult** because they appear one (or more) technology generation after their actual use. Traditional **policy intervention** - like taxation, incentives or other kinds of regulatory norms **- are not effective** because based only on macro-economic data and not on a good knowledge of micro-behaviors of user/citizen.

Rebound effects are complex issues to deal with. The main area of study of such effects is energy household consumption, where ICTs consumptions represent an increasing, even if small, part. Several studies have already done in several research areas, with **controversial results** and without the emergence of an overarching conceptual model of human behavior in energy efficiency.

To give another definition of rebound effects is out of the scope of our research. What we want to do is to give an added value against negative **rebound effects**, according to the overall interdisciplinary approach of our research**.** This contribution can be the introduction of sustainability point of view.

A certain agreement in sustainability research is reached on the assumption that efficiency principle has to be coupled to sufficiency principle. **Sufficiency principle** is not always accepted by traditional economics theory. A debate about de-growth is out of the scope of our research, but we think that the sufficiency principle has to be declined in terms of innovation. In other word not looking at the choice between growth and de-growth, but between an effective smart use of technological innovation and the business as usual paradigm (Antonelli, 2011).

We will focus on the motivations for consumers to adopt sufficiency principle in their behaviors. Models of motivation too often focus on monetary incentives alone. Whereas larger-scale users (large businesses and organizations) find significant financial savings in small efforts multiplied across the organization, individuals usually have no sense of the broader impact of small changes (see Fig. 7).

Attention to other forms of motivation needs to be explored, including the interaction with social context. Efficiency alone is not enough to reduce energy consumption, without limiting factors.

To face environmental problems **people's behaviors** have to **change**. Environmentally friendly behaviors, to make the change effective, have to be adopted by the population (Kinzig et al., 2013). There are two forces that can have impact on behavior, one linked to government actions and another linked to social pressure. Voluntary behavioral changes are usually driven by some kind of **reward**; in some cases adopting a new lifestyle has a reward in itself. For example after quit smoking or going on a diet one feels better or looses weight and this effect is perceived as individual immediate positive feedback. As far as an environmentally sustainable life style is concerned, economic rewards are not strong enough to trigger a behavioral change, while other reward mechanisms are not at an immediate and individual level. Only when a responsible life style is adopted by a collective or by a group of individuals some positive environmental effects will happen in the long run. If the adoption of a sustainable behavior is driven by awareness and such awareness shifts from an individual dimension to a shared collective one, this **turns a social appraisal into the most effective reward**. Such mechanism is the trigger for a **social norm**. An interesting question is: it is possible to look at social norm as the limiting factor able to avoid rebound effects?

The challenge of our research is based on the idea that **only a good awareness level can avoid unintended consequences**, as rebound effects are. Being aware of the environmental sustainability issues means to be able to identify a limited resource which consumption has to be reduced, means to be able to understand the impact of own actions on this resource and to be able to avoid unintended consequences, as rebound effects.

A preliminary step to avoid rebound effects is a better, deep understanding of limited resource consumption mechanisms in the interdisciplinary framework introduced above. Agent Based Modeling is a suitable way to study social mechanisms by trying to reproduce them.

We chose to model a finite resource whose consumption should be reduced. As finite resource we have chosen the energy and in particular households energy. This choice is driven by several motivations:

- This sector is very broad.

- The "ICT-related energy" is a part of total household energy costs.
- This expenditure share in the household total energy budget is small, but increasing.
- There are already available (and then easier to be modeled) sets of smart metering functions able to empowering their user.

Simulation models can be useful tools, but in particular a kind of simulation models able to reproduce the main behavioral mechanisms of people that will be involved in such a policy measure put in practice. The use of agent based modeling is suitable for policy maker purposes.

We tried to identify which are the basic fundamental behaviors of consumption of a limited resource, taking energy household as the general application field to develop our ABM.

The conceptual modeling of limited resource consumption is the same in several areas. The limited resource can be energy or water or materials, it does not matter, because the basic underlying sufficiency principle has to be accepted as the only one able to lead toward sustainability. Sufficiency principle leads to reduce consumption to avoid an overuse of the resource. We will propose an approach where looking at societal mechanisms as potential driver to put into practice sufficiency principle. In other words, we want to explore if the limiting factor can be a social limiting factor. With this aim we will focus on energy consumption for the mentioned reasons.

The examples supplied in Appendix 1 and in Appendix 2 are two potential case studies where to try and apply the model in further research developments. In both examples the idea of the informal institution is suggested, as well as the basic principles of specific awareness.

APPENDIX 2: Software induced hardware obsolescence as a rebound effect

Introduction

Electronic devices surrounding our life can be thought as being "clean" technologies. When you turn on a computer, a smart phone or a tablet, you don't see smoke billowing out from anywhere, as with a car or a factory; you can't see, smell, or taste the pollution.

No subjective feeling is more wrong. Information and communication technologies (ICTs) in the last two decades have been contributing to environmental problems: computers, electronic devices and ICT infrastructure consume significant amounts of electricity, placing a heavy burden on our electric grids and contributing to greenhouse gas emissions. ICT leaves an **environmental footprint**: the 2% of the global CO_2 emission (Gesi, 2008).

Environmental impacts occur during the use of ICTs, but higher environmental impacts often occur before and after the use phase. So environmental impacts need to be considered along the complete **life cycle**, with important consequences about consumer style and behavior.

The obsolescence of ICT equipment is a serious and rapidly increasing problem. In particular computers are getting obsolete more and more quickly, because new operating systems require faster processor, larger memory and powerful hardware. **Lifespans** are well below the functional limits of computers. It is the under spending in time that is increasing.

If such considerations are becoming the subject of specific scientific conferences and research areas, broadly called Green computing or green ICT, usually their scope is quite restricted, mainly focusing on technical aspects about energy consumption reduction.

The main concerns of green ICT are related to the energy consumption in the computer's use phase that does not depend only from hardware but also from software configuration and from its efficiency. An effective insight about ICT environmental sustainability requires paying attention also to the software features, as others responsible for the CO_2 emissions of the ICT sector. Software is also responsible for the induced hardware obsolescence: the computer lifecycle is shorter than the potential one. A software-based approach, will also allow a longer use for PCs, respecting the environment, saving energy, emissions and money and, in the meantime, moving toward cloud computing paradigm.

A sustainable balance between innovation, economy, and green aptitude can help to use computers better and longer. Environmental benefit starts from a different approach to an old issue, in a re-combination strategy.

E-WASTE

The beginning of the new century has been characterized by a general positive view of ICT as a driver for innovation. The "dot com flop" stopped the crazy idea of unlimited growth possibilities of virtual economy. In the same period the positive series of neologisms created by the prefix letter "e" (standing for *electronic*) put before a common noun (e-government, e-business, e-learning, e-health) to give it the meaning of an exciting virtual equivalent was definitively stopped by a new unpleasant neologism related to the environment: **e-waste**. For the first time the association of the prefix electronic to a common noun was not synonymous of potential virtual improvement, but of a serious physical issue (Sissa, 2008).

From then on the meaning of ICTS driven innovation phenomena started to be considered as not positive in itself, as it was in 90's.

This new turning point from a blind trust on ICTs as such, was the beginning of awareness in the professional ICT community about possible negative side effects of ICTs. Beyond the specific issues related to e-waste this awareness could lead some computer scientists to a deeper analysis about long-term systemic effects of ICTs on the environment.

E-waste is the popular, informal name for electronic products nearing the end of their useful life, like Computers, phones, notebook, monitor, servers, also known as WEEE (Waste Electrical and Electronic Equipment).

It is the rapid growth of computing that is driving e-waste production. In the next five years one billion computers will be retired (Ladou & Lovegrove, 2008). Although the exact amount is unknown, the world's production of e-waste has been estimated at 20-50 million tons per years (UNEP-UNCTAD, 2007). E-waste represents the "dark side of the ICT" (Schwarzer, De Bono, Giuliani, Kluser, Peduzzi, 2005).

The increase in turnover is directly linked to the increase in the amount of obsolete equipment, i.e. the volume of e-waste expanding worldwide that needs to be treated (Puckett, 2005).

Manufacturing computers and their various electronic and non-electronic components consumes electricity, raw materials, chemicals, water, and generates hazardous waste (Hilty, 2005). Each PC in use generates about a ton of carbon dioxide every year (Murugesan, 2008). Each stage of a computer's life, from its production, throughout its use, and into its disposal, presents environmental problems (Bridegen, Webster, Labunska, & Santilo, 2007). All these directly or indirectly increase carbon dioxide emissions and impact the environment and the trend is increasing in the business as usual (Gesi, 2008) scenario.

Changes in technology will affect the global mass of e-waste produced. Short innovation cycles of hardware led to a high turnover of devices. The lifespan of central processing unit dropped from 4-6 years in 1997 to 2 years in 2005. The average mass of 25 Kg for a personal computer was indicative (Robinson, 2009) of a desktop computer with a Catode-Ray Tube (CRT) monitor. We need to take in mind that this kind of PC represents most of the past and present computers in the e-waste stream. The advent of Liquid Crystal Displays (LCD) reduced the average weight of a desktop.

More significantly the increasing prevalence of laptop and notebook, which weigh 1-3 Kg, will significantly reduce the average mass of a discarded computer. In case of notebooks, smart phone and tablets the "power" - and associated potential e-waste production - has been shifted from the end user devices to the remote computing cloud, supported by warehouses of shared machines, which may be located everywhere.

Before going into details, we introduce some basic definitions.

The term **recycling** means that the equipment is disassembled and the components-such as plastic, glass, and metals-are recovered and used to manufacture new products. Recycling, when pursued in an environmentally sound manner, can alleviate certain pressures on natural resources.

On the other hand, the value of the resources contained in these products is often overlooked: there is an economic value at the end of their life, such as base and precious metals. Unfortunately today, even when these resources are recovered, it is frequently made via trans-boundary movement to developing countries and countries with economies in transition for reprocessing and recycling (UNEP-UNCTAD, 2007).

Effective reprocessing technology, which recovers the valuable materials (Robinson, 2009) with minimal environmental impact, is expensive. Proper Personal Computers (PCs) treatment needs new state-of-the art technologies and plants, available only in developed countries. E-waste falls under the scope of the Basel Convention (UNEP, 2006) that addresses the environmental issues related to the increasing trans-boundary movements of these wastes, and to ensure that storage, transport, treatment, reuse, recycling, recovery and disposal is conducted in an environmentally sound manner. A consistent percentage of e-waste produced in developed countries continues to be exported elsewhere, legally or not (Cobbin, 2008).

From an environmental standpoint a longer use or a direct **reuse** of products must be considered far preferable to all form of waste management. But reuse has to be sustainable. The reuse can be done locally or via trans-boundary movements of second hand equipment. Concerns are increasing about exports of used ICT devices, mainly second hand PCs, and donations from Global North countries to developing countries, including equipment, which can become quickly e-waste, leaving them to handle the disposal aspect (Bridegen, 2007). Developing countries lack the waste disposal infrastructures, environmental and health regulations, as well as the technical capacity necessary to ensure the safe disposal of hazardous waste (Puckett, 2005). Extending the lifetime of computers is therefore a form of reuse, to be done locally.

ICT lifecycle

Each stage of a computer's life, from its production, throughout its use, and into its disposal, presents environmental problems.

The basic scheme of a product life cycle includes the four phases of design, production, use and end of life. In the production phase raw materials are transformed into the product. In the use phase the product delivers the services it has been intended for.

Manufacturing computers is energy and material intensive; the fossil fuels used to make one traditional desktop computer, weigh over 200 kilograms, some 10 times the weight of the desktop itself (Kuehr &Williams, 2003). This ratio is very high compared to many other goods. For a car or refrigerator, for example, the weight of fossil fuels used for production is roughly equal to their weight.

Why should the secondary use of materials be so comparatively high for semiconductor devices? The fundamental explanation lies in the realm of thermodynamics (Williams, Ayres, & Heller, 2002).

Microchips and many other high-tech goods are extremely low-entropy, highly organized forms of matter. Given that they are fabricated using relatively high entropy starting materials, it is natural to expect that a substantial investment of energy and process materials is needed for the transformation into an organized form.

The internal structure of a PC is complex, making proper recycling a multiphase and expensive process.

The increased number of computers and their use, along with their frequent replacements, make the environmental impact of IT a major concern. **Green computing** addresses the issues: eco-design of new products eliminates hazardous substances and takes into account the must of "mimic the nature" into the life cycle of product (OECD, 2010a). Take back policies have to be adopted by the producers.

Green computing has been a big improvement in manufacturing, but we have to take into consideration that above mentioned figures are related to computers that today are the current e-waste. Green design of ICT product is improving, but the turnover and the number of devices is growing.

When the service life of the product ends, part of the product may be reused or recycled. The rest leaves the system for final disposal. In the case of a life-cycle study of an ICT devices, this means that the primary production of the metal used in production, the supply chain for the energy used in each phase, as well as the final disposal activities are traced through the exchange of chemical elements with the environment. From this point of view the current focus of Green ICT on the energy consumption of ICT devices and Data Center has a narrow focus, looking only at the energy consumption on the use phase. Environmental impact other than energy consumption may be relevant as well (Hilty, 2008).

Computer Lifecycle and software lifecycle

We mentioned above the *end of service life of the product* as the turning point from usage phase to disposal phase. The end of the service life of a PC usually is not a well-defined moment. And it is not a well-defined moment when the PC is no more able to perform common tasks. In general it is a slow process leading to use less a PC, not a breakdown. Because it is not only a matter of hardware but also of software, we have to try to address the computer lifecycle not only in terms of hardware but also in terms of software.

Software life cycle is not governed by the same physical breakages and part replacements (Open research, 2004) that contribute to hardware Total Cost of Ownership (TCO). Rather, the life cycle of software is dependent on a number of interrelated factors, most notably on the availability of a product, availability of support, functionality and hardware specifications. Within proprietary software framework, the life cycle can be defined as the period during which the manufacturer sells and supports its wares. Usually proprietary products are removed from the sales channel some time before official support is discontinued. Open Source software, like Linux, has no predefined life cycle and can remain in circulation indefinitely, although support focus may switch to newer version.

Software-Induced Hardware Obsolescence

The planned potential lifespan is longer than the effective one, almost a half of the potential one. That means to dispose products at half of their potential life span. Computers are getting obsolete very quickly because new operating systems require faster processor, larger memory and powerful hardware. Software plays a critical role in the hardware obsolescence. The effect of **Software Induced Hardware Obsolescence** (SIHO) (Sissa, 2013a) is an example of **rebound effect** (Hilty et al., 2006).

Reuse Models

Traditional business model to manage end of life equipment is driven by the model of the car: the only remaining values of an old car are the spare parts, usable to repair another car. The residual value consists of the physical objects by which the car is composed. This is the idea behind computer refurbishing, i.e. replacing some broken part or adding some components. Refurbishing, if not planned from the beginning of the product, it is not economically sustainable for computers, because of the related issues of reliability, accountability and spare parts availability. The traditional "spare part" model doesn't apply well to computers. Costs of storage, transportation, management and inventory of spare parts, plus related skills on electrical repair, made refurbishing no economically sustainable if made in safety working conditions. In any case, the production of e-waste is not decreased.

The value of high-tech equipment is mainly given by the software running on it. The idea behind the need to use computers better and longer is the so-called direct reuse, i.e. the reuse of the whole appliance, without hardware intervention, upgrading or substitution of parts. Direct reuse can be made only on still functioning equipment, that is well working but is considered obsolete for commercial reasons. If the obsolescence is a matter of software, the software can be the solution. When software helps the hardware to come closer to the ideal of load-proportional power-demand that will have an optimization effect on the use phase.

How to extend the life of obsolete computer without following the traditional *second hand* idea?

The **notion of innovation** as **a form of reaction** was introduce by Schumpeter (Schumpeter, 1947). If the context provides the opportunity for the successful **recombination** (Krafft & Quatraro, 2011) of complementary bits of knowledge, the reaction will be successful and actually creative (Arthur, 2009*).* **Novel technologies arise by re-combination of existing technologies**.

If there is a re combination potential of a PC, it cannot certainly be a trivial rearrangement of boards, microchips and electronic components. The recombination potential of a PC can be exploited by software

The challenge is not only to maintain on service longer a computer, but also to find the best software solution supplying all the functionalities for the final user needs. The goal is to avoid solutions that can be perceived from the user as "second hand solutions". The added value will be to tailor the configuration of software for the target user and to identify software solutions suitable for the available hardware.

It's important to define when the reuse is economically and socially sustainable, in order to prevent proliferation of aging, obsolete, out-of-warranty, unsupported and incompatible systems. Target groups have to be well satisfied, avoiding digital divide risks (Streicher-Porte et al., 2009). Digital divide today is no more the difference between people with computers and people without (Shreve, 2002). The digital divide is measured by what is the standard functioning level in Global North countries, compared to what is the real standard. Home made solutions will never eliminate the gap; high professional solutions, based on open source software, can be suitable for a socially sustainable reuse. A sustainable solution has to be environmentally sustainable, economically and socially sustainable (Böni et al., 2008).

Open Source Solution addresses the economic goal because the free open source software is without license fee and then there are no costs to buy software licenses. The social sustainability comes from the flexibility and the wide range of existing open source software. The range of the available OSS is large and daily increasing, allowing finding configurations suitable for any computer (Torvalds, & Diamond, 2001).

Cloud computing allows the device independence that can be reached by reusing PC as thin client (Fraunhofer Institute, 2008; Clausen, Fichter, & Hintemann, 2009) always on Internet and to access our data and application everywhere. We can think intermediate, but creative, recombination of technologies allowing all people to be connected, without having to destroy the planet by wasting potentially useful power resources, as still running PCs. This solution is not market driven, like a green ICT to be bought on the shelf. But this approach is knowledge intensive, because it is based on skilled activities of informatics. Some golden rules for software based recombination strategy in reuse can be suggested. The first is mandatory: reuse locally (UNEP-UNCTAD, 2007). It is important to donate end-of-life computers immediately, instead of keeping them in storage for months or years. Public Administrations have to simplify the donation procedures. The data clean up has to be taken into account. It can be useful to have work teams composed by donors and receiving subjects (i.e. schools or other Public administrations) able to describe the final user requirements. Informatics skills are required to match the features of - obsolete but still working - equipment with free software solutions able to satisfy the final user and to work well on the available hardware. We need criteria to evaluate the feasibility and sustainability of a donation program. A practical suggestion is to work on stocks of a large number of obsolete but homogeneous PCs (Sissa, 2008a), in order to easily can replicate their configuration.

Conclusion

Several studies recommend to pay attention to understand rebound effects by including knowledge or experiments with behavioral patterns, so that circumstances can be introduced whereby beneficial impacts are promoted and the detrimental impacts are prevented as much as possible.

By using new perspectives from innovation theory and the role that users, consumers or citizens can play in spreading and adopting beneficial behavior the rebound effects might be countered. This brings to the need for new research as well. Beyond the specific issues related to e-waste, environmental awareness could lead some computer scientists to a deeper analysis about long-term systemic effects of ICTs on the environment.

REFERENCES

Antonelli, C. (Ed.). (2011). *Handbook on the Economic Complexity of Technological Change*. Northampton. USA: EE Publishing.

Armbrust M et al. (2009). *Above the Clouds: A Berkeley View of Cloud Computing* (Technical Report No. UCB/EECS-2009-28). USA: University of California at Berkley.

Arthur, W.B. (2009). *The nature of technology. What it is and how it evolves*. New York: Free Press.

Australian Computer Society by Connection Research. (2010). *Carbon and Computers in Australia The Energy Consumption and Carbon Footprint of ICT Usage in Australia in 2010* (Report of Australian Computer Society by Connection Research). Sidney: Australian Computer Society.

Balin, P., Berthoud, F., Bohas, A., Charbuillet, C., Drezet, E., Dubois, J.D., Gossart, C. & Parry, M. (2012). *Les impacts écologiques des technologies de l'information et de la communication*. Les Ulis: EDP Sciences.

Bechtel M.M., & Scheve, K.F. (2013). Mass support for global climate agreements depends on institutional design. *PNAS, 110*(34), 13763-13768.

Behrendt S., Scharp, M., Erdmann, L., Kahlenborn W., Feil M., Dereje C., Bleischwitz R., & Delzeit R. 2007. *Rare metals. Measures and concepts for the solution of the problem of conflict-aggravating raw material extraction – the example of coltan* (UBA Texte 23/07). Dessau:Umweltbundesamt.

Berkhout, F. & Hertin, J. 2001. *Impacts of Information and Communication Technologies on Environmental Sustainability: Speculations and Evidence*. Report to the OECD. http://www.oecd.org/dataoecd/4/6/1897156.pdf

Berkhout, P.H.G., Muskens, J. C., &Velthuijsen, J.W. (2000). Defining the rebound effect. *Energy Policy 28*, 425-432.

Bicking M., Troitzsch K.G., & Wimmer M. (2010). Regulatory Impact Assessment: Modelling and Simulation to Facilitate Policy Choices. In Andreas Ernst, Silke Kuhn (Eds.), *Proceedings of the3rd World Congress on Social Simulation WCSS2010 (CD-RON).* Kassel, Germany. Center for Environmental Systems Research, University of Kassel.

Binswanger, M. (2000). Technological progress and sustainable development: what about the rebound effect?. *Ecological Economics 36*, 119 -132.

Böni, H., Streicher-Porte, M., Marthaler, C., & Camacho A. (2008). Computer for schools in developing countries - Decision making tool for sustainable supply strategies. In H. Reichl, N. F. Nissen, J. Müller, &O. Deubzer (Eds.), *Proceedings of Electronics Goes Green 2008+*. Berlin: Fraunhofer Verlag.

Boulanger P., Couder, J., Marenne, Y., Nemoz, S., Vanhaverbeke, J., Verbruggen A., & Wallenborn, G. (2013). *Household Energy Consumption and Rebound Effect* HECoRE (Final Report). Brussels: Belgian Science Policy.

Boulanger, P. (2010). Three strategies for sustainable consumption. *SAPIENS, 3* (2).

Bridegen, K., Webster, J., Labunska I., & Santilo D. (2007). *Toxic Chemicals in Computer Reloaded.* (Greenpeace Research Laboratories Technical note 06/07). Amsterdam: Greenpeace International.

Budhathoki, N. M. &Haythornthwaite, C. (2013). Motivation for open collaboration: Crowd and community models and the case of OpenStreetMap. *American Behavioral Scientist 57*(5), 548-575.

Buyya, R., Beloglazov, A., & Abawajy, J. (2012). Energy-aware resource allocation heuristics for efficient management of data centers for Cloud computing. *Future Generation Computer Systems 28* (5), 755-768.

Buyya, R., Beloglazov, A., & Abawajy, J. (2010). Energy-Efficient Management of Data Center Resources for Cloud Computing: A Vision, Architectural Elements, and Open Challenges. *Proceedings of the 2010 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA 2010).* Las Vegas, USA.

Buyya, R., Yeo, C.S., Venugopal S., Broberg, J., & Brandic I. (2009). Cloud computing end emerging IT platform: Vision, hype, and reality for delivering computing as the 5th utility, *Future generation Computer System, 25*(6), 599-616.

Cagnacci, F., Boitani, L., Powell, R. A., & Boyce, M.S. (2010). Animal ecology meets GPS - based radiotelemetry: a perfect storm of opportunities and challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1550), 2157-2162.

Clausen, J., Fichter, K., & Hintemann, R. (2009). *How to make computer green? Resource-efficient innovation in schools*. Einblincke 49/Fruhajar 2009 Carl Von Ossietzky Universitat Oldenburg, 48-51.

Cobbin, M. (2008). *Toxic Tech: Not in Our Backyard Uncovering the Hidden Flows of e-Waste* (Full Report). Amsterdam: Greenpeace International.
http://www.greenpeace.org/raw/content/international/press/reports/not-in-our-backyard.pdf

Colgan, J. (2010) *Environmental Effects of Cloud Computing*. Available at:
http://www.xuropa.com/blog/2010/01/19/environmental-effects-of-cloud-computing/

Coven, R. (2008). *Is Cloud Computing Actually Environmentally Friendly?*. Available at http://www.elasticvapor.com/2009/12/is-cloud-computing-actually.html

Coroama, V., & Hilty, L. M. (2009). Energy Consumed vs. Energy Saved by ICT - A Closer Look. In Wohlgemuth, V., Page, B., Voigt, K. (Eds.), *Environmental Informatics and Industrial Environmental Protection: Concepts, Methods and Tools, 23rd International Conference on Informatics for Environmental Protection* (pp.353-361). ISBN 978-3-8322-8397-1

Eaglea, N., Pentlandb, A., & Lazerc, D. (2009). Inferring friendship network structure by using mobile phone data. *PNAS, 106* (36), 15274–15278.

Egan, C. (2001). *The Application of Social Science to Energy Conservation: Realizations, Models, and Findings* (Report No. E002). Washington, D.C.: American Council for an Energy-Efficient Economy.

Ehrhardt-Martinez, K., Donnelly, K.A., & Laitner, J.A.S. (2010). *Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities* (Report No. E105). Washington, D.C.: American Council for an Energy-Efficient Economy.

Ehrhardt-Martinez, K. (2009), Testimony of Karen Ehrhardt-Martinez, Ph. D., Research Associate, American Council for an Energy-Efficient Economy (ACEEE), Before the United States Committee on Science and Technology, Subcommittee on Energy and Environment, ACEE, Washington D.C., April 28, 2009.

Erdmann, L., & Hilty, L. (2010). Scenario Analysis: Exploring the Macroeconomic Impacts of Information and Communication Technologies on Greenhouse Gas Emissions, *Journal of Industrial Ecology, 14*, 826–843.

European Commission (2010). *A Digital Agenda for Europe* (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions). Brussels: European Commission.

Fraunhofer Institute (2008). Environmental Comparison of the relevance of PC and Thin Client Desktop Equipment for the Climate.

Fuhr J., & Pociask S. (2007). *Broadband Services: Economic and Environmental Benefits (Report* of the American Consumer Institute). Washington D.C.: ACI (The American Consumer Institute).

GeSi. (2008). *Smart2020: Enabling the low carbon economy in the information age* (GeSi Group Report). http://www.theclimategroup.org/_assets/files/Smart2020Report.pdf

GeSi. (2010): *Evaluating the carbon-reducing impacts of ICT An assessment methodology*.

GeSi. (2012). *SMARTer2020: the role of ICT in driving a sustainable future*. http://gesi.org/SMARTer2020

Girod, B., De Haan, P., & Scholz R. W. (2011). Consumption-as-usual instead of ceteris paribus assumption for demand, Integration of potential rebound effects into LCA. *International Journal of Life Cycle Assessment, 16*, 3–11.

Göhring W. (2004). The Memorandum “Sustainable Information Society”. *18th International Conference Informatics for Environmental Protection*. Geneva: Editions du Tricorne. ISBN: 28 29 30 275-3.

Gravelle, H. & R. Rees. (2004). *Microeconomics*. Harlow: FT Prentice Hall.

Greening, L., Greene, D.L. & Difiglio, C. 2000. Energy efficiency and consumption the rebound effect -a survey. *Energy Policy* 28, 389–401.

Greenpeace International. (2011). *How dirty is your data?*. Amsterdam: Greenpeace International.

Grimm, V, Berger, U., DeAngelis, D., Polhill, J. G, Giske, J., & Railsback, S. (2010). The ODD protocol: A review and first update, *Ecological Modelling, 221*(23), 2760-2768.

Hertwich, E.G. (2005). Consumption and the rebound effect -an industrial ecology perspective. *Journal of Industrial Ecology, 9*(1–2), 85–98.

Hilty, L. M., & Lohmann, W. (2013). An Annotated Bibliography of Conceptual Frameworks in ICT for Sustainability. In: L. Hilty, B. Aebischer, G. Andersson and W. Lohmann (Eds.), *Proceedings of the*

First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich, February 14-16, 2013 (pp. 288-300). DOI 10.3929/ethz-a-007337628

Hilty, L.M., Lohmann, W., & Huang, E.M. (2011). Sustainability and ICT - an overview of the field. *Notizie di POLITEIA, 104*, 13-28

Hilty, L.M. (2008). *Information technology and sustainability. Essays on the Relationship between ICT and Sustainable Development*. Norderstedt, Books on demand GmbH

Hilty, L.M. (2007). CO2 Reduction with ICT: Prospects and Barriers. In: Hryniewicz O., Studzinski J., Romaniuk M. (Eds.): Environmental Informatics and Systems Research. Shaker Verlag Aachen, pp. 35-42

Hilty, L.M., Köhler A., Schéele, F., Zah, R., & Ruddy, T.F. (2006): Rebound effects of progress in information technology. *Poiesis & Praxis: International Journal of Technology Assessment and Ethics of Science 4* (1), 19-38.

Hilty L. M. (2005). Electronic waste—an emerging risk?. *Environmental Impact Assessment Review 25* (20), 431-435.

Hofstetter, P., Madjar & M., & Ozawa, T. (2006). Happiness and sustainable consumption—psychological and physical rebound effects at work in a tool for sustainable design. *Int J Life Cycle Ass, 11*,105–115.

Hofstetter, P., & Madjar, M. (2003). *Linking change in happiness, time-use, sustainable consumption, and environmental impacts; An attempt to understand time-rebound effects* (Final Report, Büro für Analyse & Oekologie), Zurich, March 17, 2003.

Jackson, T. (2005). *Motivating Sustainable Consumption – a review of evidence on consumer behaviour and behavioural change* (Report to the Sustainable Development Research Network). Centre for Environmental Strategy, University of Surrey.

Jia-Ching Ying, J. et al. (2010). Mining User Similarity from Semantic Trajectories. *ACM LBSN'10*. San Jose, CA, USA.

Kamel Boulos, M.N., Resch B., Crowley D.N., BreslinJ.G., Sohn G., Burtner, R., William A Pike, Eduardo Jezierski E., & Slayer Chuang K. (2011). Crowdsourcing, citizen sensing and sensor web technologies for public and environmental health surveillance and crisis management: trends, OGC standards and application examples. *International Journal of Health Geographics 2011, 10*(67). doi:10.1186/1476-072X-10-67.

Kanhere, S.S. (2011) Participatory Sensing: Crowdsourcing Data from Mobile SmartPhones in Urban Spaces, 2011 12th IEEE International Conference on Mobile Data Management

Kinzig, A.P., Ehrlich, P.R., Alston L.J., Arrow, K., Barrett, S., Buchman, T.G., Daily, G. C., Levin, B., Oppenheimer, M., Ostrom, E., & Sahari, D. (2013). Social Norms and Global Environmental Challenges: the Complex Interaction of Behaviors, Values, and Policy. *Bioscience, 63* (3), 164-175.

N. Kiukkonen, J. Blom, O. Dousse, D. Gatica-Perez, & J. Laurila (2010). Towards rich mobile phone datasets: Lausanne data collection campaign. *Proceedings of International Conference on Pervasive Services* (ACM, Berlin, 2010).

Kleinrock, L. (2005). A vision for the Internet. *ST Journal of Research 2*(1), 4-5.

Kletzan, D., Köppl, A., Kratena, K., Schleicher, S. & Wüger, M. (2002). Modelling Sustainable Consumption. Form Theoretical Concepts to Policy Guidelines. *Empirica*, *29*,131-144.

Köhler, A.R., Hilty, L.M. and Bakker, C. (2011) Prospective Impacts of Electronic Textiles on Recycling and Disposal. *Journal of Industrial Ecology, 15* (4), 496-511.

Koomey, J., Berard, S., Sanchez, M., & Wong, H. (2011a). Implications of Historical Trends in the Electrical Efficiency of Computing. *Annals of the History of Computing, IEEE*, 33 (3). 46 – 54. Stanford University, ISSN: 1058-6180, Digital Object Identifier: 10.1109/MAHC.2010.28.

Koomey, J., Berard, S., Sanchez, M., & Wong, H. (2011b). *Web Extra appendix.* http://doi.ieeecomputersociety.org/10.1109/MAHC.2010.28

Krafft, J., & Quatraro, F. (2011). The dynamics of technological knowledge: from linearity to recombination. In C. Antonelli, (Ed.), *Handbook on the Economic Complexity of Technological Change* (181-200). Northampton. USA: EE Publishing.

Kuehr, R., &Williams E. (Eds.). (2003). *Computers and the Environment: Understanding and Managing their Impacts*. Dordrect, The Netherland: Kluwer Academic Publisher.

Lane, N., Miluzzo, E., Lu. H., Peebles, D., Choudhury, & T., Campbell, A. (2010). A survey of mobile phone sensing**.** [http://dx.doi.org/10.1109/MCOM.2010.5560598] *IEEE Communications Magazine* 2010, *48*(9)**,** 140-150.

Ladou, J., & Lovegrove, S. (2008). Export of electronic equipment waste. *International Journal Occupation Environment Health*, *14*(1), 1-10.

Lepochat, S. (2011). Taking into Account the Rebound Effect in LCA: Necessities and Difficulties, *Colloquium EJC- ICT 2011*, Montreal.

Lin, G., Fu, D., Zhu, J., & Dasmalchi, G. (2009). Cloud Computing: IT as a service. *IT Pro.*

Linscheidt, B. (2001). Consumer Behaviour and Sustainable Change, Umweltökonomische Diskussionsbeiträge Nr. 99-2, Finanzwissenschaftliches Forschungsinstitut an der Universität zu Köln, 2001.

Lopez, J.C, Natvig, L., & Sissa, G. (2011). Green ICT: the information society commitment for environmental sustainability. *CEPIS UPGRADE, XII* (4), 2-5.

Manhart, A. (2010). International Cooperation for Metal Recycling From Waste Electrical and Electronic Equipment. An Assessment of the "Best-of-Two-Worlds" Approach. *Journal of Industrial Ecology, 15* (1), 13-30.

Masanet E., & Matthews, H.S. (2010). Exploring Environmental Applications and Benefits of Information and Communication Technology. *Journal of Industrial Ecology, 14*, 687–691. j.1530-9290.2010.00285.x

Maxwell, D., Owen, P., McAndrew. L, Muehmel, K. & Neubauer, A. (2011). *Addressing the Rebound Effect* (report for the European Commission DG Environment). Brussels: European Commission.

Merton, R.K. (1996). *On Social Structure and Science*. The University of Chicago Press.

Micklethwait, J. (2009). *Unlocking the cloud*. The Economist

Munck S. (2010). Indicators for measuring green ICTs http://www.giswatch.org/sites/default/files/gisw2010indicators_en.pdf

Munro, S. (2010). *Environmental Unfriendly Side Effects of Cloud Computing*. Available at http://consultingblogs.emc.com/simonmunro/archive/2010/01/12/environmentally-unfriendly-side-effects-of-cloud-computing.aspx

Murugesan, S. (2008). Harnessing Green IT: Principles and Practices. *IT Professional, 10*(1), 24-33.

National Research Council (2008). *Minerals, Critical Minerals, and the U.S. Economy*. The National Academies Press.

NIST (2011). *The NIST Definition of Cloud Computing (Draft)()*, January 2011.

Nuttall, W.J., Zhang, T., Hamilton, D.J., Roques, F.A. (2009). Sociophysics Simulations of Technology Adoption and Consumer Behavior. *Second International Symposium on Engineering Systems*, MIT, Cambridge, Massachusetts

OECD (2011). *Greening household behavior: the role of public policy*. Paris: OECD Publishing.

OECD (2010a). *Greener and smarter – ICTs the environment and Climate Change.* Paris: OECD Publishing.

OECD (2010b). *Recommendation of the Council on Information and Communication Technologies and the Environment*. Paris: OECD Publishing.

OECD (2009a). *Toward green ICT Strategies: Accessing Policies and programmeson ICT and the Environment*. Paris: OECD Publishing.

OECD (2009b). *Measuring the relationship between ICT and the Environment*. Paris: OECD Publishing.

OECD (2008a): Key ICT Indicators. www.oecd.org/sti/ICTindicators

OECD(2008b): Key Environmental Indicators. (2008) http://www.oecd.org/dataoecd/20/40/37551205.pdf

Open Research (2004). *Paying the price? A Total Cost of Ownership comparison between new and refurbished PCs in the small business, NGO and school in Africa*. www.openresearch.co.za

O'Reilly, T. (2005). *What Is Web 2.0 Design Patterns and Business Models for the Next Generation of Software.* http://oreilly.com/web2/archive/what-is-web-20.html

Ormerod, P., Rosewell, B., & Wilthshire, G. (2011). Network models of innovation process and policy implications In C. Antonelli (Ed.), *Handbook on the Economic Complexity of Technological Change (*pp. 492-532). Northampton. USA: EE Publishing.

Padgett, P.G., Steinemann, A.C., Clarke, J.H., & Vandenbergh, M.P. (2008): A comparison of carbon calculators. *Environmental Impact Assessment Review, 28*, 106–115.

Pamlin, D. (2008). *The potential global CO2 reductions from ICT use*. WWF Sweden

Parnell, R. & Larsen, O.P. (2005). Informing the Development of Domestic Energy Efficiency Initiatives: An Everyday Householder-Centered Framework. *Environment and Behaviour, 37*(6), 787-807.

Popp, D., Newell, R.G. & Jaffe, A.B. (2009). *Energy, the environment, and technological change* (NBER working paper series). Cambridge, MA: National Bureau of Economic Research.

Puckett, J., Westervelt, S., Gutierrez, R., & Takamiya, Y. (2005). *The digital dump. Exporting re-use and abuse to Africa*. Seattle: Basel Action Network.

Robinson, B.H. (2009). An Assessment of global production and environmental impact. *Science of the Total Environment*, *408*. 183-191.

Saenz, A. (2011). *Japan's Nuclear Woes Give Rise to Crowd-Sourced Radiation Maps In Asia and US (24 March 2011).* [http:/ / singularityhub.com/ 2011/ 03/ 24/ japans-nuclear-woes-give-rise-to-cr owd-sourced-radiation-maps-in-asia- and-us/

Saviotti, P. (2011). Knowledge, complexity and networks. In C. Antonelli, (Ed.), *Handbook on the Economic Complexity of Technological Change* (pp. 141-180). Northampton. USA: EE Publishing.

Schluep, M., Müller, E., Hilty, L. M., Ott, D., Widmer, R. & Böni, H. (2013). In: ICT4S 2013: Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich, February 14-16, 2013, 45-51

Schumpeter, J. A. (1947) The creative response in economic history. *Journal of Economic History, 7*. 149-159.

Schwarzer, S., De Bono, A., Giuliani, G., Kluser, S., & Peduzzi, P. (2005). *E-waste, the hidden side of IT equipment's manufacturing and use*.
http://www.grid.unep.ch/product/publication/download/ew_ewaste.pdf

Shreve (2002). Charities say no to obsolete crap. Wired
http://www.wired.com/culture/lifestyle/news/2002/01/49537

Simon, H. (1957). "A Behavioral Model of Rational Choice", in Models of Man, Social and Rational: Mathematical Essays on Rational Human Behavior in a Social Setting. New York: Wiley

Sissa, G. (2013a). An awareness based approach to avoid rebound effects in ICTs. In L. M. Hilty, B. Aebischer, G. Andersson and W. Lohmann (Eds.), *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability, ETH Zurich, February 14-16, 2013* (pp. 248-254). DOI 10.3929/ethz-a-007337628

Sissa, G. (2013b). Longer Use, Better Use: How to Avoid Software Induced Hardware Obsolescence. In P. Ordóñez de Pablos (Ed.), *Green Technologies and Business Practices: An IT Approach* (pp. 163-174). Hershey, PA: Information Science Reference. doi:10.4018/978-1-4666-1972-2.ch009

Sissa, G. (2011a). Utility computing: green opportunities and risks. *CEPIS UPGRADE, XII* (4), 16-21.

Sissa, G. (2011b). Assessment criteria for policy on ICT and climate change. In W. Pillman, S. Shade, & P. Smits (Eds.), *EnviroInfo 2011 – 25th Symposium Informatics for Environmental Protection* (pp. 253-260). Aachen: Shaker Verlag.

Sissa, G. (2011c). Public policies on ICTs for dematerialisation: how to plan, monitor and assess the outcomes. *Notizie di POLITEIA, 104*, 67-78.

Sissa, G. (2010). Green software, *CEPIS UPGRADE, XI*(3), 53-63.

Sissa G. (2008a): How Public Administration can contribute to a sustainable ICT. OECD Workshop on ICT and environmental challenges, Copenhagen, 20-22 May 2008. http://www.oecd.org/dataoecd/42/24/40833678.pdf

Sissa G. (2008b). *Il computer sostenibile*. Milano: Franco Angeli.

Smajgl A., Brown D.G., Valbuena, D., & Huigen, M.G.A. (2011). Empirical characterization of agent behaviours in socio-ecological systems. *Environmental Modelling & Software*, *26* (7), 837-844.

Smelser N.J., & Swdberg, R. (Eds.). (2005). *The handbook of economic sociology. Second edition.* Princeton: Princeton University press.

Som, C., Hilty, L. M., & Köhler, A. R. (2009). The Precautionary Principle as a Framework for a Sustainable Information Society. *Journal of Business Ethics 85* (3), 493-505. DOI 10.1007/s10551-009-0214-x

Sorrell, S. (2009). The rebound effect: definition and estimation. In J. Evans and L. C. Hunt (Eds.), *International Handbook on the Economics of Energy* (pp. 199-233). Cheltenham: Edward Elgar Publishing.

Sorrell, S. (2010). Energy, Economic Growth and Environmental Sustainability: Five Propositions. *Sustainability, 2*(6), 1784-1809.

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy, 38*(9), 1356-1371.

Sorrell, S., & Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics 65*(3), 636-649.

Sorrell, S. (2007). The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, UK-ERC, London, October 2007. ISBN 1-903144-0-35.

Spagnolli, A., Corradi, A., Gamberini, L., Hoggan, E., Jacucci, G., Katzeff, C., Broms, L., & Li, J. (2011). Eco-Feedback on the Go: Motivating Energy Awareness. *Computer, 44*(5), 38-45.

Spintasanti, L., Celli, F., & Renso, C. (2010). Where you stop is who you are: understanding peoples' activities. in 5th BMI'10, User Behaviour Modelling, Karlsruhe, Germany

Starkey, R. (2012). Personal carbon trading: A critical survey Part 1: Equity. *Ecological Economics, 73*, 7-18.

Streicher-Porte M., Marthaler C., Boni H., Schluep M., Camacho A., & Hilty L. (2009). One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. *Journal of Environmental Management, 90* (11), 3498-3511.

Sun Microsystem (2009). Take your business at a higher level – A cloud computing primer

UKERC (2007). UKERC Review of Evidence for the Rebound Effect - Supplementary Note: Graphical illustrations of rebound effects.

UNEP-UNCTAD (2007). Capacity Building Task Force on Trade, Environment and Development, Background Note – Electrical and Electronic Equipment in the International Symposium. Environmental Requirements and Market Access: Turning Challenges into Opportunities. Geneva

UNEP (2006). Nairobi Conference on Basel Convention to Address the Growing Challenge of Electronic Wastes, Nairobi

Theis, T., & Tomkin, T. (Eds.). (2012). *Sustainability: A Comprehensive Foundation*. Huston: Rice University.

Torvalds L., & Diamond D. (2001). *Just For Fun: The Story of an Accidental Revolutionary*. New York, New York, United States: HarperCollins. ISBN 0-06-662072-4.

van den Bergh, C.J.M. (2011). *Industrial energy conservation, rebound effects and public policy* (UNIDO Development Policy, Statistic and Research Branch Working Paper 12/2011). Vienna: United Nations Industrial Development Organization.

Wäger, P., Lang, D., Bleischwitz, R., Hagelüken, C., Meissner, S., Reller, A., & Wittmer, D. (2010). Rare metals – Raw materials for technologies of the future. SATW, Swiss Academy of Engineering Sciences.

Wesley Schultz, P., Nolan, J.M., Cialdini, R.B., Goldtsein, N.J., & Griskevicius, V. (2007). The Constructive, Destructive, and Reconstructive Power of Social Norms. *Psychological Science 18* (5), 429-434.

Williams E.D., Ayres. R.U., & Heller M. (2002). The 1.7 Kilogram microchip: energy and material use in the production of semiconductor devices. *Environmental Science & Technology, 36*(24), 5504-5510.

Xie, K., Deng, K., & Zhou, X. (2009). From trajectories to activities: a spatio-temporal join approach. In Xie, K., Zhou, X., *GIS-LBSN 2009* (pp. 25-32). Seattle, Washington: ACM 2009.

Yan, Z., Chakraborty, D., Parent, C., Spaccapietra, S., & Aberer, K. (2011). SeMiTri: A Framework for Semantic Annotation of Heterogeneous Trajectories. 14th International Conference on Extending Database Technology (EDBT), 2011

Yan, Z.(2009) Towards Semantic Trajectory Data Analysis: A Conceptual and Computational Approach, VLDB '09, August 24-28, 2009, Lyon, France

Zapico, J. L., Brandt, N. & Turpeinen, M. (2010): Environmental Metrics. *Journal of Industrial Ecology, 14* (4), 703–706.

PART TWO: CONCEPTUAL FRAMEWORK FOR MODELING

A full exploitation of ICTs environmental potential benefits needs taking into account the **social dimension of ICT as a service**, where there is a shift of role from user to co-producer. After the overview on ICTs effects on the environment of the previous part, we will focus on the role that users, consumers or citizens can play in spreading and adopting beneficial behavior. We will try to highlight that the enabling factor of this active participative role is the collective situational awareness about environmental effects of actions that can counter possible rebound effects and make a green behavior easier.

In order to describe and to model such behavior, an interdisciplinary overview of useful concepts will be done, drawing from social science, computation social science, social network analysis, social influence and institution, as well as from Human-Computer interaction, the conceptual building blocks we need of.

Agent Based Model (ABM) simulation is the proposed as approach to study such individual and collective behavioral changes in consuming a limited-resource by using ICT-based services. We will than depict a conceptual model of households energy consumption.

We will focus on the background social mechanisms in Chapter 3 and we will introduce in Chapter 4 the potential of Agent-Based Modeling to describe at the micro level individual behaviors and to observe at the macro level the emerging general effects of such behaviors. In particular in Chapter 5 and in Chapter 6, we propose a conceptual model to explore environmental awareness spread mechanisms, highlighting the importance of facilities, provided by advanced smart metering functions, in empowering users to turn such extended awareness into more sustainable behaviors

3. BUILDIN BLOCK: FROM AN INDIVIDUAL TO A SOCIAL DIMENSION

3.1 Introduction

A purpose of the presented research is to explore the role of the environmental sustainability awareness level of people into driving their behavior, whether they are users, households, customers, or citizens. While the term "users" emphasizes the idea of an activity, households refer to a domestic place and include the persons living there. Customers have different rights and duties towards energy suppliers, whereas citizens are people belonging to a public community, like e.g. a city, a town, a district or a specific building.

According to Oxford Dictionary's definition "Awareness is a concern about and well-informed interest in a particular situation or development". The awareness concept is very different from the information concept. People can be full of information about something without being aware about it. Above all awareness is an individual aptitude that is developed and shaped inside a social context: an institution where social reward is the motivation for a sustainable behavior.

While a large research activity focuses on opinion dynamics, less attention has been given to the spread mechanism of awareness, and namely environmental awareness.

The concept of collective awareness is meant to create an extended consciousness of the environment, of the consequences of our own actions on it, and to encourage taking informed and sustainability-aware decisions. An extended awareness can be enabled by ICTs, for instance by decentralized and federated social networks, where environmentally aware, grassroots processes and practices to share knowledge, to achieve changes in lifestyle, production and consumption patterns, will set up more **participatory processes.**

Staats, Harland and Wilke (2004) found in their longitudinal study that one of the most important contributing factors for changing behaviors and energy savings were supportive social environments. In addition ICT based feedback mechanisms (Holmes, 2007; Froehlich, Findlater, & Landay, 2010; Kirman Linehan, Lawson, & Foster, 2010) are effective in reducing energy consumption (Ehrhardt-Martinez, Donnelly, & Laitner, 2010; Abrahamse, Steg, Vlek, & Rothengatter 2007; Fischer, Piccinno, & Ye, 2008) and have been implemented and analyzed in Human–computer interaction (HCI) domain. HCI involves the study, planning, and design of the interaction between people (users) and computers. It is often regarded as the intersection of computer science, behavioral sciences, and design. Researches in the HCI have (Fischer, 2010) been focused on the importance to involve final user in a participatory design process.

Such researches have shown that participatory processes are based on some psychological mechanisms, like social proof or informational social influence, that are very meaningful in an ICT-based social dimension where there is a shift of role from passive user to aware and active user.

The mechanisms of "motivating social environments" (Abrahamse et al., 2007), "psychological ownership" (Pierce, Kostova, & Dirks, 2002), and "social proof" (Cialdini, 2009) are building blocks of social influence.

3.1.1 Motivating social environment

Measuring and understanding are the first steps to be able to act smart. For example personal carbon accounting is necessary for citizens to understand and manage their individual carbon footprint, while smart meters, with related services, can reduce household energy consumption.

A research corpus identifies as essential to **empower individuals** providing **feedback, goal setting, and tailored information** (Abrahamse et al., 2007). Interventions work better when used in combination, because different households are prevented from action by different barriers (Gardner & Stern, 2002).

Such underlying societal and psychological mechanisms can be enabled by ICT-based socio-technical interventions (Fischer, 2012) that going beyond simple presentations of facts can motivate people (Constabile, Dittrich, & Fischer, 2011) to change behavior for reaching the goal of reducing a limited (or critical) resource consumption, as for example **energy**.

3.1.2 Psychological ownership

Psychological ownership (Pierce et al., 2002) describes a state in which a person feels closely connected to an object or idea, to the degree that it becomes part of an "extended self". As soon as people see something as its own, its value raises and is more likely to invest time and effort in it.

In a meta-review of research on psychological ownership, Pierce and colleagues (2002) have found several requirements for psychological ownership: (1) *control*, (2) *investment of self*, (3) *intimate knowing*, and (4) *modifiable targets*. In research on psychological ownership several requirements have been identified, like for example modifiable targets (Fisher, 2012).

3.1.3 Social proof

Social proof (Cialdini, 2009; Fisher, 2010) describes the effect that people act a certain way because they observe others acting this way. In such situations, the fact that others choose something acts as proof that this choice is preferable. Those researches show that it is important to share collective goals.

Social proof, also known as **informational social influence**, is a psychological phenomenon where **people assume the actions of others in an attempt to reflect correct behavior** for a given situation. This effect is prominent in ambiguous social situations where people are unable to determine the appropriate mode of behavior, and is driven by the assumption that surrounding people possess more knowledge about the situation.

There are two basic steps for building a collective environmental situational awareness. The first is to access real-time to easily understandable information about own resource consumption, the second is to compare individual lifestyles against some ecological/environmental benchmark. However, energy consumption is completely individualistic and invisible to the consumers themselves and to others (Ehrhardt-Martinez et al., 2010). The strong importance, as we well see, of smart metering functions derive from such consideration (OECD, 2011). They can implement what we have defined as social proof.

Basic steps for the building of a collective environmental situational awareness are accessing real-time and easily understandable information on resource consumption, and comparing individual lifestyles against some ecological/environmental benchmark. Aggregated data can be used to evaluate the performances of larger entities (communities). It is very important to identify the scale of the community, i.e. the range of social influence on such a community and the mechanism of community building. Example of scale of community can be the ZIP Code area in a city as, for example, in the *Urban ecomap*[31] of San Francisco in the United States.

While consumers are driven by a mix of basic needs, personal desires and social images (EC, 2011), more generally individuals are replacing common background or geographic proximity with a sense of well-defined purpose and the successful common pursuit of this purpose is the condensation point for human connection.

One research contribution of this PHD thesis consists of an analysis of the spread of awareness between neighbors. Because neighborhood's relationships can be topologically or socially defined or given by a mix of them, the concepts of social influence and threshold models - taken from analytical sociology that are more and more popular in social network analysis - have to be introduced.

3.2 Social influence mechanisms

Social influence is thus not a singular phenomenon, or even (yet) a well-defined family of phenomena, but rather a blanket label for a loose congregation of social, psychological, and economic mechanisms, including:

- Identifying with (or distancing oneself) from certain social groups;
- Avoiding sanctions;
- Obeying authority;
- Reducing the complexity of the decision making process;

---

[31] http://urbanecomap.org

- Inferring otherwise inaccessible information about the world;
- Gaining access to a particular network;
- Reaping the benefits of coordinated action.

Precisely what these different mechanisms have in common, and to what extent their differences, when they exist, can be overlooked for the purpose of constructing models of individual choice, ought therefore to be a matter of considerable interest to "analytical sociology."

3.2.1 Social spreading phenomena

Recent years have witnesses great attention to study collective phenomena emerging from the interaction of individual as elementary units in social structures, in a wide list of topics, ranging from opinion, and cultural and language dynamics to crowd behavior, hierarchy formation, human dynamics and social spreading.

Opinion dynamics deals with the competition between different possible responses to the same political question or issue where the alternatives have the same or at least comparable levels of plausibility, so that in the interaction between two agents each of them can in principle influence the other (Castellano, Fortunato, & Loreto 2009).

In phenomena like the propagation of rumors or news, the interaction is instead intrinsically asymmetric: possible states are very different in nature (Castellano et al., 2009). The flow is only from those who know to those who do not. The propagation of rumors or news is an instance of the vast class of social spreading phenomena, which includes the diffusion of fads, the adoption of technological innovations, and the success of consumer products mediated by word of mouth.

Many models introduced for these phenomena assume that a local threshold in the fraction of active neighbors must be overcome for the spreading process to occur.

When considering rumor spreading, some of the relevant questions to address are similar to those for epidemiology: How many people will eventually be reached by the news? Is there an "epidemic threshold" for the rate of spreading, separating a regime in which a finite fraction of people will be informed from one with the information remaining confined to a small neighborhood?

Other issues, more connected to technological applications, deal with the cost of the spreading process and its efficiency.

3.2.2 Social Network Analysis and social contagion

Social network research is studying how the influence network - that is, the network of "who influences whom" - can impact the dynamics of collective decisions, determining, for example, the likelihood that large "cascades" (Watts & Duncan, 2002) of influence can originate from small initial seeds, the ability of prominent individuals to trigger such cascades, and the importance of group structure in triggering and propagating large cascades.

Models of social influence, moreover, tend to assume that all actors involved are of the same kind, whereas in reality, individuals may be influenced by a variety of actors - for example, peers, role models, media organizations, and high profile individuals, each of which may exert a different kind of influence, and may in turn be influenced differently. A growing research area inside social network analysis is focusing on a special case of influence response functions - namely, deterministic threshold functions, according to which individuals adopt a new state based on the perceived fraction of others who have already adopted the same state.

Threshold models are already understood in certain limiting cases, like in particular, the all-to-all approximation in which all individuals are influenced equally by the states of all others. Other studies (Watts& Duncan, 2002) proceed systematically up the chain of complexity, reviewing the dynamics of cascades of influence on random networks. Watt & Dodds (2009) models of networks advance on the random network model, by including some notions of group structure.

Models of social influence, moreover, tend to assume (often implicitly) that all actors involved are of the same kind, whereas in reality, individuals may be influenced by a variety of actors - for example, peers, role models, media organizations, and high profile individuals, each of which may exert a different kind of influence, and may in turn be influenced differently.

3.2.3 Threshold model of social influence

A research area of growing importance inside social network analysis is now focusing on a special case of influence response functions - namely threshold functions, according to which individuals adopt a new *state* based on the perceived fraction of others who have already adopted the same state.

Threshold models are already understood in certain limiting cases, like in particular, the all-to-all approximation in which all individuals are influenced equally by the states of all others. Other studies (Watts & Duncan, 2002) proceed systematically up the chain of complexity, reviewing the dynamics of cascades of influence on random networks. Other researchers (Watt & Dodds, 2009) models of networks are including some notions of group structure.

The notion of threshold is fundamental in the present paper to design the conceptual model of environmental awareness and related consumption patterns. The classical Granovetter's threshold model (Grannovetter, 1978) has been adapted in research works to a network framework where in contrast to the all-to-all assumption, individuals are assumed to be influenced directly only by a small subset of immediate "neighbors" - a more realistic assumption.

3.2.4 Committed agent and social influence

An interesting notion for our purpose is about a potential commitment of agents. Committed agents (Lu, Koriss, & Sztmansky, 2009) are defined as nodes that can influence other nodes to alter their state through the usual prescribed rules, but which themselves are immune to influence. The effect of having "uninfluenceable" agents has been considered to some extent in prior studies. Biswas & Sen (2009) considered, for two-state opinion dynamics models in one dimension, the case where some individuals are "rigid" in both segments of the population, and studied the time evolution of the magnetization and the fraction of domain walls in the system.

Xie et al. (2011) show how the prevailing majority opinion in a population can be rapidly reversed by a small fraction of randomly distributed committed agents who consistently proselytize the opposing opinion and are immune to influence. Xie and colleagues show that when the committed fraction grows beyond a critical value around the 10%, there is a dramatic decrease in the time taken for the entire population to adopt the committed opinion.

3.2.5 Tipping point

The notion of "tipping point" has been coined by Morton M. Grodzins in studies on white flight[32] such as "Metropolitan Segregation" (1957). The tipping point is the critical point in an evolving situation that leads to a new and irreversible development. The term is said to have originated in the field of epidemiology when an infectious disease reaches a point beyond any local ability to control it from spreading more widely.

The term is used in many fields, like sociology (Gladwell, 2000) climatology or economics. In physics a tipping point is an example of hysteresis in which the point at which an object is displaced from a state of stable equilibrium into a new equilibrium state qualitatively dissimilar from the first.

Journalists apply it to social phenomena, demographic data, and almost any change that is likely to lead to additional consequences. Marketers see it as a threshold that, once reached, will result in additional sales.

In some usage, a tipping point is simply an addition or increment that in itself might not seem extraordinary but that unexpectedly is just the amount of additional change that will lead to a big effect. The notion of tipping point has been linked in recent researches to the notion of committed agent (Xie et al., 2011) and social norm (Kinzig et al., 2013).

---

[32] White flight is a term that originated in the United States, starting in the mid-20th century, and applied to the large-scale migration of whites of various European ancestries from racially mixed urban regions to more racially homogeneous suburban or exurban regions.

3.3 Conclusion

Trying to make a synthesis we can say that measures like setting relevant goals, gaining commitment, giving feedback, prompting behaviors are basic steps toward developing new social norms for "environmentally aware" behavioral changes, while items like the reference with time series of individual consumption, the comparison with others consumers, the dynamical redefinition of own reduction goals and the sharing of collective reduction goals are the basic functions of a smart metering system.

In the next chapters we will use some of the above-introduced concepts. The notion of **social diversity** (Ugander**,** Backstrom, Marlow & Kleinberg, 2012) will be introduced in order to simulate a network of neighbors composed by different types of agents, which are more or less influential on the basis of their level of environmental awareness, as introduced in Chapter 5 and described in Chapters 6.

4. BUILDING BLOCK: AGENT BASED MODELING

4.1 Introduction

An Agent Based Model (ABM) allows defining a set of scenarios (simulation experiments) to study the emergence of collective phenomena that are impossible to foresee at individual level. Agent-based models (ABM) can be used "…to model social systems that are composed of agents who interact with and influence each other, learn from their experiences, and adapt their behaviors so they are better suited to their environment" (Macal & North, 2010).

It is important to recognize the relatively unique characteristics of ABMs in simulation. With ABM, the researcher explicitly describes the decision processes of simulated actors at the micro level (Gilbert, 2008; 2005). Structures emerge at the macro level as a result of the actions of the agents and their interactions with other agents. Developing such models requires gaining information about how agents make their decisions, how they forecast future developments, and how they remember the past. What do they believe or ignore? How do agents exchange information? And, does the structure of agent interactions affect the macro-level scale phenomena?

ABMs are widely used in economics, social science, environmental science and more in general in complex systems analysis (Conte et al. 2012; Salerno et al, 2011;Tesfatsion & Judd, 2006).

As Jannsen & Ostrom (2006) state, and it is now relatively well established, as a result of experimental research on social dilemmas, that the narrow model of "economic man" focused primarily on monetary returns is not a good foundation for explaining behavior outside of open competitive situations. Individuals are capable of learning to trust others and of following norms of reciprocity, but in every culture there exists some individuals who are well modeled by the notion of homo oeconomicus (Ostrom 1998; 2005). Individuals who want to achieve collective objectives over time must find a wide variety of *institutional mechanisms* that *enable them to create fair rules of contribution* and distribution and ways of monitoring people's contributions without squelching cooperation by over-monitoring.

Without these mechanisms, a few individuals can begin to grab benefits. Then, levels of trust and cooperation plummet rapidly. Modeling these two or three-level dilemmas, however, using formal analytical models has proved to be extremely difficult (Greif & Laitin, 2004). Thus, the findings about the complexity of human choice revealed in extensive experimental research are core motivating factors leading scholars to use ABMs more extensively than before (Jannsen & Ostrom, 2006; Gilbert & Terna, 2000; Epstein, 1999).

One of the most successful methodologies used in social dynamics is agent-based modeling (Borrill & Tesfatsion, 2010; Borshchev & Filippov, 2004). The idea is **to construct the computational devices -** known as agents with some properties **-** and then simulate them in parallel to model the real phenomena. The goal is to address the problem of the **emergence from the lower micro level of the social system to the higher macro level**.

The notion of agent has been important in the development of the concept of artificial intelligence, which traditionally focuses on the individual and on rule-based paradigms inspired by psychology. In this framework, the term *actor* is used to indicate interactive objects characterized by a certain number of internal states, acting in parallel and exchanging messages. In computer science, the notion of an actor turned in that of an *agent* and more emphasis has been put on the interaction level instead of autonomous actions.

The artificial life community has been the first in developing agent-based models, but since then agent-based simulations have become an important tool in other scientific fields and in particular in the study of social systems (Axelrod, 2007). Epstein and Axtell (1996) introduced, by focusing on a bottom-up approach, the first large-scale agent model (the Sugarscape) to simulate and explore the role of social phenomena such as seasonal migrations, pollution, sexual reproduction, combat, trade and transmission of disease, and culture.

Agents interact either directly or in an indirect way through the external environment, which provides feedback about the activities of other agents. Direct interactions are typically local in time and ruled by the underlying topology of the interaction network.

Populations can be homogeneous or heterogeneous. A crucial feature of agent-based models is that the agents can interact, that is, they can pass informational messages to each other and act on the basis of what they learn from the messages. The messages may represent spoken dialogue among people or more indirect means of information flow, such as the observation of another agent or the detection of the effects of another agent's actions. The possibility of modeling such agent-to-agent interactions is the main way in which agent-based modeling differs from other types of computational models.

Agent-based simulations have now acquired a central role in modeling complex systems and a large literature has been developing in the past few years about the internal structure of the agents, their activities, and the multi-agent features (Axelrod & Tesfatsion, 2006; Borrill & Tesfatsion, 2010).

In particular, the richness of detail one can take into account in ABM makes this methodology very appealing for the simulation of social systems, where the behavior and the heterogeneity of the interacting components are not safely reducible to some stylized or simple mechanism.

4.1.1 Agent Based Modeling of behaviors

A broad research corpus shows how behaviors (Railsback & Grimm, 2011) can easily be modeled according to an ABM (Agent Based Model) approach. Such research crosses the disciplinary borders between several disciplines, as economics (Ostrom & Janssen, 2006; Fagiolo, Moneta, & Windrum, 2007), energy (Nuttall, Zhang, Hamilton, & Roques, 2009), sociology (Ligtvotet, Ghorbani, & Chappin, 2010), environmental science (Smajgl, Brown, Valbuena, & Huigen, 2011), computer science (Borrill &Tesfatsion, 2004), as well as complex systems (Janssen, Radtke, & Lee, 2009), and social network analysis.

An Agent Based Model is proposed to study individual and collective behavioral changes toward sustainability using ICT-based services.

An ABM approach is particularly suitable when the emergence of a collective behavior, impossible to foresee at an individual level, is an important consideration. Agent-based simulation as a modeling approach enables to build models where individual entities and their interactions are directly represented. An ABM approach allows the modelers to represent in a natural way multiple scales of analysis, the emergence of structures at the macro or societal level from individual action, and various kinds of adaptation, none of which is easy to do with other modeling approaches.

4.1.2 Agent Based Modeling in technology adoption and consumer behavior

Agent-based modeling is an important tool to investigate socio-ecological processes (Filatova, Verburg, Parker, & Stannard, 2013). Its use is driven by increasing demand from decision makers (Bicking, Troitzsch, & Wimmer, 2010*)* to provide support for understanding the potential implications of decisions in complex situations as for example technology adoption (Nuttall et al., 2009; Hamilton, Nuttall, & Roque, 2009) processes.

Agent-based models of consumer behavior integrate economic, marketing, psychology, sociology, engineering and computer sciences. For example, de Haan and colleagues (2009) use an agent based micro-simulation model of consumer choice of new cars to assess the potential occurrence of rebound effects, including potential direct rebound effects (more vehicles being purchased, increase in average car size, more kilometers being driven) but excluding indirect rebound effects (increased consumption of other goods or services).

4.1.3 Agent Based Modeling for research activities

Axelrod (2007) put forward the notion of simulation as a third way of undertaking scientific research, after induction – i.e. the discovery of patterns in empirical data (not to be confused with mathematical induction)- and deduction – that involves specifying a set of axioms and proving consequences that can be derived from them. According to Axelrod (2007) "starting with a set of explicit assumptions, simulation does not prove theorems but instead generates data that can be analyzed inductively, as a way of conducting thought experiments. Some questions can be answered with simulation experiments". Referring to Axelrod and Tesfatsion (2005):

> *Simulation in general, and ABM in particular, is a third way of doing science in addition to deduction and induction. Scientists use deduction to derive theorems from assumptions, and induction to find patterns in empirical data. Simulation, like deduction, starts with a set of explicit assumptions. But unlike deduction, simulation does not prove theorems with generality. Instead, simulation generates data suitable for analysis by induction. Nevertheless, unlike*

> *typical induction, the simulated data come from a rigorously specified set of assumptions regarding an actual or proposed system of interest rather than direct measurements of the real world. Consequently, simulation differs from standard deduction and induction in both its implementation and its goals. Simulation permits increased* ***understanding of systems through controlled computational experiments****.*

There are several possible goals of simulation and Axelrod (2007) lists seven of them: prediction, performing tasks, training, entertaining, educating, existence proofs, and discovery; prediction, existence proofs, and discovery are the main scientific contributions.

Axtell (2000) explains as exist three distinct uses of agent modeling techniques. One such use — the simplest — is conceptually quite close to traditional simulation in operations research. This use arises when equations can be formulated that completely describe a social process, and these equations are explicitly soluble, either analytically or numerically. In the former case, the agent model is merely a tool for presenting results, while in the latter it is a novel kind of Monte Carlo analysis.

A second, more commonplace usage of computational agent models arises when mathematical models can be written down but not completely solved. In this case the agent-based model can shed significant light on the solution structure, illustrate dynamical properties of the model, serve to test the dependence of results on parameters and assumptions, and be a source of counter-examples.

Finally, there are important classes of problems for which writing down equations is not a useful activity. In such circumstances, resort to agent-based computational models may be the only way available to explore such processes systematically, and constitute a third distinct usage of such models (Axtell, 2000).

A simulation might attempt to explain a phenomenon or it might attempt to predict the outcome of a phenomenon. It might be used to explore a phenomenon, to play, in order to understand the interactions of elements of the structure that produces the phenomenon.

4.2 Conclusions

Exploration is perhaps the most interesting example of what can be done in research activity with simulation models. It allows answering several research questions. How sensitive is the model behavior (and hopefully the real-world behavior) to changes in the behavior of a single actor, or of all actors, or of the limits of interactions between players? Under what conditions does it change to another general form of behavior? Just what ranges of behavior can the system generate? We will to answer in the next chapters.

5. BUILDING BLOCK: ENVIRONMENTAL AWARENESS SPREAD AND ITS EFFECTS ON LIMITED RESOURCE CONSUMPTION

5.1 Introduction

The prevailing Global North[33] life style is not sustainable in terms of energy consumption, carbon dioxide emission, and depletion of scarce resources.

Solutions to the sustainability problem can only be found in a combination of technological and social developments. For example, energy saving has emerged as an important issue, but there are many steps to take until it becomes a social practice, supported by *accepted technologies*. The role of technology may be to increase energy efficiency or to give energy feedback, both of which have to become part of social practice to be effective.

In this chapter we focus on the basic insight from social psychology that individuals are influenced by the decisions, actions, and advice of other individuals, both consciously and unconsciously. Understanding how and when "social influence" arises should therefore be considered as a central component in any theory of collective social behavior. The chapter introduces some basic building blocks for a model of mechanisms of social interaction and their effects on environmental collective behavior. As mentioned in previous parts, the overall goal of the presented research is to study how to reduce (or to optimize) the consumption of a limited resource, leveraging on social norms and environmental awareness. We look at the individual behavior from a perspective that goes beyond the traditional "homo oeconomicus" paradigm by including psychological and societal influential mechanisms, which may lead to more sustainable consumption patterns.

The integration of a new service - namely an ICT-based service- into current household practices is not straightforward. To be correctly used, instruments have to be appropriated, i.e. contextualized in daily routines. The *appropriation concept* is used to describe *how users integrate objects into their lives*, households or network, i.e. into an existing network of objects, practices and meanings (Klopfert & Wallenborn, 2011; Pierce, Schiano & Paulos, 2010). Moreover they have to be perceived as tools to comply with social norms (Allcott, 2011). For example if household energy saving is an emergent social norm, smart metering functions are the tools allowing a choice architecture, as defined by Kinzig and colleagues (2013).

One way to extend the social norm is to use **rewards** for "good behaviors" (e.g. incentives, not necessarily financial). Community engagement can also be an effective tool, making use of social relations and networks, and moving social norms away from the acceptance of wasting energy.

A new emphasis is given to the role that social norms can play to foster behavioral changes toward more sustainable lifestyles. The main objectives are to explore how environmental awareness can drive behavioral changes toward sustainability and how the availability of smart metering functions can foster households in reducing or optimizing resource consumption. The chapter will not focus on rebound effects as such - a broader research field described in Chapter 2 - but on the **social aspects** that can play as **limiting factor** to avoiding or reducing them

5.2 Conceptual framework: environmental awareness, behaviors and social norms

Since several studies recommend to include behavioral patterns in environmental sustainability researches, so that circumstances can be introduced whereby beneficial impacts are promoted and the detrimental impacts are prevented as much as possible (OECD, 2010), we focus on the role that users, consumers or citizens can play in spreading and adopting beneficial behavioral changes.

While voluntary behavioral changes are usually driven by some kind of **reward**, namely individual short-term rewards, positive environmental effects happen in the medium-long run and only if a responsible life style is adopted by a collective of individuals where a social appraisal becomes the reward and defines a social norms. We have started to define the conceptual underlying conditions of such societal aspects in previous chapter. We have than to complete the conceptual framework referring it to environmental related concepts and behaviors, in order to can decline in a social computing dimension such social norm system.

---

[33] The economically developed societies of Europe, North America, Australia, and others

5.2.1 Environmental sustainability awareness

As mentioned in previous parts, purpose of the presented research is to explore the role of the environmental sustainability awareness level of people into driving their behavior, whether they are users, households, customers, or citizens. While the term "users" emphasizes the idea of an activity, households refer to a domestic place and include the persons living there. Customers have different rights and duties towards energy suppliers, whereas citizens are people belonging to a public community, like e.g. a city, a town, a district or a specific building. Those terms will be all used.

In chapter 3 we supplied the awareness definition. One of main **research contribution** consists of an **analysis of the spread of awareness** among agents and their neighbors. Because neighborhood's relationships can be topologically or socially defined or given by a mix of them, the concepts as social influence and threshold models - taken from analytical sociology that are more and more popular in social network analysis - have to be declined in a environmental sustainable dimension.

In Chapter 3 we have shortly mentioned as a research area of growing importance inside social network analysis is now focusing on a special case of influence response functions - namely threshold functions, according to which individuals adopt a new *state* based on the perceived fraction of others who have already adopted the same state. The classical Granovetter's threshold model (Grannovetter, 1978) has been adapted in research works to a network framework where in contrast to the all-to-all assumption, individuals are assumed to be influenced directly only by a small subset of immediate "neighbors" - a more realistic assumption. **One of the assumptions of this thesis is that the influence on individual is given by a direct influence of the neighbors in a given radius of influence and by a reinforcement of the agent believes.** The notion of **social diversity** (Uganders et al., 2012) is introduced in order to simulate a network of neighbors composed by different **types of agents**, which are more or less influential on the basis of their **type**.

5.2.2 Environmental challenges, behavioral changes and social norms

To face environmental problems governments have to change people's behaviors (e.g. reducing material consumption).

There are two forces that can have impact on behavior. One is linked to government actions and a second one is linked to social pressure.

Decision makers have several instruments to push towards a behavior change.

These instruments are:

- Active norms management: advertising, campaign, appeals
- Financial interventions: taxes, fines, allowances, subsides
- Regulations: laws, standards
- Changing architecture: making desired behavior more convenient.

Each of these policy instruments potentially influences personal in different ways. All these instruments can be more or less effective, but all of them require funds and new expenses, and sometimes, despite great efforts, results are poor (e.g. the prohibition law against alcohol in the U.S.).

Environmental friendly behaviors, to make the change effective, have to be adopted by the majority of the population (Kinzig et al., 2013). Social Norms and Global Environmental Challenges: the Complex Interaction of Behaviors, Values, and Policy

The researches of Kinzig and colleagues (2013) focus on the complex interaction of behaviors, values, and policy and link the concept of social norm to environmental challenges. Kinzig and colleagues refer to a research track on social consensus related to the notion of committed minorities (Xie et al., 2011; Lu, Korniss, & Sztmanski, 2009; Biswas & Sen, 2009) and their influence in the consensus process. Some researches use the notion of "tipping point" that is reached when the change in behavior is attained by a certain part of the population - the rest will follow (Xie et al., 2011).

Voluntary behavioral changes are usually driven by some kind of rewards; in some cases adopting a new lifestyle has a reward in itself. For example after quit smoking or going on a diet one feels better or looses weight and this effect is perceived as individual immediate positive feedback. As far as an environmentally sustainable life style is concerned, economic rewards are not strong enough to trigger a behavioral change, as for example in the case of energy costs, as showed in Figure 7 of Chapter 2.

Other reward mechanisms are not at an immediate and individual level. Only when a responsible life style is adopted by a collective or by a group of individuals some positive environmental effects will happen in the long run. If the adoption of a sustainable behavior is driven by awareness and such awareness shifts from an individual dimension to a shared collective one, this turns a social appraisal into the most effective reward. Such mechanism is the trigger for a social norm.

A **social norm** can be defined (Ellickson, 2001) as "a rule governing an individual's behavior that third parties other than state agents diffusely enforce by means of social sanctions". The idea of social sanction is strictly related to the notion of social reward.

If an environmentally friendly behavior becomes a social norm it will be carried on without any need for controls, fines or law enforcement. According Kinzig and colleagues (2013) "Effective policies are ones that induce both short-term changes in behavior and longer-term changes in social norm".

The individual regardless of what others may think chooses personal norms. The individual himself sets these norms and feels guilty if he is not respecting them or feels pleasure when he is respecting them. Social norms are persistent and, once adopted, will be followed even after the state intervention ceases.

Changing the conditions influencing behaviors**,** often referred as "*choice architecture*", is related to make behaviors more convenient and more visible, e.g. recycling rates increase when recycling containers are widely scattered (there is one near every apartment block) and can be used for all materials (glass, plastic, paper etc.) so there is no need to recycle different materials in different places. Making behaviors convenient may strengthen both personal and social norms. Making behaviors more visible is showing people what others are doing.

Sociotechnical ICT-based systems, as smart metering advanced functions, can be pivotal for effectiveness of social norms, because implement the above mentioned notion of "choice architecture" (OECD, 2011).

5.2.2.1 Typical human behavior in relationship to energy consumption

People use energy at home and at work, but it is largely invisible. For most of them electricity just comes out of a socket in the wall. Most people do not think about the energy they are using and their energy consumption is measured on devices they barely know that they exist. At home their monthly bills serve as a reminder that they spent too much but with no indications how they can change their behavior to use less. At work, they may not get any feedback at all and they often do not care because someone else will pay the bill.

5.2.2.2 Issues with encouraging changes in energy consumption

Feedback information (from bills or sensors) is complex and dull. Interactions with energy information usually are poorly designed to modify behavior. It is difficult to draw correlations between actions and consequences -standard metering results in data being aggregated on a monthly basis, such that determination of when and where energy is used is difficult.

Models of motivation are limited and too often focus on monetary incentives alone. Whereas larger-scale users (large businesses and organizations) find significant financial savings in small efforts multiplied across the organization, individuals usually have no sense of the broader impact of small changes.

Attention to other forms of motivation needs to be explored, including the interaction with social context.

These problems all involve the **intersection of individual as well as group behavior and technology**. Only if the community as a whole changes its behavior, can technology succeed. And only if individuals are willing to change can the community change.

To understand other aspects of motivation in the energy domains, a study of Boulder residents (Farhar, 2009) surveyed what factors influenced involvement in the SmartGridCity project.

These findings identified the following motivational factors:

- Practical: "I will benefit from it." Reasons included getting feedback on electricity consumption, saving money, and gaining knowledge.
- Altruistic: "I want to do something helpful." Reasons included reducing environmental impacts, helping collect data, and caring about the planet.
- Technical: "I want to know more about what they're doing." Reasons included professional interest, technological curiosity, and staying informed about what's happening around town.

- Moralistic: “We should all do what is right.” Reasons included helping others become more aware, encouraging personal responsibility, and generational equity.

5.2.2.3 Smart metering functions as enabling factors

Three different points of view about the smart meter can be introduced (Klopfert & Wallenborn, 2011):

1) It is conceived as a tool to raise consumer awareness and promote energy savings;
2) It is considered as part of the smart grid;
3) It is a tool for changing the electricity market.

The thesis looks at smart metering functions from the first point of view of increased awareness and energy saving perspective, as facilitators of households in changing their behavior (OECD, 2011). They can empower households giving them the ability to perform actions that lead to a better awareness of the effects of their behaviours.

From the point of view of consumers, one feature of smart meters is to provide accurate information about consumption during a given interval of time, usually known as “feedback”. There are basically two kinds of feedback: historical or real time. Historical feedback gives information on what happened. Its frequency and format are variable; it requires interpretation and advice. Real time feedback gives the instantaneous consumption and draws the attention on what is happening. This therefore requires a specific display, usually designed to be mobile or clip-on, and linked to the smart meter. For users, this display device takes different names: in-house displays (IHD), Real-time display (RTD), energy monitors, etc. In the thesis we refer mainly to IHD and, in particular, to related ICT-based smart functions. Another important feature is the comparison with neighbors.

5.3 Conclusion

To allow and improve the understanding of above described mechanisms we propose an Agent Based Model approach to study the individual behaviors in household energy consumption and in energy consumption reduction. We will propose in the next chapter a conceptual model to explore awareness spread and the importance of facilities provided by advanced smart metering functions to turn such extended awareness into more sustainable behaviors. We will describe the implementation of this model in Chapter 7.

6. A MODEL FOR AN ENVIRONMENTAL AWARENESS APPROACH TO SUSTAINABILITY

6.1 Assumptions of an awareness-driven model of limited resource consumption reduction

6.1.1 Limited resource and sustainability at a local scale

Environmental sustainability addresses the issue of limited resources availability and the risk of its overuse. In principle limited resource availability would lead to competition among users and such a competition can be represented in different ways, for example as "the market". Those ideal mechanisms are actually triggered in a community (i.e. a limited area of households) when the community consumption variation is strong enough to lead to scarcity (or it is perceived as risky). When the relative size of the limited resource consumption is not large enough to significantly modify its direct availability, competition is not triggered. As pointed out in the introduction, the relative scale is important (Conceptual Framework Working Group of the Millennium Ecosystem Assessment, 2003). If the scale of the system we want to model is smaller than a certain level, this competition mechanism is not triggered in the population of such a system.

The spatial extent of the proposed model is an urban district or a geographically limited area of a Global North country, where usually the resource (energy as well water) is supplied by utilities companies. Energy - as well as water - is not immediately perceived in an urban community of the Global North as a limited resource, because everybody can buy as much as he wants. Nor its price is affected by a possible immediate overuse. No competition - in traditional terms - for the limited resource is triggered among agents because the resource is available at a geographically limited urban area level and is possible to buy it without a direct perception of its price modification.

Assumption 1: No market competition mechanisms for the limited resource at the system scale.

While a "common good" - modeled by Janssen and colleagues (2009) in their experiments about Common Pool Resource dilemma - is a resource shared by multiple users that can consume it without limitation because it is collectively owned by everybody, in the present case energy is not a common good because such resource is traded on the market.

Assumption 2: The limited resource is not a common good

6.1.2 Resource consumption reduction and sustainability

Nevertheless resource usage has to be reduced (or optimized) for environmental related issues. A resource can be defined as "environmentally critical" if its consumption has to be reduced, regulated or optimized (in case of agents that are *prosumers* instead of consumers) for reasons related to environmental issues. Such reasons can be, for example:

- availability is different in given periods (of the day in the case of energy, of the season in the case of water);
- availability depends on external uncontrolled factors (like e.g. energy supply from foreign countries and their dirty sources);
- resource consumption increases GHG production:
- there are mechanisms leading to rebound effects and nullifying efficiency improvements;
- availability and optimal use depends on peak hours and consumption patterns have to match such a constraint to avoid losses or overuses.

As consequence of such items the resource consumption has to be reduced. Such a goal can be perceived as an emerging social norm. An environmentally aware behavior takes into account such a resource as "environmentally significant".

Assumption 3: Resource consumption has to be reduced to reach environmental sustainability.

Energy, for example, has to be reduced for several different reasons, most of them listed above and related to environmental issues and such perception is shared by citizens of a specific area. Energy reduction is becoming a social norm, and there is an agreement about the need to reduce its consumption (or to optimize it in a smart grid system).

The consumption reduction need is triggered not by direct perceived limited availability, but by social norm, playing the role of limiting factor, in terms of collective rewards and punishments.

The purpose of our model is to explain and better understand the mechanisms leading a group of households *to perceive* a resource as "critical" for environmental sustainability and to try and reduce its consumption.

An overall goal of our model is to support decision makers in local sustainability programs or campaigns. Often environmentally motivated reduction programs and behavioral changes programs are launched by local government or by utilities companies, like in Western Australia (Anda et al., 2013).

The idea is to pivot on social norms (instead of prescriptive norms) as triggers for voluntary individual behavioral changes to reach the sustainability goals.

The idea, as described in previous chapters, is that environmentally oriented consumption styles are driven but by social mechanisms. A key principle to deal with those issues is "**sufficiency**". The sufficiency constraint is strictly linked with the concept of **limiting factors**. Traditionally policy interventions are playing at a general level to give limiting factors in terms of laws or economic measures. Without going in details about the effectiveness of tax policies or incentives, as already mentioned, the proposed model plays at a different dimension: the social dimension.

In such a dimension it is matter of social norms and **personal reputation** in a **social institution**. Social norms are able to penalize someone who tends to an overuse. Such limiting factor is more effective than, for example, market prices mechanisms that are not heavy enough to modify behaviors only for economic motivations, as discussed in Chapter 2.

Assumption 4: Voluntary behavioral changes are triggered by social influence and the limiting factor is socially driven.

To give a description of the proposed model of awareness spread and resource consumption, the ODD (Grimm et al., 2010) protocol, as widely used for ABM (Schreinemachers & Berger, 2011) is supplied, in Part three.

6.1.3 Other assumptions

By default the limited resource is overused by the most part of agents. The consumption is not sustainable and some consumption reduction is mandatory for long-term sustainability.

The resource to be reduced is energy, but could be as well water or other resource supplied by a utility company/supplier.

There are some smart metering functions and they are available in different combinations. Their availability empowers agents, as discussed below.

The system starts when an overall reduction goal is defined and stops when it is reached.

6.2 The model purpose

The model simulates the micro-behaviors of individuals about a limited-resource consumption. The resource is overused by the most part of individuals and some consumption reduction is mandatory for long-term sustainability. The Agent Based Model (ABM) aims to represent at a macro-level how awareness can spread in the community, how the dynamic of such awareness can impact on individual reduction goals and consumptions, how the availability of smart metering functions can impact on the consumption and reduction behaviors. The awareness of individual agents is defined by the influence of influent agents in the surrounding, by a general perception of environmental aptitude of the community, by a social reinforcement about the concordance of individual and collective consumption trends. The *main purpose* is to observe at a macro-level how *a social norm emerges* about sustainability.

6.2.1 The resource

The limited resource considered here is energy, but could be water as well. It has to be reduced and there is an overall reduction goal to be reached. Agents cannot know the overall reduction goal value.

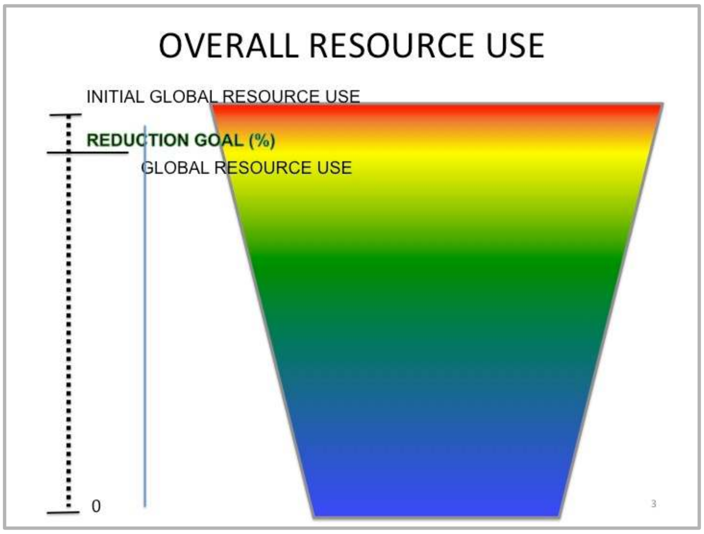


Figure 8 - Overall resource use

6.2.2 The agents

Agents are households, living a fixed and defined area. The size of the group of such households is such that overuse does not lead to market price increasing. That means the people detracting environmental issue with an unaware environmental behavior have not price mechanism to counter their overconsumption. Green people, i.e. people with high awareness, can decide to limit their privacy rights about their own consumption information and accept to share with the community their own consumption data. Such voluntary mechanism of "privacy versus reputation" is an emerging trend. Becoming a green *opinion leader* is a goal to reach (Griskevicius, Tybur & Van den Bergh, 2010; Wesley Shultz, Nolan, Cialdini, Goldtsein, & Griskevicius 2007).

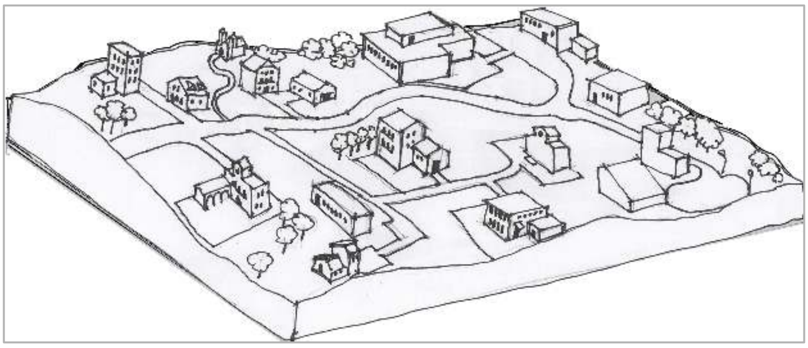


Figure 9 - A geographic area with households

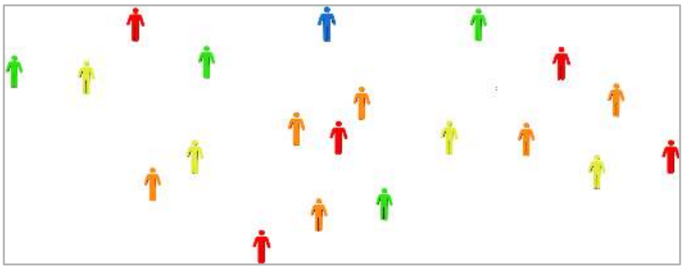


Figure 10 - The agents

Agents do not move and their position is always the same.

Each agent is a consumer of the limited resource and has his **own resource consumption**[34] (own) that changes each run. The own resource consumption is given by the difference with the previous run and a **reduction goal** (rg) that is reached with a certain **rate**, W. The reduction goal and the rate to reach it are different type by type.

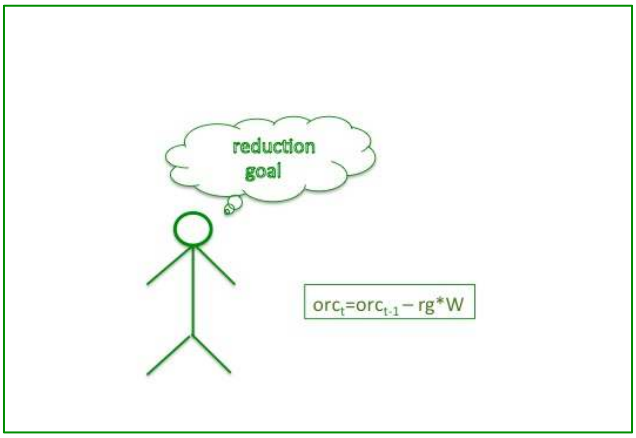


Figure 11 - Reduction goal and individual own resource consumption of an agent

An agent can be empowered by the availability of some smart metering functions. In other word, households share the potential availability of infrastructure for some smart metering functions that are part of the background infrastructure.

Such four smart functions are:

- In-home metering;
- Individual feedback about the individual own consumption of the limited or critical resource;
- Information about green leaders and their low consumption profile, that are taken as reference;
- Personalized advice for consumption reduction.

Each smart function affects the consumption pattern of the agent.

6.2.3 Agent typing

The notion of social diversity is introduced in order to simulate a network of neighbors composed by different types of agents, which are more or less influential on the basis of their level of environmental awareness. There are five types of agent: blinds, indifferents, spectators, actives, and evangelists[35].

- Blind agents have negative environmental behaviors. As detractors of the need to prevent an overuse of the resource, their reduction goals are negative: their resource consumption increases. Their awareness level is the lowest, can be negative and they have a significant negative influence on neighbors. They became more aware only if a significant part of their neighborhood is green and if social norms became really significant, but usually they don't increase enough their awareness to change type. They are sensible only to negative social reinforcement. They are mocking other agents. Their consumption patterns are independent of the smart metering functions that instead empower others types of agents.

- Indifferent agents are neutral about the environmental sustainability goal. They usually compose the larger group in the initial configuration. Their consumptions are constants, with only some possible small reduction under very specific conditions, i.e. when they are supplied with some combination of smart metering functions. They don't have influence on neighbors, but are influenced by them. They are responsive to positive or negative social reinforcement.

---

[34] Own resource consumption is the term used to indicate the individual resource consumption of an agent.

[35] The use of the term "evangelist" is taken from the innovation field jargon, where is widely used without any religious meaning.

- Spectator agents are quite stable in their behavior, but are open to listen and to observe their neighbor's behaviors. Under the availability of smart metering function they become able to measure, to compare and to understand and accept suggestions, as well as active and evangelist agents. They can have reduction goal. They don't have influence on their neighbors, but are influenced by them. They are responsive to positive or negative social reinforcement.

- Active agents are "aware people", engaged into reduction of resource consumption. They have a significant positive influence on neighbors. They allow other people to look at their own data in order to show beneficial behavior results and to share reduction goal with other. They are responsive to positive social reinforcement.

- Evangelist agents are green activists that, in addition to actives, are able to supply new resource into the system, by producing the resource, for example when they produce renewable energy at a local scale with solar panels[36]. They have a strong influence on neighbors, but are not influenced by them. Their awareness never decreases. They are responsive to positive social reinforcement.

Each type of agent has different awareness and consumption reduction patterns, as described below. In Table 1 are supplied examples of electricity saving, as well as water saving actions, that can be performed by five types of agents. Activist agents (evangelists) are also able to addict new resources into the systems. In the case of energy they are energy *prosumers*, in the case of water they are recyclers. *Consumption patterns have reduction patterns.*

Agent	**Electricity Saving Action Examples**	**Water Saving Action Examples**	**Effect**
Blind (mocking others)	Leaving all lights on for neighborhood to see	Leaving on sprinklers on garden for neighborhood to see	Negative = increasing usage
Indifferent (no diffusion)	Reducing heating/cooling thermostat slightly	Not leaving tap running when brushing teeth	Neutral = small decreasing usage
Spectator (no diffusion)	Turning off a light when not needed	Reducing garden irrigation time	Positive = medium decreasing usage
Active (showing others)	Use washing machines full loaded in off-peak period	Taking shorter showers	Positive = large decreasing usage
Evangelist (encouraging others)	Installing solar photovoltaic power system	Installing rainwater tank or grey-water reuse	Positive + additive = Decreasing usage and recycling

Table 1- Example of reduction patterns

An agent belongs to one and only one type at time. **Agents interact** between them **by proximity** and **cannot move** around. According to the number and the type of neighbors in a given radius of influence each agent changes his awareness. The size and kind of influence of neighbors in a given radius depends on their type. Different types of agents influence differently the awareness of their neighbors.

---

[36] Or by recycling the resource, for example when they recycle water for gardening irrigation.

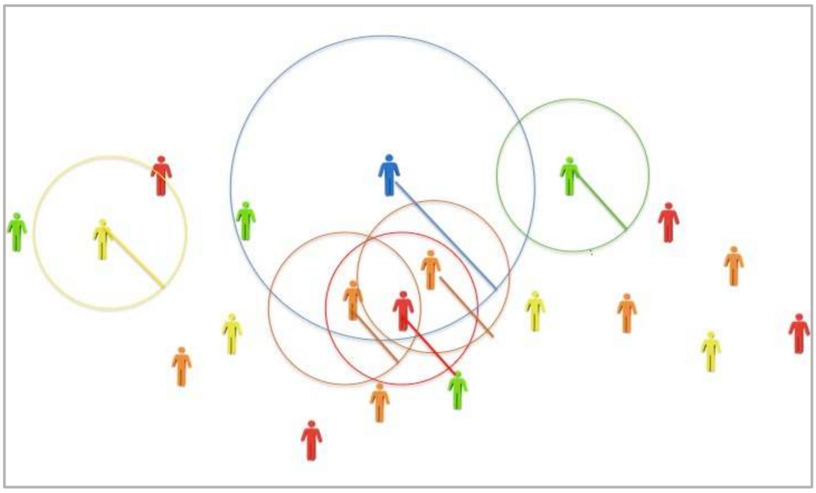


Figure 12 - Influence radius

Such influence radius is double for the evangelist agents. Another influence mechanism is social reinforcement. Awareness is also modified by influence of a whole “green” attitude of the community, as we will see later.

6.2.4 Agent behavior

The agent is a consumer of energy, he can have an individual reduction goal, and can be empowered by the availability of some smart metering functions. The agent has its own resource consumption that changes each run. The own resource consumption of an agent is given by the difference with the previous run and a reduction goal that will be reached with a certain speed, W. The reduction goal and the rate to reach it are different type by type.

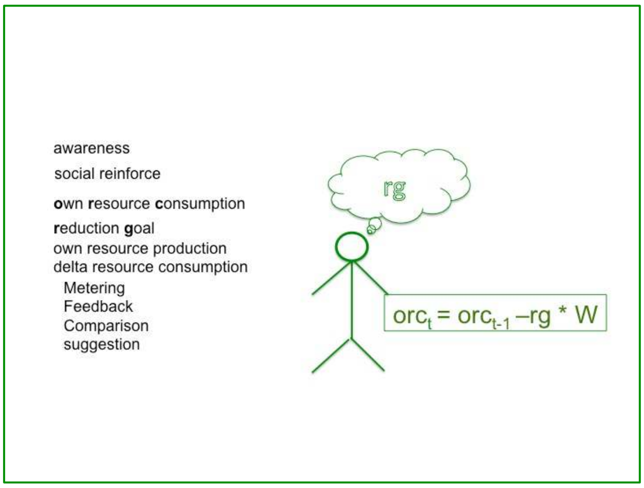


Figure 13 – Agent attributes: reduction goal and individual own resource consumption of an agent

Agent has several attributes. A fundamental attribute is the **awareness**. Awareness is quantified by an “awareness level”, increasing as the agent acquires knowledge and sensibility about environmental issues in general and in particular on the effect of his own behavior on the specific case. It is affected by several factors. The awareness level can change by interaction with neighbors and the change happens under different conditions (depending on other agent types and number, and on the general system conditions). Awareness level is a numerical quantity.

The threshold level of an agent for changing the type to belong to is different from each agent type. More aware agents have a higher threshold to shift to a most aware type, but they can never decrease their

awareness and their awareness increases faster than in other less aware agents. There is a cascade effect, limited only by the influence sphere of the agents. Threshold levels activate the switch of type.
While every agent can increase or decrease their awareness level, ***evangelists are committed agents***, while **blinds** are **quasi-committed** agents. All awareness levels that typify an agent as indifferent, observer, activist, or evangelist can increase or decrease by interaction with neighbors. The threshold to change the status is different from one level to another. The threshold to shift from activist to evangelist is higher than other thresholds. There is another feature of agent, the one that can influence the awareness level that is a kind of *aptitude to a social behavior.* Different types have different patterns of consumption and of reduction.

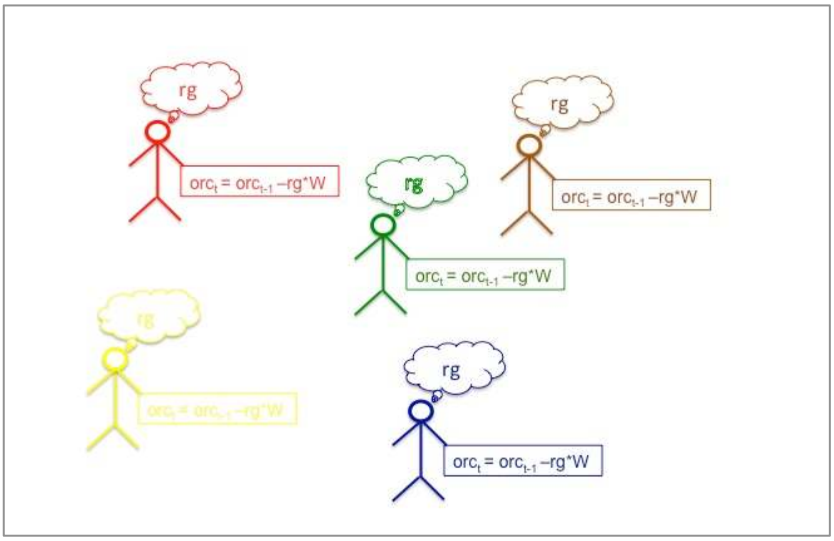


Figure 14 – Agent types and their own individual consumption

When the above-mentioned smart metering functions are available, they can empower agents allowing them the ability to perform some actions. Agents can become able to measure the resource consumption, to have an individual feedback about his own consumptions, to have a comparison with other agents and to receive suggestions and advices about resource consumption reduction.

Some smart metering function can impact the individual consumption in several ways. When the agent is able to perform metering and comparison, his reduction goal is more ambitious (see for details ODD in the next chapter).

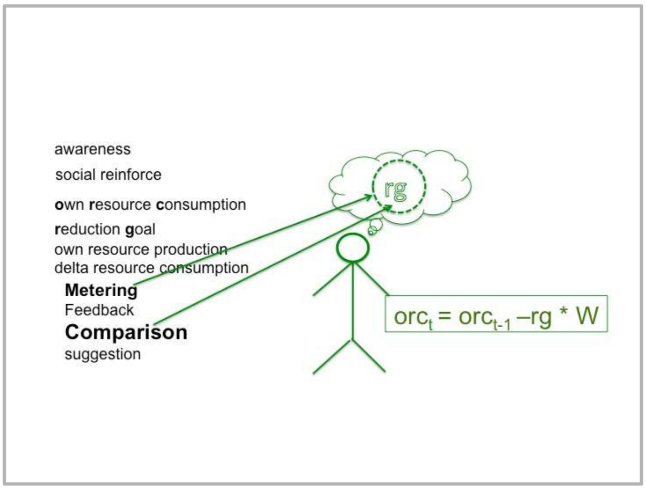


Figure 15 - Agent able to measure and compare with neighbors has a more ambitious reduction goal

When an agent is able to have feedback about his historical consumption or to receive suggestion the rate to reach the reduction goal is larger.

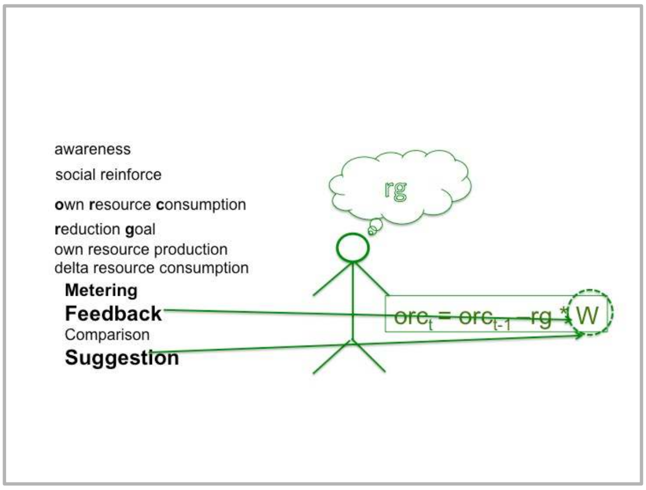


Figure 16 - Agent able to metering and feedback is quicker in reaching reduction goal

Awareness is modified also by a mechanism of **social reinforcement**. There is a comparison between the individual agent consumption trend and the global resource use trend. When they are concordant there is positive social reinforcement and such social reinforcement is added to the awareness, increasing it.

The system identifies both individual consumption trend types (i.e. reduction versus increment) and an overall consumption trend.

The agents know the global trend about the resource consumption, but not the overall reduction goal nor the global resource use level (see figure 8). When their behavior trends are concordant with the general consumption trend, the agents can "reinforce" their beliefs and this social reinforcement, in turn, changes their awareness. The general consumption trend is the relative difference of the global resource level (GRL).

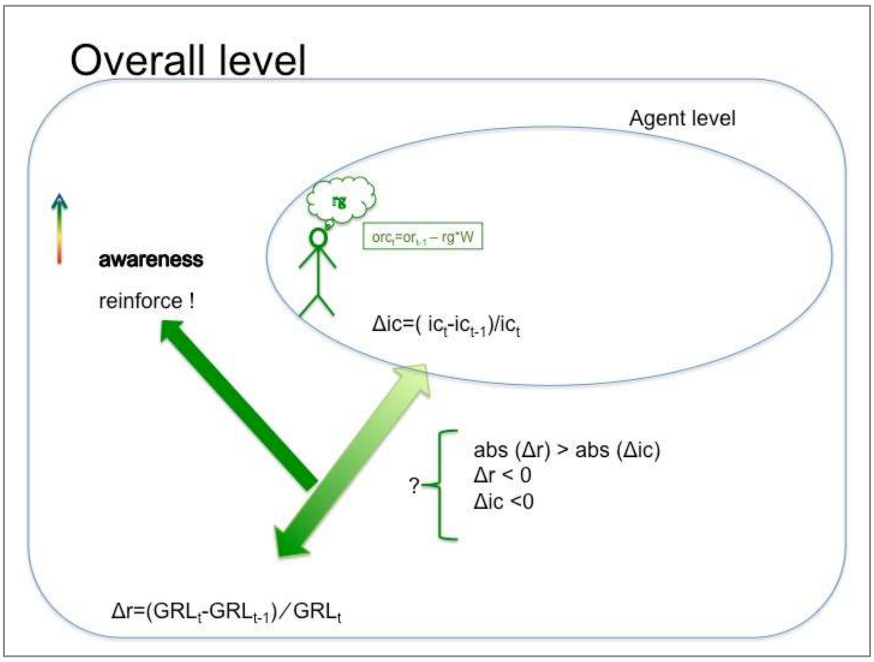


Figure 17 - Positive reinforcement and awareness enhancement

Positive reinforcement happens when both individual both global consumption trends are of reductions.

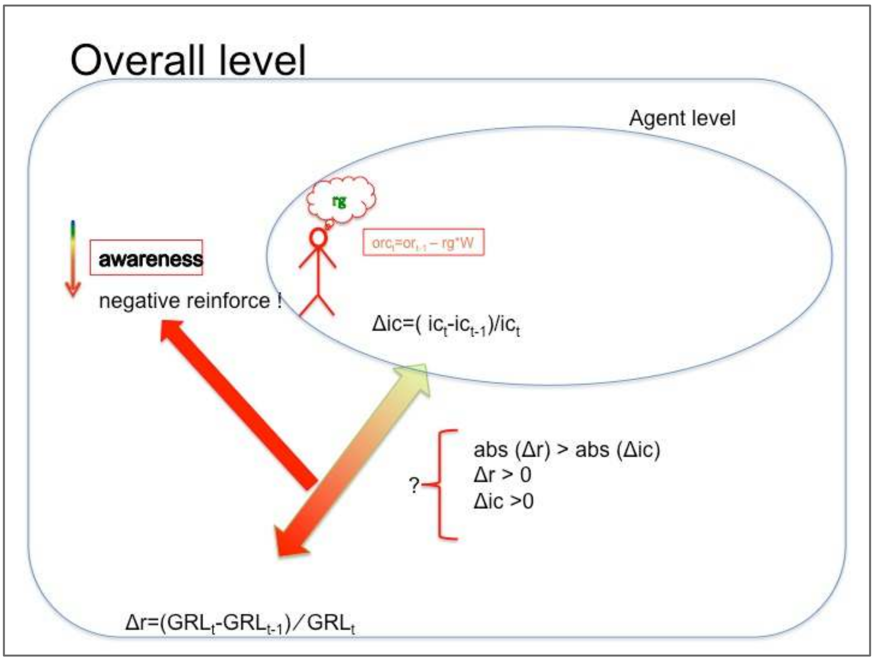
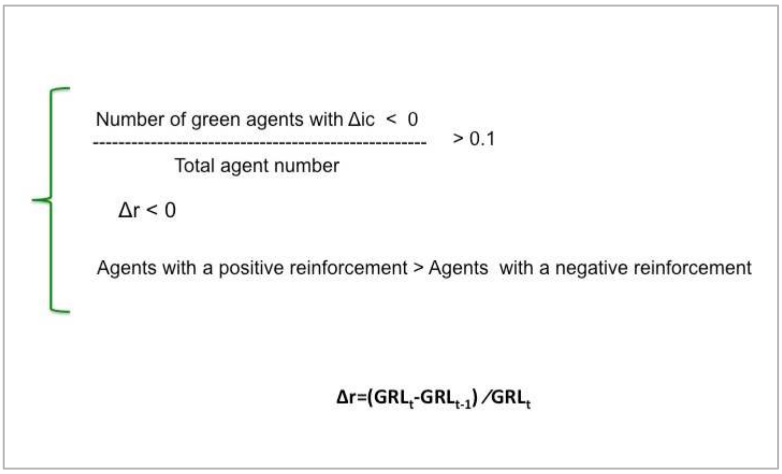


Figure 18 - Negative reinforcement and awareness decrease

Negative reinforcement happens when both individual both global consumption trends are of increasing.
In other words awareness changes by local and global influence of neighbors and by social reinforcement. By changing awareness an agent can change the type he belongs to and such type determines new consumption/reduction patterns.
An empirical definition of social norm widely used in the research area of global environmental challenge (Kinzig et al. 2013) said that when enough people or certain people, e.g., those with disproportionate social influence (Christakis & Fowler, 2009) adopt these norms, there may be a tipping point (Gladwell, 2000; Levin et al. 1998) such that the proenvironment norms become widely shared and environmentally friendly behaviors become pervasive. We consider this relationship between social norm and tipping point a key for our research and we decided to introduce it in our model.
According to the researches of Xie and colleagues (2011), we suppose that the tipping point depends on a low 10% of the population, if the minority is "consistent and inflexible" in its beliefs. Before giving a definition of **tipping point** toward a **social norm,** we have to introduce the notion of committed and quasi-committed agent.
For us committed agents are evangelists, i.e. the most aware and influent agents, while actives and blinds are "quasi-committed" agents. The notions of commitment and "quasi-commitment" are useful notions when linked to the concept of social reinforcement. Once a committed (evangelist) or quasi-committed agent (a blind or an active) is reinforced in his belief, this reinforcement is persistent and the agent remains reinforced as it was (positively or negatively), while not committed agents (spectators and indifferents) are responsive to positive or negative reinforcements.



$$\begin{cases} \dfrac{\text{Number of green agents with } \Delta ic < 0}{\text{Total agent number}} > 0.1 \\ \Delta r < 0 \\ \text{Agents with a positive reinforcement} > \text{Agents with a negative reinforcement} \end{cases}$$

$$\Delta r = (GRL_t - GRL_{t-1}) \,/\, GRL_t$$

Figure 19 - Tipping point toward sustainability

We define a tipping point as condition becoming true when the number of committed (or quasi committed) agents adopting a behavior is at least the 10% of the population and their consumption trend is concordant with the overall consumption trend and the number of agents with concordant reinforcement is greater than the number of agents with concordant reinforcement of other sign.

Only evangelist agents produce resource. The overall use of the limited resource is given by the difference between consumption and production.

The overall consumption is given by the sum of the consumption of the agents.

When a global reduction goal is someway established the system reaches such a goal several runs after such the tipping point is defined. We can say that a sustainability social norm emerges.

The proposed ABM aims to study the relationship between the tipping point for a sustainability social norm and the goal reaching. The smart metering functions empower agents.

If they are made available in already sustainable contexts they short the time needed to reach the reduction goal. When they are introduced in a not sustainable context (see Chapter 8 for scenario examples), they can allow to change the trend of collective behaviors and to allow the emergence of a sustainable behavior.

The system is composed by a set of agents. Individual agent behaviour can consist in:

a) to consume the resource
b) to produce the resource (as a *prosumer*)
c) to identify which quantities to take into consideration, and to measure his own consumption of this quantity
d) to receive, understand and apply suggestions
e) to receive feedback from own individual historical consumption
f) to compare with friends/colleagues/neighbors his own consumption
g) to accept to show his own consumption and share it with neighbors

The item a) is a feature of all type of agents, while b) is only of evangelists. Items from c) to g) are activated by the availability of the related specific smart metering functions, differ for different types of agent and affect the individual resource consumption. Items e), f), g) are activated only for more aware agents, i.e. spectators, actives and evangelists.

Local influence derives from interactions with agent's neighbors. Agents are reactive, initiating their actions to achieve their internal goals, and responding to others. Agent state can change continuously by the interaction with other agents.

REFERENCES

Abrahamse, W., Steg, L., Vlek & C., Rothengatter, T. (2007). The Effect of Tailored Information, Goal Setting, and Tailored Feedback on Household Energy Use, Energy-Related Behaviors, and Behavioral Antecedents. *Journal of Environmental Psychology*, *27*(4), 265–276.

Allcott, H. (2011). Social norms and energy conservation. *Journal of Public Economics, 95*(9–10), 1082 - 1095.

Anda, M., Le Grey Brereton, F., Breman, J., & Paskett, E. (2013). Smart metering infrastructure for residential water efficiency: results of a trial in a Behavioral Change program in Perth, Western Australia. In: L. Hilty, B. Aebischer, G. Andersson and W. Lohmann (Eds.), *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability.* ETH Zurich (pp. 116-122). DOI 10.3929/ethz-a-007337628

Axelrod R., & Tesfatsion, L. (2006). A guide for newcomers to agent-based modeling in the social sciences, in K.L. Judd & L. Tesfatsion (Eds.), *Handbook of Computational Economics, Vol. 2: Agent-Based Computational Economics* (pp. 1647-1658). Amsterdam: North-Holland.

Axelrod, R. (2007). Simulation in the social sciences. In J.P. Rennard (Ed.), *Handbook of research on nature inspired computing for economic and management* (pp. 90–100). Hershey: Idea Group.

Axtell, R. (2000). Why agents? On the Varied Motivations for Agent Computing in the Social Sciences, in Proceedings of the Workshop on Agent Simulation: Applications, Models and Tools. Chicago: Argonne National Laboratory.

Biswas, S., & Sen, P.(2009). Model of binary opinion dynamics: Coarsening and effect of disorder. *Phys. Rev. E* 80, 027101.

Borrill, P.L., & Tesfatsion, L. (2010). *Agent-Based Modeling: The Right Mathematics for the Social Sciences?*. Working Paper No. 10023, ISU Economics Department.

Borshchev, A., & Filippov, A. (2004). From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *The 22nd International Conference of the System Dynamics Society*. Oxford

Boulanger P., Couder, J., Marenne, Y., Nemoz, S., Vanhaverbeke, J., Verbruggen A., & Wallenborn, G. (2013). *Household Energy Consumption and Rebound Effect HECoRE* (Final Report). Brussels: Belgian Science Policy.

Castellano C., Fortunato, S., & Loreto, V. (2009). Statistical physics of social dynamics. *Reviews of Modern Physics. 81*(2), 591-646.

Christakis, N.A., & Fowler, J.H. (2009). *Connected: The Surprising Power of Our Social Networks and How They Shape Our Lives*. New York: Little, Brown and Company.

Cialdini, R. (2009). *Influence: Science and Practice*. 5th Eds. Boston: Pearson

Conceptual Framework Working Group of the Millennium Ecosystem Assessment. (2003). *Ecosystems and Human Well-being*. Chapter 5. *Dealing with Scale* (pp. 107–124). ISBN 155634030. London: Island Press.

Conte R., Gilbert, N., Bonelli, G., Cioffi-Revilla, C., Deffuant, G., Kertesz, J., Loreto, V., Moat, S., Nadal, J. P., Sanchez, A., Nowak, A., Flache, A., San Miguel, M., & Helbing, D. (2012). Manifesto of computational social science. *The European Physical Journal Special Topics, 214*(1), 325-34.

Costabile, M., Dittrich, Y., & Fischer, G. (2011). From Consumers to Owners: Using Meta design Environments to Motivate Changes in Energy Consumption. *Lecture Notes in Computer Science* 6654, 319-324. Doi: 10.1007/978-3-642-21530-8_33.

de Haan, P., Mueller, M.G. & Scholz, R.W. (2009). How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars − Part II: Forecasting effects of feebates based on energy-efficiency. *Energy Policy, 37*(3), 1083-1094.

Dick, H., Eden, H., & Fischer, G. (2011). From Consumers to Owners: Using Meta-Design Environments to Motivate Changes in Energy Consumption. In M. Costabile, Y. Dittrich, G. Fischer, & A. Piccinno (Eds.), *Proceedings of End-User Development - Third International Symposium, IS-EUD 2011, Volume 6654,* (pp. 319-324). Heidelberg: Springer Berlin.

Egger, S. (2006). Determining a sustainable city model. *Environmental Modelling & Software 21*(9), 1235-1246.

Ellickson, RC. (2001). The market for social norms. *American Law and Economic Review 3* (1), 1- 49.

Ehrhardt-Martinez, K., Donnelly, K.A., & Laitner, J.A.S. (2010). *Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities* (Report No. E105). Washington, D.C.: American Council for an Energy-Efficient Economy.

Epstein, J. M. (1999). Agent-Based Computational Models And Generative Social Science. *Complexity 4*(5), 41-60.

Epstein, J. M, & Axtell, R. L. (1996). *Growing Artificial Societies: Social Science from the Bottom Up*. The MIT Press

EC [European Community]. (2011). *Consumer 2020 From Digital agenda to Digital action* (Report).

Fagiolo G., Moneta, A., & Windrum, P. (2007). A Critical Guide to Empirical Validation of Agent-Based Models in Economics: Methodologies, Procedures, and Open Problems. *Computational Economics, 30* (3), 195–226.

Farhar, B. C. (2009). The Xcel Smartgridcity™ Project: Community Context and Household Perceptions. Presentation to *RASEI Brown Bag*, University of Colorado,

Fischer, G. (2012). Context-Aware Systems -The 'Right' Information, at the 'Right' Time, in the 'Right' Place, in the 'Right' Way, to the 'Right' Person. *Proceedings of the Conference on Advanced Visual Interfaces (AVI 2012* (pp. 287-294). Capri-Italy: ACM.

Fischer, G. (2011). Understanding, Fostering, and Supporting Cultures of Participation. *Interactions 18*(3), 42-53

Fischer, G. (2010). End User Development and Meta-Design: Foundations for Cultures of Participation. *Journal of Organizational and End User Computing, 22*(1), 52-82. doi:10.4018/joeuc.2010101901.

Fischer, G. (2009). End-User Development and Meta-Design: Foundations for Cultures of Participation. In V. Pipek, M. B. Rossen, B. deRuyter, V. Wulf (Eds.), *End-User Development* (pp. 3-14). Heidelberg: Springer.

Fischer, G., Piccinno, A., & Ye, Y. (2008). The Ecology of Participants in Co-Evolving Socio-Technical Environments. In P. Forbrig, Paternò, F. (Eds.), *Engineering Interactive Systems Lecture Notes in Computer Science 5247* (pp. 279-286). Heidelberg: Springer.

Engineering Interactive Systems. *Proceedings of 2nd Conference on Human-Centered Software Engineering*. Volume LNCS 5247, pp. 279-286.

Fischer, C. (2008). Feedback on Household Electricity Consumption: A Tool for Saving Energy? *Energy Efficiency*.

Filatova, T., Verburg, P.H., Parker D.C., Stannard, C.A. (2013). Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling & Software 45*, 1-7.

Froehlich, J., Findlater, L., & Landay, J. (2010). The Design of Eco-Feedback Technology. In: *Proceedings of CHI Conference*. (pp. 1999–2008). Atlanta :ACM.

Gardner, G. T., & Stern, P. C. (2002). *Environmental problems and human behavior (2nd ed.)*. Boston: Pearson Custom Publishing.

Ghorbani, A., Dignum, V. & Dijkema, G. (2011). An Analysis and Design Framework for Agent-based Social Simulation. In *Proceedings of the First International Workshop on Agent-Based Modeling for Policy Engineering (AMPLE 2011).*

Gilbert, N. (2005). *Agent-based social simulation: Dealing with complexity*.

Gilbert, N. (2008). *Agent-based models*. London: Sage publication.

Gilbert, N., & Terna, P. (2000). How to build and use agent-based models in social science. *Mind & Society, 1*(1), 57-72.

Gladwell, M. (2000). *The Tipping Point: How Little Things Can Make a Big Difference*. Little, Brown and Company.

Granovetter, M. (1978). Threshold Models of Collective Behavior. *AJS 83*(6), 1420–1443.

Greif, A., & Laitin, D. (2004). A Theory of Endogenous Institutional Change. *American Political Science Review* (4), 633-652. doi:10.1017/S0003055404041395.

Grimm, V, Berger U., U, DeAngelis D, Polhill, J. G, Giske, J., & Railsback, S. (2010). The ODD protocol: A review and first update. *Ecological Modelling, 221*, 2760-2768.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R.A., Vabø, R., Visser, U., & DeAngelis, D.L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling, 198*, 115–126.

Griskevicius, V., Tybur, J, & Van den Bergh, B. (2010). Going green to be seen: Status, reputation, and conspicuous conservation. *Journal of Personality and Social Psychology, 98*(3), 392-404.

Grodzins, M. (1957). Metropolitan Segregation. *Scientific American 197*, 33-47.

Harris, G. (2002). Integrated assessment and modelling: an essential way of doing science. *Environmental Modelling & Software, 17*, 201–207.

Haefner, J. W. (2005). *Modelling biological systems: Principles and applications* (2nd ed.). New York: Springer.

Hamilton, D.J, Nuttall, W.J., & Roques, F.A. (2009). *Agent Based Simulation of Technology Adoption.* (EPRG Working Paper 0923). Cambridge: Electricity Policy Research Group.

Holmes, T. (2007). Eco-Visualization: Combining Art and Technology to Reduce Energy Consumption. In *Proceedings of Creativity & Cognition* (pp. 153–162). Washington, D.C.: ACM.

Janssen, N.A., Radtke, N.P., Lee, A. (2009). Pattern oriented modelling of Commons Dilemma Experiments. *Adaptive Behaviour, 17*(6), 508–523. DOI:10.1177/1059712309342488.

Janssen, M. A., Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society, 11*(2), 37.

Janssen, M. A., de Vries, B. (1998). The battle of perspectives: a multiagent model with adaptive responses to climate change. *Ecological Economics, 26* (1), 43-65.

Kinzig, A.P., Ehrlich, P.R., Alston L.J., Arrow, K., Barrett, S., Buchman, T.G., Daily, G. C., Levin, B., Oppenheimer, M., Ostrom, E., & Sahari, D. (2013). Social Norms and Global Environmental Challenges: the Complex Interaction of Behaviors, Values, and Policy. *BioScience, 63* (3), 164-175.

Kirman, B., Linehan, C., Lawson, S., & Foster, D. (2010). There's a Monster in My Kitchen: Using Aversive Feedback to Motivate Behaviour Change. In *CHI 2010* (pp. 2685–2694).

Kletzan, D., Köppl, A., Kratena, K., Schleicher, S. & Wüger, M. (2002). Modelling Sustainable Consumption. Form Theoretical Concepts to Policy Guidelines. *Empirica, 29*, 131-144.

Klopfert, F., & Wallenborn, G. (2011). *Empowering consumers through smart metering* (a report for the BEUC). Brussels: the European Consumer Organisation.

Levin SA, et al. 1998. Resilience in natural and socioeconomic systems. Environment and Development Economics 3: 221–262

Ligtvoet, A., Ghorbani, A., Chappin E. (2010). A methodology for agent-based modelling using institutional analysis – applied to consumer lighting, In: *ATES 2010.*

Y. Liu, Y., Gupta, H., Springer, E., & Wagener, T. (2008). Linking science with environmental decision making: Experiences from an integrated modelling approach to supporting sustainable water resources management. *Environmental Modelling & Software 23*, 846-858.

Lorentz, A., & Woersdorfer, J. S. (2009). *Energy-efficient household appliances and the rebound effect – A model on the demand for washing machines*. Jena: Max Planck Institute of Economics. (Jena – June 2009).

Lu, Q., Korniss, G., Szymanski, B.K. (2009).The Naming Game in Social Networks: Community Formation and Consensus Engineering. *J Econ Interact Coord 4*, 221-235.

Macal, C.M. & North, M.J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation, 4*, pp. 151-162.

Nuttall, W.J., Zhang, T., Hamilton, D.J., & Roques, F.A. (2009). Sociophysics Simulations of Technology Adoption and Consumer Behavior. *Second International Symposium on Engineering Systems*, MIT, Cambridge, Massachusetts, June 15-17, 2009.

OECD (2011). *Greening household behavior: the role of public policy*. Paris: OECD Publishing.

OECD (2010a). *Greener and smarter – ICTs the environment and Climate Change*, Paris: OECD Publishing.

Ostrom, E. (1998). A behavioral approach to the rational choice theory of collective action. *American Political Science Review, 92*(1), 1–22.

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton, New Jersey: Princeton University Press.

Pierce, J.L., Kostova, T., & Dirks, K.T. (2002). The State of Psychological Ownership: Integrating and Extending a Century of Research. *Review of General Psychology* 7(1), 84-107. doi: 10.1037/1089-2680.7.1.84

Pierce J., Schiano D., & Paulos E. (2010). Home, Habits, and Energy: Examining Domestic Interactions and Energy Consumption. *Proceedings of CHI 2010 Conference*, April 10–15, Atlanta.

Railback, S.F., & Grimm, V. (2011). *Agent-based and Individual Based Modelling.* Princeton, New Jersey: Princeton University Press.

Salerno, J., Yang, S.J., Nau, D., & Chai, S.K. (Eds.) (2011). Social Computing, Behavioral-Cultural Modeling and Prediction. 4th International Conference, SBP 2011, College Park, MD, USA, 29-31, Springer-Verlag, Berlin.

Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology, 1*, 143-186.

Schreinemachers, P., & Berger, T. (2011). An agent-based simulation model of human environment interactions in agricultural systems. *Environmental Modelling & Software 26*, 845-859.

Sissa, G. (2013). An awareness based approach to avoid rebound effect in ICT. In L. Hilty, L. Aebischer, B. Andersson, W. Lohmann (Eds.), *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability (248-254).* ETH Zurich. ISBN I978-3-906031-24-8 DOI 10.3929/ethz-a-00733762

Smajgl, A., Brown, D.G., Valbuena, D., & Huigen, M.G.A. (2011). Empirical characterization of agent behaviors in socio-ecological systems, *Environmental Modelling & Software 26* (7), 837-844.

Staats, H., Harland, P., & Wilke, H.A. (2004). Effecting Durable Change. A Team Approach to Improve Environmental Behavior in the Household. *Environment and Behavior 36*, 341–367.

Tesfatsion, L., & Judd, K. (2006). *Handbook of computational economics 2*. Amsterdam: North Holland.

Theis, T., & Tomkin, T. (Eds.). (2012). *Sustainability: A Comprehensive Foundation*. Huston: Rice University.

Ugander, J., Backstrom, L., Marlow, C., & Kleinberg, J. (2012). Structural diversity in social contagion. *Proceedings of the National Academy of Science*, *109*(16), 5962–5966.

Watts, D. J., & Duncan J. (2002). A simple model of information cascades on random networks. *Proceedings of the National Academy of* Science 99(9). 5766-5771.

Watts, D. J., P. S. Dodds, & Newman M. E. J. (2002). Identity and search in social networks. *Science, 296*, 1302-1305.

Watts, D.J., & Dodds, P.S. (2009). Threshold models of social influence. In P. Hedström, P. Bearman (Eds.) *The Oxford Handbook of Analytical Sociology* (pp.475–497). Oxford :Oxford University Press.

Wesley Schultz, P., Nolan, J.M., Cialdini, R.B., Goldtsein, N.J., & Griskevicius, V. (2007). The Constructive, Destructive, and Reconstructive Power of Social Norms. *Psychological Science 18* (5), 429-434.

Xie, J., Sreenivasan, S., Korniss, G., Zhang, W., Lim, C., & Syzmanski, BK. (2011). Social consensus through the influence of committed minorities. *Physical Review E* 84, 01130, 1-8.

PART THREE: AGENT BASED MODEL IMPLEMENTATION

We will implement an Agent Based Model (ABM) to explore mechanisms of social influence in energy consumption, as well as the smart metering functions that can be provided to households can facilitate their behavioral changes.

We will describe the implementation of this model - SAM4SN (Spread of Awareness Model for Social Norm) - using the standard protocol ODD (Objective, Design, Details) for ABM.

We will use SAM4SN to explore from what does it depend whether this system reaches sustainability is a question that needs to perform different and multiple experiments to find an answer. The methodological approach consists of playing experiments to increase understanding of the limited resource consumption mechanisms. An agent-based computational model is the tool to explore such processes systematically.

Some explorative simulation experiments leading to sustainable or no sustainable scenarios are supplied in Chapter 8, while Chapter 9 deals with the choice of stakeholder validation as validation strategy.

A set of sensitivity analysis experiments in Chapter 10 allow us to consider as original result a new indicator of sustainability: the sustainability tipping point. An overall scope of our model is to support decision makers in local sustainability programs or campaigns.

In the conclusion we highlight that although the presented ABM refers to energy use, the overall conceptual model behind it can apply to other types of limited resources, according to the definition given in this Introduction.

7. ODD (Overview, Design concepts and Details)

ODD stands for Overview, Design concepts and Details, and is a protocol to standardize the published descriptions of individual-based and agent-based models (ABMs) (Grimm et al., 2006). The ODD is organized around the three main components to be documented about a model: Overview, Design concepts, and Details. These components encompass seven sub elements that must be documented in sufficient depth for the model's purpose and design to be clear and replicable for a third party: Purpose, State Variables and Scales, Process Overview and Scheduling, Design Concepts, Initialization, Input, and Submodels. ODD protocol is widely popular in the ABM community.

In addition to the original 2006 publication, Grimm and colleagues have continued to publish updates to the protocol, with examples of its application to research projects (Grimm et al., 2010).

An experimental version of the ODD protocol has been proposed by Muller and colleagues (2013) to describing human decisions in agent-based models. ODD+D is an extension of the ODD-protocol at a very early stage. Because the ODD-protocol is more and more a de-facto standard[37] in the community of ABM developers, we decided to be compliant with to the official version of ODD-protocol.

7.1 PURPOSE

The model simulates the micro-behaviors of individuals about the consumption of a limited resource. The *overall goal* is to observe at a macro-level how *a social norm emerges* about sustainability or unsustainability.

The system simulates how awareness spreads in a community of agents, how the dynamic of such awareness impacts on individual reduction goals and on resource consumption, how the availability of smart metering functions can impact on such mechanisms. The awareness of individual agents is defined by the influence of influent agents in the surrounding, by a general perception of environmental aptitude of the community, by a social reinforcement about the concordance of individual and collective consumption trends when social norms became true.

There is an overall reduction objective that the system can reach or not. The reaching of such objective corresponds to a sustainable consumption or, in short, to sustainability.

The *agents* are households. Agents don't move and their position is always the same. This choice of non mobile agent is driven by the consideration that agents are sharing the infrastructure where are available the smart metering functions, that are a part of the infrastructure where households live.

Such smart metering functions are:

- In home metering;
- Individual feedback about the individual own consumption of the limited resource;
- Information about green leaders and their low consumption profile, that are taken as reference;
- Personalized advice for consumption reduction.

The *resource* which consumption has to be reduced is **energy**, but could be water as well. Such resource is available on the model system scale without limitation. It has to be reduced for environmental sustainability related issues, but is perceived by agents without availability limitation. The size of the community is such that overuse does not lead to market price increasing. That means the people detracting environmental issue with an unaware environmental behavior have not price mechanism to counter their overconsumption.

Green people, i.e. people with high awareness, can decide to limit their privacy rights about own consumption information and accept to share with the community their own consumption data. Such voluntary mechanism of "privacy versus reputation" is an emerging trend in green communities, where to become a *green opinion leader* is a goal to reach (Griskevicius et al., 2010; Wesley Shultz et al., 2007). Awareness is a feature of each agent. It changes by interaction with neighbors in a given radius, by influence of a green aptitude of a community and by a mechanism of social reinforce. In other words awareness changes by local interactions and by a global social influences.

Each agent belongs to a type, according to his awareness level. Because the typing defines the consumption patterns and the potential reduction patterns, the awareness spread leads to behavioral changes of agents in resource consumption. When the above mentioned smart metering functions empower agents allowing them the ability to measure the critical resource, to have an individual feedback about his own consumptions, to have a comparison with other agents and giving him suggestions about resource consumption reduction, the consumption patterns changes.

The system identifies both individual consumption trends (i.e. reduction versus increment) and overall consumption trend.

---

[37] http://www.openabm.org/page/standards

The agents know the global trend about the resource consumption. When their behaviors are concordant with the general consumption trends the agents "reinforce" their beliefs and such social reinforcement in round changes their awareness. By changing awareness an agent can change the type he belongs to and such type determines new consumption/reduction patterns.

An empirical definition of social norm widely used in the research area of global environmental challenge (Kinzig et al., 2013) said that when enough people or certain people adopt these norms, there can be a tipping point (Levin et al., 1998; Gladwell, 2000) such that the proenvironment norms become widely shared and environmentally friendly behaviors become pervasive.

This tipping point may be as low as 10% of the population, if the minority is "consistent and inflexible" in its beliefs (Xie et al., 2011).

According with the above mentioned researches we define a *tipping point for a social norm* when the number of committed agents (actives and evangelists or blinds, i.e. the most aware and influent agents) adopting a behavior is at least the 10% of the population, their consumption trend is concordant with the overall consumption trend and the number of agents with concordant reinforcement is greater than the number of agents with concordant reinforcement of opposite sign.

When a global reduction goal is someway established (it can be a reduction program played by a local government or an information campaign) the system reaches such a goal several runs after such the tipping point is defined. We can say that a social norm toward sustainability emerges and we call it sustainability social norm. The ABM aims to study the relationship between the tipping point for a sustainability social norm and the goal reaching.

The smart metering functions empowers agents with measuring, individual feedback, comparison with others and availability of practical suggestions about green behaviors. Such smart functions play a role toward sustainable behaviors. If they are made available in already sustainable contexts they short the time needed to reach the reduction goal.

When (see Chapter 8 for examples) they are introduced in a not sustainable context, they can contribute to change the trend of collective behaviors and to allow the emergence of a sustainable behavior.

7.2 ENTITIES, STATE VARIABLE AND SCALE

7.2.1 ENTITIES

The entities of the models (i.e. the agents) are people involved in the consumption of one limited or critical resource. Each agent is a household. There are five types of entity: blinds, indifferents, spectators, actives, and evangelists.

- Blind agents have negative environmental behaviors. As detractors of the need to prevent an overuse of the resource, their environmental sustainability goals are negative. Their consumption increases and they are mocking other green agents (i.e. actives or evangelists). Their awareness level is very low and they have significant negative influence on neighbors. They represent a constraint against the reaching of tipping points. Usually they don't increase enough their awareness to change type. They became more aware only if a significant part of their neighborhood is green and if social norms became really significant. They are responsive only to negative social reinforcement. Their consumption patterns are independent of the smart metering functions that empower others types of agents. They are quasi-committed agents.

- Indifferent agents are neutral about the environmental sustainability goal. They usually compose the larger group in the initial situation. Their consumptions are constants, with only some possible small reduction under very specific conditions, i.e. when they are supplied with combination of smart metering functions. They don't have influence on neighbors, but are influenced by them. They are responsive to positive or negative social reinforcement.

- Spectator agents are quite stable in their behavior, but are open to listen and to observe their neighbor's behaviors. Under some combinations of smart metering functions they can have reduction goal. They do not have influence on their neighbors, but are influenced by them. They are responsive to positive or negative social reinforcement.

- Active agents are green people, engaged into reduction of resource consumption. They have a significant positive influence on neighbors. They allow other people to look at their own data in order to show beneficial behavior results and to share reduction goal with others. They are responsive to positive social reinforcement. They are quasi-committed agents.

- Evangelist agents are green activists that, in addition to active agents, are able to supply new resource into the system by producing the resource, for example when they produce renewable energy at a local scale with solar panels. They are prosumers. They have a strong influence on neighbors, but are not influenced by them. Their awareness never decreases: an evangelist is forever. They are responsive to positive social reinforcement. They are committed agents.

The agents belong to one and only one type at time. Each type of agent has a shape and a color, as described below in Table 2:

TYPE OF AGENT	SHAPE	COLOR
Blind	Cross	Red
Indifferent	Triangle	Brown
Spectator	Square	Yellow
Active	Pentagon	Green
Evangelist	Circle	Blue

Table 2 - shape and colors of agent types

7.2.1.1 PARAMETERS

Main parameters of the ABM are:

- The maximum number of each type of agent.
- The radius of influence of neighbors in awareness spread.
- The threshold to type shift.
- The reduction-goal coefficient of every type of agent.
- The reduction rate for every type of agent.
- The parameters to set the sustainability social norms.
- The influence parameters for the social reinforcements.

In Appendix 3 of this chapter the complete list of parameters.

7.2.2 STATE VARIABLES

Within the agent-based component, the ABM has two hierarchical levels: agents, representing households, and subclasses of agent with different environmental aptitude and behaviors.
Micro behaviors of different agent types have been described in Table 1.
State variables of the agents include the location of the agent and the availability of smart metering functions in such a location.
Each agent belongs to a type, according with his awareness level. Agent can be or not be supplied by smart functions of metering.
Each agent has a goal about the limited or critical resource to be reduced or optimized. Each agent reaches his individual goal at a given rate.
Evangelists and actives compose a green cluster. The green fraction is the ratio of green agent and the whole number of agents.

7.2.2.1 Globals variables

Each run the number of agents belonging to a type can change, while total number of agents is constant. Main global variables are:

- `the current number of blinds`
- `the current number of indifferents`
- `the current number of spectators`

- `the current number of actives`
- `the current number of evangelists`
- `the resource consumption`
- `the resource production`
- `the resource use level`
- *`the delta-resource, i.e. the relative variation of the resource`*
- *`a "sustainability" tipping point`*
- *`a "unsustainability" tipping point`*
- *`the green fraction, i.e. the percentage of active and evangelist over the whole population`*

7.2.2.2 Agent variables

A state variable of agents is the `awareness`, a cardinal numerical quantity.
Other agent variables are:

- `own resource consumption`
- `resource reduction goal,`
- `own resource production`

Different types of agent have different awareness; such awareness is a continuous variable, as showed in Figure 20.
Other agent variables are:

- `old-own-resource-consumption`
- `delta-individual-consumption`
- `social reinforcement`
- `metering`
- `feedback`
- `comparison`
- `suggestion`

Another feature an agent is his green competition index that is the rate with an agent try to reaches the reference consumption of the agent with the minimal consumption inside the overall system (see Fig.25).

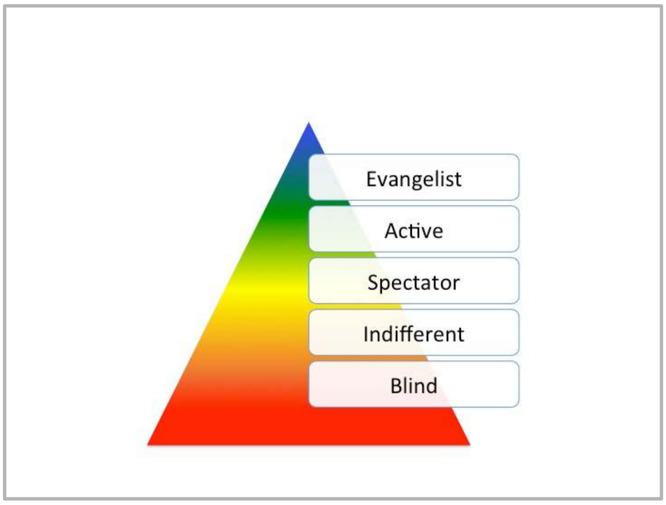


Figure 20 – Agents types and awareness levels

7.2.3 TEMPORAL EXTENT

The time unit is the tick. One time step corresponds to a day and the time horizon is *of one-two years at maximum* (no limits have been setup).

7.2.4 SPATIAL DIMENSION

The community is composed of agents. On a patch, representing the location (address) of one household, there can be one and only one agent. The maximum number of agents is smaller than the maximum number of patches. The dimension of the world is a square of 33 x 33 cells. Only one agent can occupy each cell. The maximum number of the agents is 800.

The spatial extent could be a portion of a city or of a geographic area where smart metering functions are all (or a subset) available is the modeled world.

In a real application case of SAM4SN model, the household positions would be given as input data, as well as the enabling smart metering functions.

The only random variable that is used is to assign the initial position of the agents.

7.3 PROCESS OVERVIEW AND SCHEDULING

7.3.1 PROCESS

The main procedure calls several sub-procedures:

- **Update of awareness**
- **Update of types**
- **Update of reduction goals**
- **Update of consumption**
- **Social Reinforcement**

When reduction goal is achieved the system stops.

Each agent looks around himself to verify how many neighbors and of what type there are in the given radius. According to specific conditions he changes his awareness level. The rules to update awareness are different for each agent types, as described in detail in section 7.7.1.

Awareness is modified on the basis of influence of neighbors in a given radius, as qualitatively showed in Fig. 12 and quantitatively described in section 7.7.1.

The radius of influence is 2, for an overall spatial dimension of 33x33 cells. The most influent agents, the evangelists, have a double influence radius, i.e. 4.

The awareness is affected also by a perception of the overall "pro environment" aptitude. For some types of agents - spectators and actives - also a given fraction of green neighbors on the whole population can increase awareness. This represents a kind of general community based social pressure that leads to an additional increase of awareness.

We can say that if the 30% of the whole population is composed by green agents (i.e. active or evangelist) this light-green percentage will increase the awareness (see Fig. 22 for details) of a spectator, while "to be impressive for active" agents such green percentage must be stronger, i.e. the 80% of the whole population (Fig. 23).

For blind agents, which are strongly against changing their position of negation about environmental issues, only very green neighbors can change their awareness and only if no other blind agents are on the neighbors.

The awareness depends also from the social pressure by a parameter that measures the *reinforcement* that an agent receive from the comparison between his own consumption trend and the overall one; when such trend is concordant the agent is reinforced in his believes and desire. Such reinforcement impact on awareness. When the individual behavior tends toward a sustainable consumption and the overall trend is the same or better the reinforcement is positive and the awareness increases.

After the *upgrade of awareness* of each agent, when agent awareness is beyond a given threshold the system *updates* the membership of the agents to a type. Each agent has an own consumption pattern. Such pattern depends on the type of agent and on the availability of smart metering functions. Such smart metering function are the enablers to make agents able to measure the resource that he consumes, to have feedback on his individual consumption, to compare his own consumption with other agents, namely the agent with the lowest consumption that will act as a reference, and some suggestion to reduce his own consumption.

Such abilities correspond to general abilities that can be enabled by ICT-based smart metering functions, but that can be enabled also otherwise. For example a behavior change program can enable them by the help of people acting as supporter or testimonial.

Each type of agent has a reduction goal that drives the consumption pattern, as described below from (6) to (19) (see section 7.7.2).

In general the own resource consumption is given by the difference of the previous consumption less the reduction goal, as described in (6).

The reduction goal depends also on the smart metering function of "metering" and of "comparison" (see from (7) to (11) and Figure 24).

Each type of agent has a different consumption patterns and such consumption is updated on the basis of the individual reduction goal. Both are updated each run according to several context conditions as described in Table 1.

The overall consumption is evaluated on the basis of the individual consumption and also on the resource production. Production of the resource is given by individual household renewable energy production.

7.3.2 SCHEDULING

In the main procedure the state variables are assigned a new value when the new value is stored until all agents have executed the process, and then all are updated at once (synchronous updating). Time is simply represented by using time steps: assuming that time moves forward in chunks. When the overall reduction goal (as given by the user) is achieved, the system stops.

7.4 DESIGN CONCEPTS

7.4.1 BASIC PRINCIPLES

The behavioral changes needed to reach the overall goal of reducing the consumption of a resource are driven by the awareness of agents involved in. Such agent awareness can change interacting with neighbors. The awareness level defines the own resource consumption of the types of agent.

Special agents, so-called "blinds", are not genuine about environmental issues; when they are neighbors of another agent they have a negative effect and can decrease the awareness of the neighbors. The hypothesis underlying the model is that awareness spread process depends on direct interaction of each agent with immediate neighbors. Only spectator and active agents are influenced also by a global perception on how many green agents are in the world and this has a kind of social influence on aware agents, further increasing their awareness level.

Agents interact between them by proximity. According to the number and the type of neighbors in a given radius each agent changes his awareness. When the awareness reaches a given value (threshold), the agent changes the type he belongs to. There are several thresholds. The main hypothesis of this model is that the influence of neighbors depends on their type and for each type the awareness changes are different. The threshold to change the type to belong is different from each agent type. Greener agents have a higher threshold to shift to a more aware type, but they never decrease their awareness and their awareness increase faster than in other less green agents. There is a kind of cascade effect, limited only by the influence sphere of the agents.

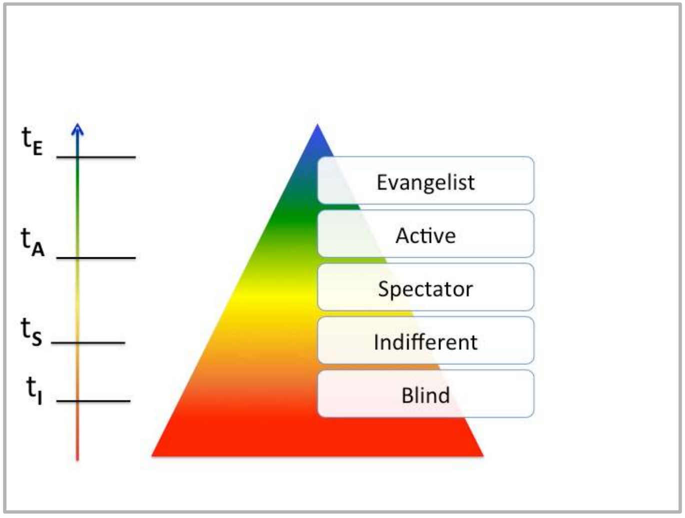


Figure 21 – Multiple Thresholds

Threshold values to switch from one type to another are:

$t_{Indifferent}$ = 8 (the threshold from blind to indifferent)
$t_{Spectator}$ = 16 (the threshold from indifferent to spectator)
t_{Active} = 100 (the threshold from spectator to active)
$t_{Evangelist}$= 2000 (the threshold from active to evangelist)

As described in Chapter 6, each type of agent has different awareness as well consumption reduction patterns. Examples have been supplied in Table 1 of electricity saving actions that can be performed by five types of agents. Evangelist agents are activists and are also able to addict new resources into the systems. In the case of energy they are energy *prosumers*.
The own resource consumption (orc_i) of each agent depends on the type of agents and on tits reduction goal.
In general at time t is given by:

$$(1)\ \mathbf{orc_{i(t)} = orc_{i(t-1)} - rg_{i(t)} * W_i} \qquad \text{with i: \{blind,indifferent,spectator,active,evangelist \}}$$

The own resource consumption (orc_i) of each agent is the difference between the previous resource consumption and the individual reduction goal, multiplied by the speed to reach it.
The availability of smart metering functions allows several possible scenarios.
The reduction goal (rg_i) is different for type of agent and depends on the availability of the smart metering function of the feature of agents to perform metering and comparison.
Such reduction goal is reached with a given rate W_i that depends on the smart metering functions of individual feedback and suggestions.
The proposed ABM aims to relate such consumption pattern to the availability of specific functions of smart metering systems. A basic assumption is that consumption behaviors are driven by awareness, but there are some empowering factors, like the availability of smart metering functions.
Availability of smart metering function enables the agent to know the own consumption of the resource and to identify an individual reduction goal.
If such metering function is coupled with the feedback function, the reduction goals are faster to reach.
The simultaneous availability of metering and comparison functions enables agents to identify which is the more "green resource consumer" and to set their own reduction goal to a shared goal that is given by the minimum consumption in the community, according a competition index (see Section 7.7.2.1.3 and Figure 25 for details).
When metering, feedback and tips & tricks functions are available all together, the rate to reach the reduction goal is the highest.
There is a social reinforcement function depending on the comparison between the global trend of consumption and the individual trend of consumption. When the relative global trend is concordant and higher in absolute value than the individual one, the reinforcement variable is set to 1 when both are negative (i.e. a reduction is the trend) or is set to -1 when both are negative (i.e. an increase of consumption is the trend). See par.7.7. 6 for details).
Awareness depends on such reinforce, because its value is added to the awareness level. When the global trend and the individual one are of reduction, and the first is higher than the second in absolute value, the awareness increases.
When the global trend and the individual one are of increase, and the first is higher than the second in absolute value, the awareness decreases.

7.4.2 EMERGENCE

Sustainable or unsustainable scenarios of consumption emerge on the basis of initial conditions about number of types of agent and smart metering functions set up. Some initial scenario configurations lead to decrease resource consumption, i.e. to invert the initial trends.
A Sustainability social norm can emerge. When it emerges usually is persistent.
The overall reduction goal is reached some runs after the sustainability social norm is established.
Empowering the agents with function of metering, individual feedback, comparison with other agents and suggestion to improve its behavior allow to reaches the reduction goal.

7.4.3 INTERACTION

There is a direct interaction by neighbors and by the global percentage of green agents.
The belonging drives the communication to a given breed, because the (implicit) assumption is that awareness level is related to a similar communication level, able to involve neighbors (more aware agents are more communicative).

7.4.4 STOCHASTICITY

The initial position of each agent is choose randomly, under the only condition of only one turtle per patch: each agent represents an household. In Chapter 8 some experiments will presents the stochastic behavior of the model.

7.5 INITIALISATION

The initial state of the model world, i.e. at time t = 0, depends parameters that are supplied by user-interface: the number of agents of each type, the available metering functions, the global resource consumption value, and the overall reduction goal value.

7.5.1 USER DEFINED VALUES

The initialization values supplied by the user are the following state variables:

- The initial numbers of different types of agents (range is between 0 and maximum value) are supplied by a slider on the Interface:

- `N-blind`
- `N-indifferent`
- `N-spectator`
- `N-active`
- `N-Evangelist`

The maximum number of agents is different by type:
Max number of Blinds = 50
Max number of Indifferent = 300
Max number of Spectators = 300
Max number of active = 200
Max number of evangelist = 50

The total number of agents is constant and is given by the sum of the number of different types**.** *The total number of agents is a bit smaller than the total number of patches of the world.* Most influent agents, i.e. blinds and evangelists, are in general less than other types of agent. Are also supplied by the sliders on the Interface:

- The `Initial global resource consumption`(its value is between 0 and 50000).

- The `overall reduction goal` is expressed in percentage (Its value is between 0 and 100).

- The available smart metering functions are setup by switchers. User defines which combination of metering function is available, by a mix of ON-OFF functions:

- `metering-availability`
- `individual-feedback`
- `neighbor-comparison`
- `Tips&Tricks`

- The `seed` parameter is supplied by the user. It is assigned to the random-seed function (used to allocate agents on free cells in the initialization phase)

- `Sustainability-tipping-point` and `unsustainability-tipping-point` are set up to false.

7.5.2 AGENT CREATION AND INITIALIZATION

Shapes and colors of each type of agent are set up according to Table 1.

Agents of the different types are created. They are randomly allocated on a cell: the `seed` value is used to find a position. When this cell is not empty, the system looks for another cell and so on.
On each cell there can be only one agent and the agents do not move around.

The `initial awareness values` of the agents are different for each type and correspond to the minimum value of the type.
The minimum awareness level is:

Blind =0
Indifferent = 8
Spectators = 16
Active =100
Evangelist = 2000

- The `initial own resource consumption` (i.e. the initial individual consumption of the limited resource) is different by type. It is evaluated on the basis of the idea that an agent of type *i* consumes C_i times more than an evangelist agent – the most aware and less consuming type of agent - where C_i:

$C_{active} = 1.1$
$C_{spectator} = 1.2$
$C_{indifferent} = 1.3$
$C_{blind} = 1.4$

This assumption corresponds to a consumption of a blind agent of 40% more than an evangelist, and so on.
To assign an initial value to iorc we need to multiply such coefficient for the elementary unit of consumption. An elementary unit of consumption (euc) is defined, on the basis of the Initial global resource consumption (*Igrc*) value, as:

$$(2)\ euc = \frac{Igrc}{\sum_i N_i * C_i}$$

with i: $\{blind, indifferent, spectator, active, evangelist\}$

The initial-own-resource-consumption ($iorc_i$) for the different types of agents is given by:

$$(3)\ iorc_i = euc * C_i$$

- The `individual reduction goal` of each types is set to 0:

$$(4) rg_i = 0$$

- The `own resource consumption` is set to the initial-individual-resource-consumption.
- The `reinforce` agent variable is set to 0.
- The `individual resource production` is an attribute of evangelist agents. It is setup to the 1% of his initial-own-resource-consumption.
- The agent variables related to the empowering of agents by enabling the ability of metering, feedback, comparison and suggestion are setup according to user choice about smart metering function availability.

- `Metering` is set to TRUE if metering-availability is switched ON
- `Feedback` is set to TRUE if individual-feedback is switched ON
- `Comparison` is set to TRUE if neighbor-comparison is switched ON
- `Suggestion` is set to TRUE Tips&Tricks is switched ON

7.6 INPUT DATA

At the current prototyping stage the model does not use input from external sources[38]. In further developments and use of the model on real cases such data will be features of the specific infrastructure of a specific geographic area.

7.7 SUBMODELS

7.7.1 UPDATE OF AWARENESS

At each run the awareness of the agents is updated according to the neighbors influence. The awareness diffusion mechanism is driven by the principle that the more influential neighbors are those at the two boundary of awareness scale: evangelist and active (at the top) and blind (at the bottom). We call evangelist and active agents "green agents".

The awareness changes each run, as a variation of the previous run.

For each type *i* of agents (i.e.: blind, indifferent, spectator, active and evangelist) the awareness at a given time t is given by:

$$(5)\ a_{it} = a_{i(t-1)} + \Delta a_i$$
$$a_{i0} = \mathrm{k}_{i0}$$

where, for every *i*:

$$(6)\ \Delta a_i = \alpha_i v_{gr} + \varepsilon_i v_e + \beta_i v_b + \gamma_i n_{gr30} + \delta_i n_{gr80} + sr_i$$

and

α_i= awareness **local** increment coefficient1 (for agent of type *i)*
ε_i =awareness **local** increment coefficient2 (for agent of type *i)*
β_i= awareness **local** decrement coefficient (for agent of type *i)*
Υ_i= awareness **global** light-green increment coefficient (for agent of type *i)*
δ_i =awareness **global** strong-green increment coefficient (for agent of type *i)*

	$i = blind$	$i = indifferent$	$i = spectator$	$i = active$
α_i	1	1	1	0
ε_i	0	0	0	2
β_i	-2	-1	-1	0
γ_i	0	0	1	0
δ_i	0	0	0	1

Table 3 – awareness local and global coefficients for type of agents

The first two terms are related to local influence mechanisms, while the third and fourth are related to an overall influence mechanism. The fifth term is related to reinforcement in belief of the agent.

Evangelists are top-level environmentally aware agents, and their awareness cannot decrease; they never became a less aware type of agent. So is meaningless to further increase the awareness of an evangelist agent.

Evangelists are the most influent agents and their influence radius is double than the other type of agents.

Referring to (6) v_{gr}, v_e v_b, $n_{gr30\text{-}80}$, n_{gr80} are dummy variables:

v_{gr} = *1 if there is at least one active agent in the influence radius or an evangelist in influence radius * 2*
v_e = *1 if there is at least one evangelist agent in influence radius * 2*
v_b = *1 if there is at least one blind in the influence radius*
n_{gr30} =*1 if the percentage of green agents(i.e. active or evangelist) is more than 30% of the whole population*
n_{gr80}= *1 if the percentage of green agents is more than 80% of the whole population*

k_{i0} is the setup value of awareness and is a constant for each type of agents (5):

---

[38] Real smart metering availability for a given geographic area will be supplied as system input.

	$i = blind$	$i = indifferent$	$i = spectator$	$i = active$	$i = evangelist$
k_{i0}	0	8	16	100	2000

Table 4 – set up constants for type of agents

Third and fourth terms depend on the green agentset.

Green agentset is composed by active and evangelist agents. When its value is more than 30% of the whole population, spectator awareness increases, under a light global influence represented by the "light green" coefficient

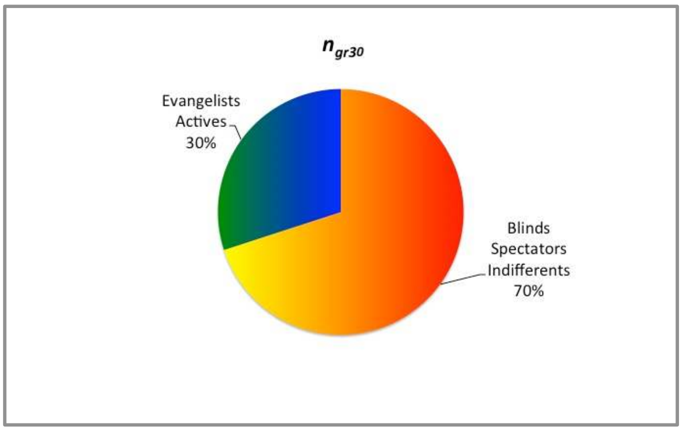


Figure 22 - Light-green percentage

When the green agentset is composed by more than 80% of the whole population, active awareness increases, under a strong global influence, represented by the "strong green" coefficient.

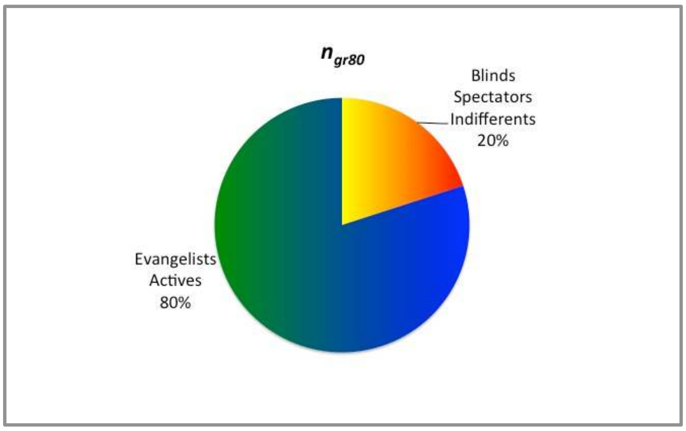


Figure 23 - Strong-green percentage

The term *sr* in expression (6) is the social reinforcement of the agent about his individual behavior and depends on the comparison between the global resource consumption and its own consumption trend; r can be +1, 0 or -1 (see section 7.7.5). It affects awareness level.

7.7.2 UPTADE OF TYPES

An agent changes his type when his awareness passes a given threshold (see Figure 21).

7.7.3 REDUCTION GOALS

As observed in (1) the individual reduction goal varies according to agent type.
For blind agents is independent from the availability of any facilitating conditions, because blind agents want to increase its consumption despite any evidence of need to reduce the resource consumption.

$$(7)\ \mathbf{rg_{blind} = iorc_{blind} * K_{blind}}$$

where K_{blind}= -0.01.
The reduction goal is negative. The blind agents increase of 1% of its initial-consumption (iorc) the own consumption.
For the other types of agents the individual reduction goal depends of the availability of two smart metering functions:

- `metering-availability`
- `neighbor-comparison`

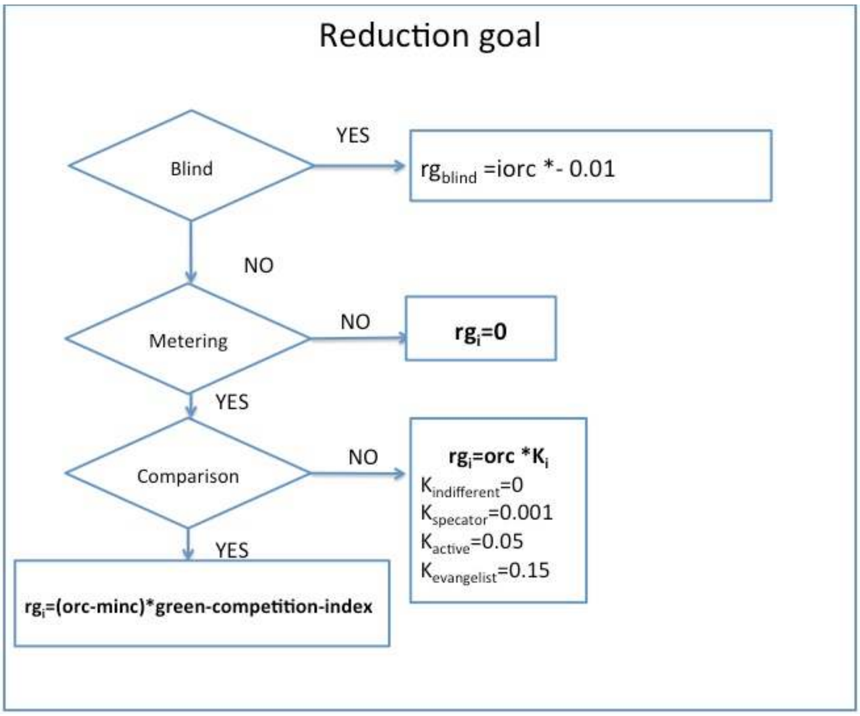


Figure 24 - Reduction goals of agents

7.7.3.1 No metering

If no metering function is available, the reduction goal is zero and the consumption is constant for every type of agent, apart blind agents that increases their consumption (see above).

$$(8)\ rg_i = 0$$
$$(9)\ \mathbf{orc_{i(t)} = orc_{i(t-1)}}$$

7.7.3.2 Metering

When the metering function is available the reduction goal (rg) at time t is a given percentage of the individual own resource consumption at t-1 ($orc_{i(t-1)}$).

$$(10)\ \mathbf{rg_i = orc_{i(t-1)} * K_i}$$

where K_i is a consumption modification coefficient., depending on agent type:

$K_{evangelist}$= 0.15
K_{active} = 0.05

$K_{spectator} = 0.001$
$K_{indifferent} = 0$

7.7.3.3 Comparison

When the function of comparison with neighbors is available, agents know the consumption of less consuming agents and then they set their own reduction goal on the basis of the minimum consumption of other agents.

(11) $\mathbf{rg_{i(t)} = (orc_{i(t-1)} - min\_cons_{t-1}) * green\text{-}competition\text{-}index}$

The reduction goal depends on the minimum known consumption and is given by the difference between the previous consumption of the agent and the reference consumption of another agent that has the minimal consumption ($min\_cons_{t-1,}$). Such difference is multiplied by a competition index.
The minimal consumption of agents is given by the consumption of a green agent which consumption is the minimal in the whole systems.
In the model when the smart metering function called neighbor-comparison is set to ON, all agents have as the feature of comparison set to TRUE.
The basic idea behind is that in real situation green agents accept **to relax their privacy constraint about individual consumption for social reputation**. For sake of simplicity, all agent consumptions are available to identify the minimal consumption among agents.
The green-competition-index gives a weight of the aptitude of an agent to emulate the less consuming agents. It is depending on the awareness of the agent, and is defined for indifferent, spectators and evangelist, but not for blinds, as:

(12) $\boldsymbol{green - competiton - index = 1 - \frac{1}{awareness - 8}}$

(13) $\boldsymbol{green - competiton - index = 0}$ **if awareness < 8**

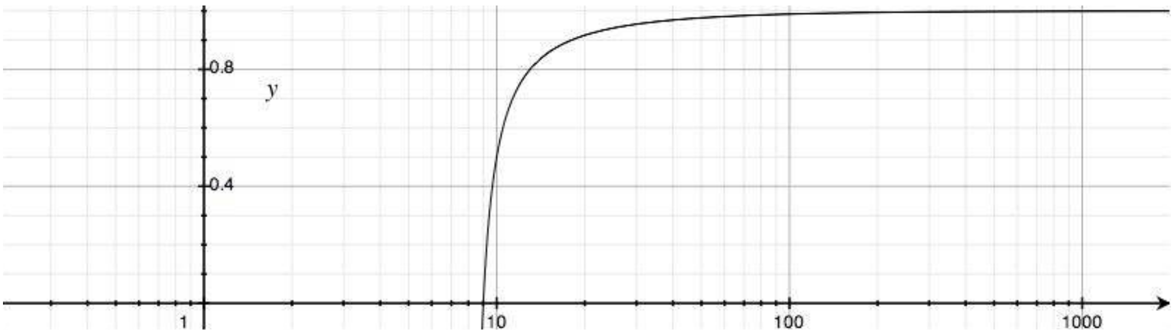


Figure 25 - Green competition index

For blind agents, i.e. with awareness <8, green-competition-index=0
Green competition index is small for low aware agents and increases for more aware agents till reaching the value of 1 for evangelists.

(14) $\mathbf{rg_{i(t)} = (orc_{i(t-1)} - min\_cons_{t-1}) * green\text{-}competition\text{-}index}$

7.7.4 INDIVIDUAL RESOURCE CONSUMPTION

The own resource consumption depends on the reduction goal. It is computed as the difference between the previous tick resource consumption and the individual reduction goal that has to be reached with a given rate W_i

(15) $\mathbf{orc_{i(t)} = orc_{i(t-1)} - rg_{i(t)} * W_i}$

The blind agent has a negative reduction goal (see (7) and Fig. 24).

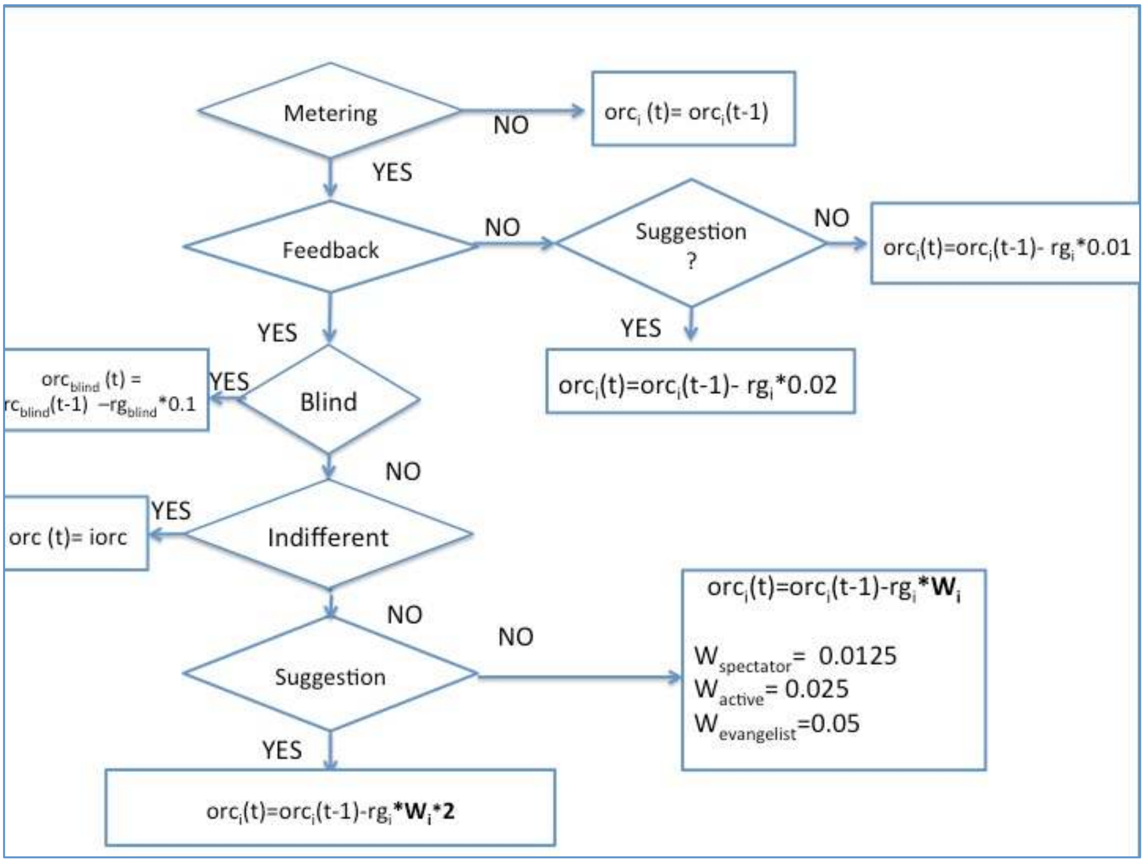


Figure 26 – Own resource consumption of an agent

The rate to reach the reduction goal depends of the availability of three smart metering functions:

- `metering-availability`
- `individual-feedback`
- `Tips&Tricks`

7.7.4.1 No Metering

When no metering functions are available the own resource consumption is the same of the previous run:

(16) $\mathbf{orc_{i(t)} = orc_{i(t-1)}}$

7.7.4.2 Only metering

The own resource consumption is given by the old own resource consumption less the reduction goal by the rate to reach it, as shown in above. When metering function but not feedback and not suggestion functions are available, $\mathbf{W_i}$ is the same for every types and is :$\mathbf{W_i}$ **= cost** = **1/100**.

(17) $\mathbf{orc_{i(t)} = orc_{i(t-1)} - rg_{i(t)} * 0.01}$

7.7.4.3 Only metering and feedback

If metering and feedback but not suggestion functions are available, the reduction goal is the same of (17), but the rate to reach such goal depends on the type of the agent.

(18) $\mathbf{orc_{i(t)} = orc_{i(t-1)} - rg_{i(t)} * W_i}$

$W_{evangelist} = 0.05$

$W_{active} = 0.025$

$W_{spectator} = 0.0125$
$W_{indifferent} = 0$
$W_{blind} = 0.1$

7.7.4.4 Tips& tricks

When there is the availability of the Tips& tricks function, the households is supplied by personalized suggestion about possible improvement in his behavior.
If both metering and Tips& tricks smart functions are supplied, the rate to reach the individual goal doubles.

(19) $\mathbf{orc_{i(t)} = orc_{i(t-1)} - rg_{i(t)} * W_i * 2}$

7.7.4.5 Resource production

The only type of agent able to produce resource in addition to consume it is the evangelist.
(20) $\mathbf{orp_{evangelist} = orc_{evangelist} * 0.02}$
The evangelist produces the 2% of his consumption.
The overall resource production is the sum of all resources produced by evangelists.

7.7.4.6 Global Resource use

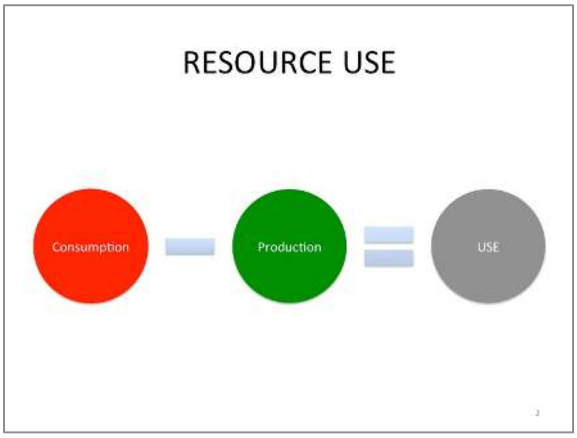


Figure 27 - Global resource use

The Global resource use is given by the difference between overall consumption and overall production.

7.7.5 SOCIAL REINFORCEMENT

Social Reinforcement is a variable of each agent. Reinforcement relies on the comparison between the global trend of resource use (Δr) and the individual trend ($\mathbf{\Delta_i c}$) of consumption, as below described.

7.7.5.1 Global resource use trend

Global-resource-use (GRU) is given by the difference between Global resource Consumption and Global Resource production:
(21) $GRU=GRC-GRP$

The overall delta of resource use at time t is:

(22) $\Delta R=GRU_t- GRU_{t-1}$

The global resource use trend is given by the relative delta of resource use:

(23) $\Delta r=(GRU_t - GRU_{t-1})/ GRU_t$

7.7.5.2 Individual resource consumption trend

The individual resource consumption trend is given by:

(24) $\Delta ic=(orc_t - orc_{t-1})- orp_t/ orc_t$

where:
orc_t is the own-resource-consumption at time t
orp_t is the own-resource-production at time t (orp_t different from 0 only for evangelists).

7.7.5.3 Agent social reinforcement

The default value of social reinforcement is set to zero.
When the relative global trend (Δr) is concordant and higher in absolute value than the individual one (**Δic**) the social reinforcement (*r*) variable change for some type of agents.
When both are negative (i.e. the reduction is the trend, both at a global and individual level) the social reinforcement (sr) is set to 1 for active agents.

(25) $\Delta r <0$ and $\Delta ic <0 \rightarrow sr =1$

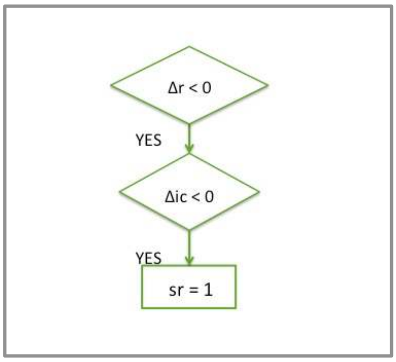


Figure 28 – Social reinforcement of active agent

The same conditions for evangelist agents with also the condition that the relative overall reduction is greater than the relative individual one:

(26) $\Delta r <0$ and $\Delta ic <0$ and $|\Delta r| > |\Delta ic| \rightarrow sr =1$

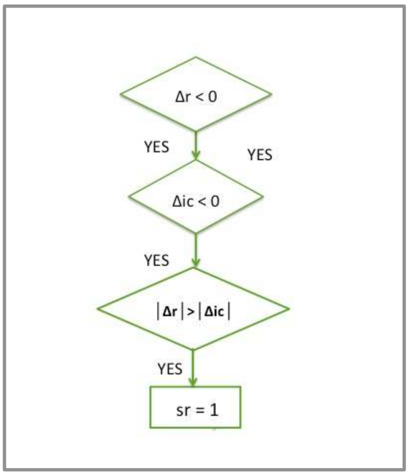


Figure 29 – Social reinforcement of evangelist agent

For indifferent and spectator agents the condition for the positive reinforcement are the same, but they can have also a negative reinforcement. When the trend is of increasing, both at a global and individual level, the social reinforcement is set to -1 for indifferent and spectator agents.

(27) $\mathbf{\Delta r > 0 \text{ and } \Delta ic > 0 \text{ and } |\Delta r| > |\Delta ic| \rightarrow r = -1}$

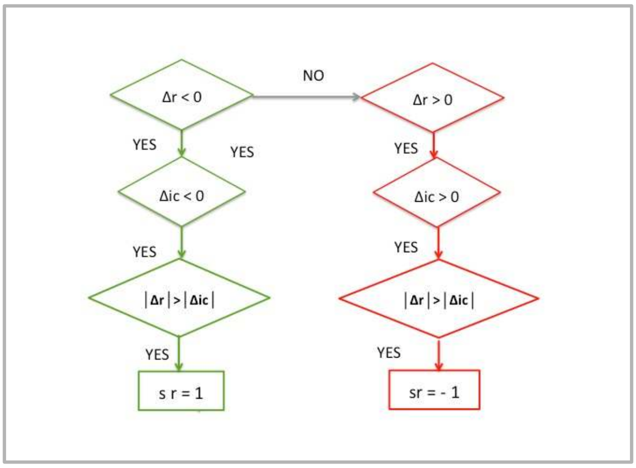


Figure 30 – Social reinforcement of spectator and indifferent agents

Blind agents can have only negative reinforcement.

(28) $\mathbf{\Delta r < 0 \text{ and } \Delta ic < 0 \rightarrow r = 1}$

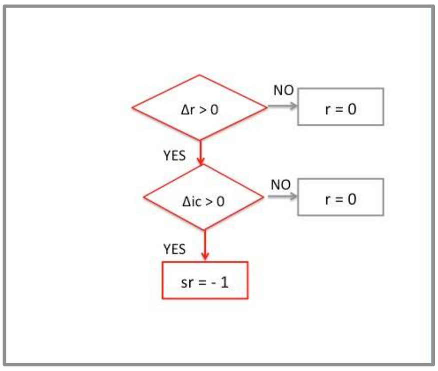


Figure 31 - Social reinforcement of blind agent

In details looking at the social reinforcement for the different types of agent, we can see that the reinforcement appear under certain conditions, that are different by types.

The only agent with the social reinforcement put to zero is the blind, to avoid overestimate his negative effect on reaching the tipping point for sustainability.

Other agents are maintaining their previous social reinforcement and change it only when the above described condition happens. This choice is driven by the need of representing a feeling of the agent about the consumption trend, with some "inertia" and not as a real time value at all.

7.7.5.4 Social reinforcement and awareness

Awareness depends on such social reinforce, because its value is added to the awareness level. When the global trend and the individual one are of reduction, and the first is higher than the second in absolute value, the awareness increases.

When the global trend and the individual one are of increase, and the first is higher than the second in absolute value, the awareness decreases.

(29) $\Delta a_i = \alpha_i v_{gr} + \beta_i v_b + \gamma_i n_{gr30} + \delta_i n_{gr80} + \boldsymbol{sr}$

7.7.6 TIPPING POINTS

We are looking for two social norms: sustainability and unsustainability social norms. A sustainability social norm is somehow announced by the reaching of a tipping point. It emerges when a given percentage of committed agents has a consumption trend that is concordant with the overall one. By default the tipping points are set to false. The tipping point toward sustainability is reached when the relative number of green agents with a negative delta individual consumption is greater than the 10% of the total number of agents. In addition the total number of green agents with a positive reinforcement must be greater than the total number of unaware agents with a negative reinforce.

$$\frac{\textbf{Number of actives \&evangelists with } \Delta ic < 0}{\textbf{Total number of agent}} > 0.1$$

AND $\Delta r<0$

AND **Number of agents with social reinforcement = 1 > Number of agents with social reinforcement = -1**

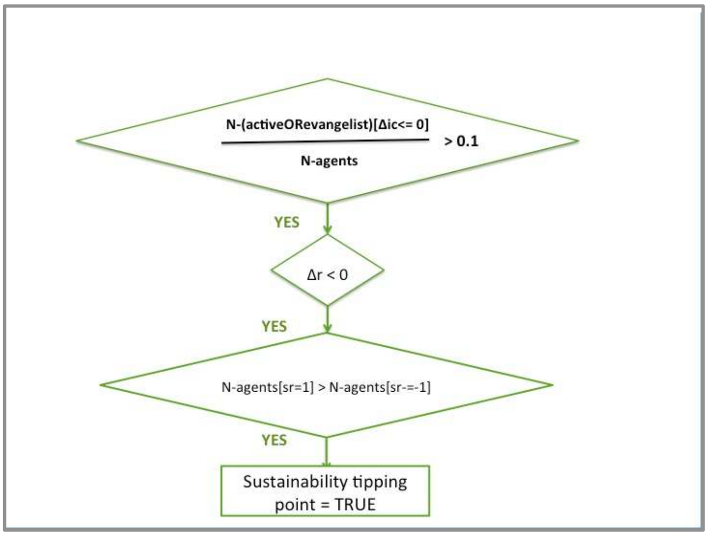


Figure 32 - Sustainability tipping point

An unsustainability tipping point emerges when the relative number of blinds with a positive delta individual consumption is more than the 10% of the total number of agents and the total number of blind agents with a negative reinforce is greater than the total number of green agents with a positive reinforce.

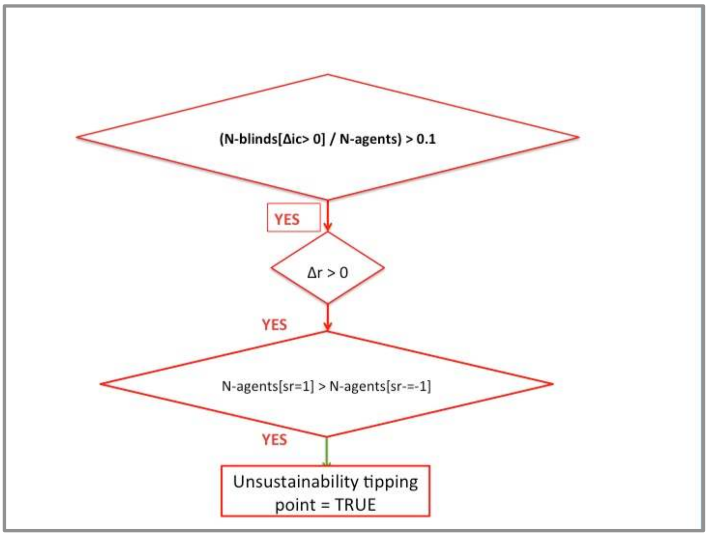


Figure 33 – Unsustainability tipping point

Number of blinds with Δic > 0
-- > 0.1
Total number of agent

AND Δr>0
AND **(Number of agents with social reinforcement = -1) > (Number of agents with social reinforcement = 1)**

7.7.7 UPDATE OF OVERALL RESOURCE USE

The value of previous run is saved.
After that each individual consumption is updated as below described, the global resource consumption is evaluated as well the global resource production. The overall resource use is given by the difference between the overall resource consumption and the overall resource production.
When the global resource use is smaller than (see Fig. 8) the difference between the initial resource use and the absolute overall reduction goal the model stops.

7.8 PARAMETRS AND MODEL CALIBRATION

In Appendix 3 to this chapter there is the full list of parameters.

In depicting an overall view in implementing the modeling framework, the steps of calibration and validation (Windrum, Fagiolo, & Moneta, 2007; Railback & Grimm, 2011) are clearly identified.

Parameters are coherent with the designed model that is an artifact able to produce the behaviors we want to investigate. Parameters have been defined according to a plan of experiments, which led to identify a subset of possible values, the effect of which consists of the behavior of the model.

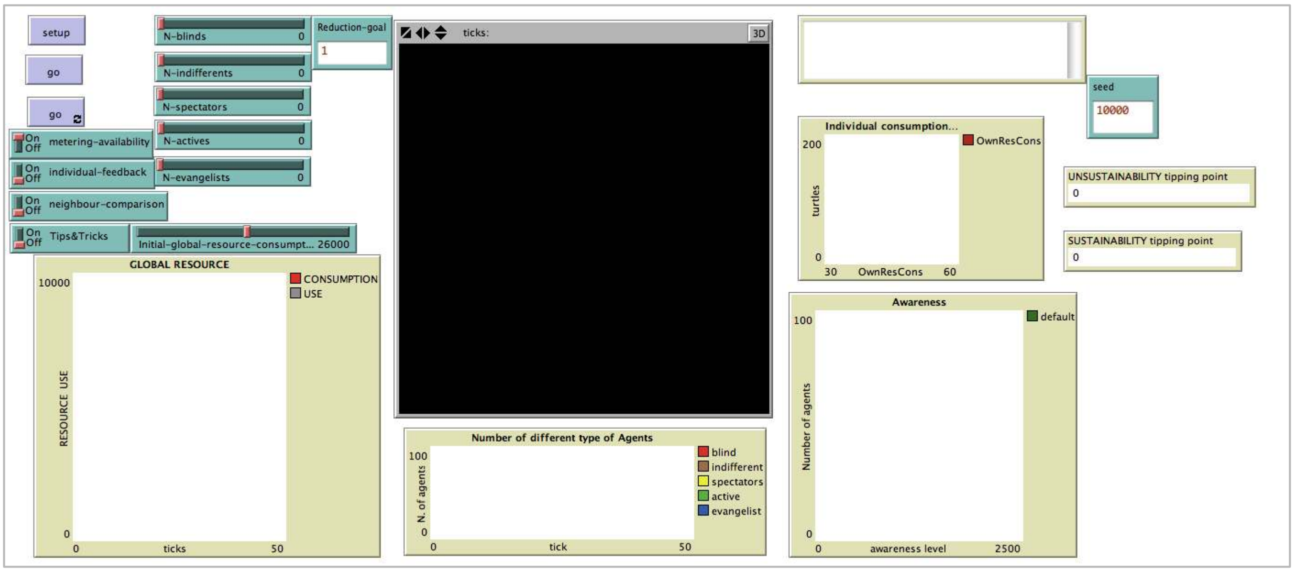
The model shows emergent properties of two types: planned, as for example the effects of the types on consumption and unforeseen, like the tipping point.

7.9 MODEL IMPLEMENTATION

The ABM that has been presented in previous chapter has been implemented in NetLogo 5[39]. The model is called SAM4SN: Spread of Awareness Model for Social Norm.

NetLogo is a programmable modeling environment for simulating natural and social phenomena. NetLogo was designed and authored by Uri Wilensky, director of Northwestern University's Center for Connected Learning and Computer-Based Modeling and is freely available from the NetLogo website[40]. NetLogo is widely used in the ABM developer's community.

The interface of NetLogo is divided into two main parts: NetLogo menus and the main window. At the top of NetLogo's main window are three tabs labeled "Interface", "Info" and "Code". The interface tab is where you watch the SAM4SN model run (Figure 34).



N-blinds 0
N-indifferents 0
N-spectators 0
N-actives 0
N-evangelists 0
Reduction-goal 1
Initial-global-resource-consumpt... 26000
seed 10000
UNSUSTAINABILITY tipping point 0
SUSTAINABILITY tipping point 0

Figure 34 - Netlogo interface of SAM4SN

Some visual representations of output and statistical evaluations that will be presented in the next chapter have been obtained using the statistic packages of **R**. R[41] is a free software programming language and a software environment for statistical computing and graphics. The R is widely used among statisticians and data miners for developing statistical software and data analysis.

Sensitivity analysis that will be described in Chapter 10 has been performed by using the *BehaviourSpace* utility of NetLogo 5 package.

---

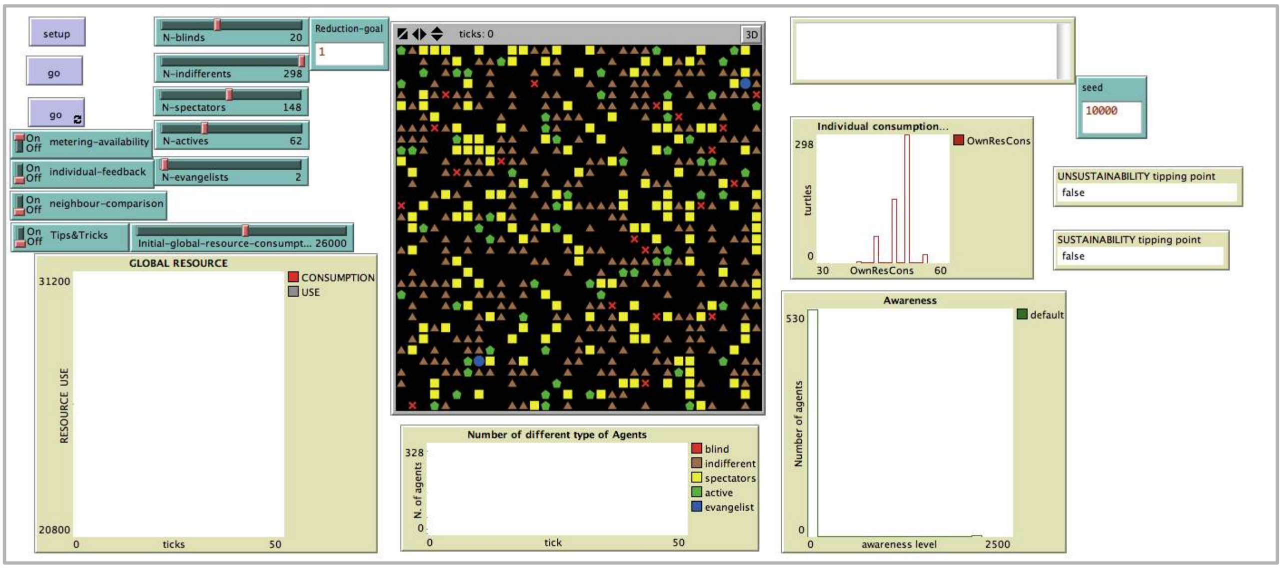
[39] Wilensky, U.(1999). NetLogo.http://ccl.northwestern.edu/netlogo/.Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL

[40] http://ccl.northwestern.edu/netlogo/download.shtml

[41] R is freely available under the GNU General Public License at http://www.r-project.org

7.10 MODEL INTERFACE

In Figure 35 you can see SAM4SN, as visualized in NetLogo 5.

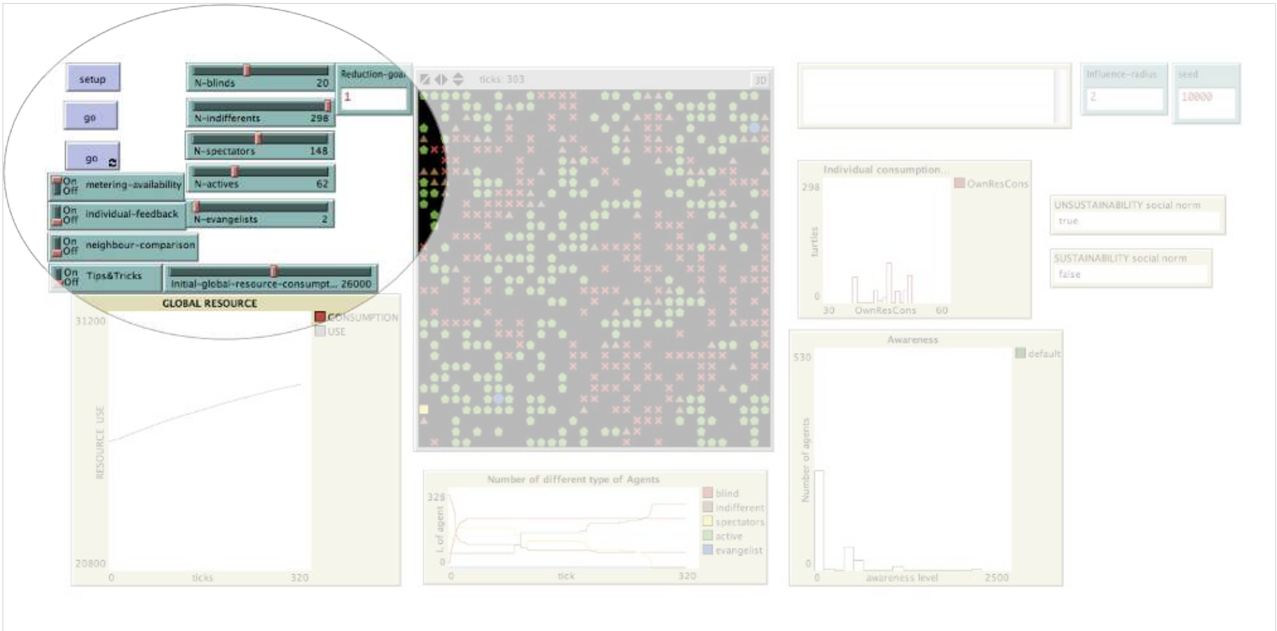


N-blinds 20
N-indifferents 298
N-spectators 148
N-actives 62
N-evangelists 2
Reduction-goal 1
On Off metering-availability
On Off individual-feedback
On Off neighbour-comparison
On Off Tips&Tricks
Initial-global-resource-consumpt... 26000
seed 10000
UNSUSTAINABILITY tipping point false
SUSTAINABILITY tipping point false

The user interface is composed by several input and output areas that are defined by the programmer. Input areas consist of sliders, switchers and windows that allow the user to enter the input data. Output areas consist of several plots and output windows that display some features of the system.

The initial state of the model world, i.e. at time t = 0, is given by the parameters supplied by the users. Such parameters are:

- the number of agents of each type;
- the initial global resource consumption value;
- the overall reduction goal (in percentage)
- the smart metering functions availability.



N-blinds 20
N-indifferents 298
N-spectators 148
N-actives 62
N-evangelists 2
Reduction-goal 1
On Off metering-availability
On Off individual-feedback
On Off neighbour-comparison
On Off Tips&Tricks
Initial-global-resource-consumpt... 26000
influence-radius 2
seed 10000
UNSUSTAINABILITY social norm true
SUSTAINABILITY social norm false

Figure 36 – SAM4SN user initialization

There are five input sliders, on the top left corner of the screen:

- *N-blinds*
- *N-indifferents*
- *N- spectators*
- *N-actives*
- *N-evangelists*

They allow the final user, as showed in Figure 36, to define the number of agents of each type.

The initial global resource consumption is defined in absolute value (without specifying the measure unit), and its value is supplied using the slider *initial-global-resource-consumption*.

The overall reduction goal is given in percentage, and is supplied using the *reduction-goal* slider.

User defines the combination of available smart metering functions, by switching to ON or to OFF the switchers:

- *metering-availability*
- *individual-feedback*
- *neighbor-comparison*
- *Tips&Tricks*

The *metering-availability* function is a pre-condition for the availability of the other three smart functions.

Three buttons, on the top left corner of the screen, allow the user:

- to setup the system (*Setup button)*
- to run it for a single run (*GO* button)
- or forever (forever GO button)

On the top right of the screen there is an input window: *seed.* By it the user can set the seed of the random values.

The scenarios described in Chapter 8 have been obtained using 10000 as value assigned to such a parameter.

The discussion about the stochastic behavior of SAM4SN and the results of experiments using different seed will be supplied in Chapter 8.

The central window describes the status of all agents and is composed by a grid of 33x33 cells. On each cell there can be one agent. Agents have different color and shapes, as described in Chapter 7 (par. 7.2.1). When the system runs, the windows change because agents change the type they belong to.

Output areas are:

- A temporal plot of the global resource consumption (in red) and of the global resource use (in grey).
- A temporal plot of the number of different types of agent (in red, brown yellow, green and blue) (see Fig. 1).
- A histogram of awareness values of agents, in green.
- A histogram of individual consumption of agents (own resource consumption), in red.
- Two monitor windows with the value of the logical variables sustainability-tipping-point and unsustainability-tipping-point.
- An output window with a message describing when the system reaches the reduction goal and stops.

APPENDIX 3: List of parameters

Parameters	Reference formula	Notation in ODD	Values
General			
Max-N-blinds			50
Max-N-indifferents			300
Max-N-spectators			300
Max-N-actives			200
Max-N-evangelists			50
In-radius			2
Sustainability Tipping point	Percentage of active or evangelists agents on the whole population		10%
Unsustainability Tipping point	Percentage of blind agents on the whole population		10%
Max-reduction-goal			100
Max-initial-global-resource-consumption			50000
Relative Initial Consumption (referred to evangelist agent consumption)	$iorc_i = C_i * euc$		
Blind		C_{blind}	1.4
Indifferent		$C_{indifferent}$	1.3
Spectator		$C_{spectator}$	1.2
Active		C_{active}	1.1
Initial reduction goal	rgi(t=0)	0	
Initial resource consumption	$orc_i(t=0)$	iorci	
Social reinforcement	reinforce(t=0)	0	
AGENT AWARENESS			
Initial awareness			
Blind			0
Indifferent			8
Spectator			16
Active			100
Evangelist			2000
Awareness thresholds			
Blind- indifferent			8
Indifferent- spectator			16
Spectator- active			32
Active-evangelist			2000
Awareness increment			
Local influence	$\alpha_i v_{gr} + \varepsilon_i v_e + \beta_i v_b$		
α_i= awareness **local** increment coefficient1		α_i	
Blind			1
Indifferent			1
Spectator			1
Active			0
ε_i =awareness **local** increment coefficient2		ε_i	
Blind			0
Indifferent			0
Spectator			0

Active			2
β_i= awareness **local** decrement coefficient		β_i	
Blind			-2
Indifferent			-1
Spectator			-1
Active			0
Global influence	$\gamma_i n_{gr30}+\delta_i n_{gr80}$		
light green percentage of green agent on the whole population	n_{gr30}		30%
strong green percentage of green agent on the whole population	n_{gr80}		80%
global light-green increment coefficient	γ_i		
Blind			0
Indifferent			0
Spectator			1
Active			0
global strong-green increment coefficient	δ_i		
Blind			0
Indifferent			0
Spectator			0
Active			1
REDUCTION GOAL	$rg_i = orc_i(t-1) * K_i$		
REDUCTION GOAL Coefficient	$\mathbf{K_i}$		
Blind			-0.01
With Metering			
Indifferent			0
Spectator			0.001
Active			0.005
Evangelist			0.15
INDIVIDUAL CONSUMPTION	$\mathbf{orc_i(t) = orc_i(t-1) - rg_i(t) * W_i}$		
Rate to reach the reduction goal	$\mathbf{W_i}$		
Blind			0.1
With only Metering			
Indifferent, Spectator, Active, Evangelist			0.01
With only Metering & Suggestion			
Indifferent, Spectator, Active, Evangelist			0.02
With only Metering &Feedback			
Indifferent			
Spectator			
Active			
Evangelist			
With Suggestion			
Indifferent, Spectator, Active, Evangelist			$\mathbf{W_i *2}$
Resource production			
Blind, Indifferent, Spectator, Active			0
Evangelist	$\mathbf{orp_{evangelist} = orc_{evangelist} * 0.02}$		

Table 5 – List of parameters

8. SCENARIOS

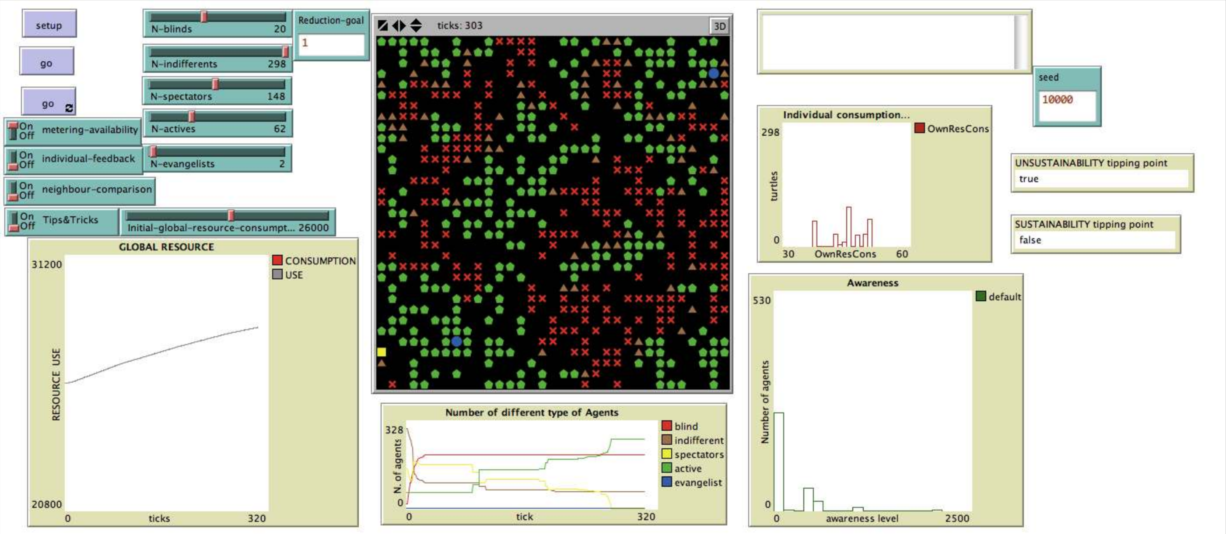
In this chapter we will present several SAM4SN configurations.

As showed in Figure 36, the user interface allows initializing the model. In this chapter we will show that there are scenarios, which lead to overuse of the resource and scenarios in which this does not happen because the social influence mechanism has a positive effect, i.e. sustainable behavior emerges.

We will observe from which initial conditions and parameters it depends whether the system can reach a sustainable state.

8.1 Scenario 1: unsustainability

We can detect one possible initial configuration that will lead to an emergent behavior shown in Figure 37.



N-blinds 20
N-indifferents 298
N-spectators 148
N-actives 62
N-evangelists 2
Reduction-goal 1
Initial-global-resource-consumpt... 26000
seed 10000
UNSUSTAINABILITY tipping point true
SUSTAINABILITY tipping point false
ticks: 303

Figure 37 - Scenario 1: unsustainability

N-blinds	20
N-indifferents	298
N-spectators	148
N-actives	62
N-evangelists	2
Initial global resource consumption	26000
Overall reduction goal	1
metering-availability	ON
individual-feedback	OFF
neighbour-comparison	OFF
Tips&Tricks	OFF

Table 6 – Initial Configuration of Scenario 1

In scenario 1 the resource reduction goal is never reached, because the overall consumption increases, as showed in detail in Figure 38, where we can see the resource use temporal plot. The time unit is of one day.

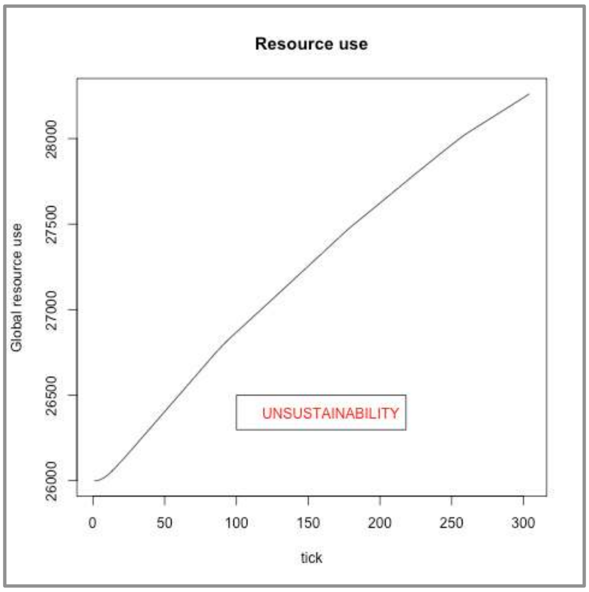
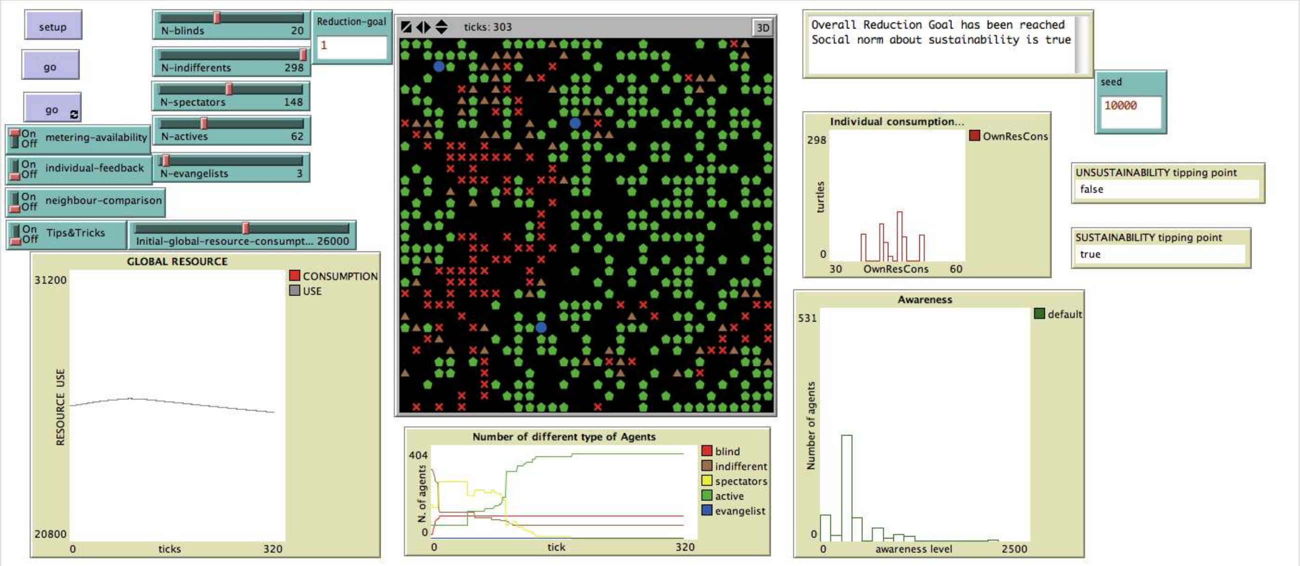


Figure 38 - Resource use in Scenario 1

The collective resource use of scenario 1 is not trivial to forecast based on the individual agents' behaviors. Even a very small difference in the configuration can strongly change the overall behavior.

8.2 Scenario 2: sustainability



N-blinds 20
N-indifferents 298
N-spectators 148
N-actives 62
N-evangelists 3
Reduction-goal 1
On Off metering-availability
On Off individual-feedback
On Off neighbour-comparison
On Off Tips&Tricks
Initial-global-resource-consumpt... 26000

```
Overall Reduction Goal has been reached
Social norm about sustainability is true
```

seed 10000
UNSUSTAINABILITY tipping point false
SUSTAINABILITY tipping point true

Figure 39 - Scenario 2: sustainability

N-blinds	20
N-indifferents	298
N-spectators	148
N-actives	62
N-evangelists	3
Initial global resource consumption	26000
Overall reduction goal	1
metering-availability	ON
individual-feedback	OFF
neighbour-comparison	OFF
Tips&Tricks	OFF

Table 7 – Initial Configuration of Scenario 2

Changing the initial number of only one unit of most influential type of agent - the evangelist - the awareness spread leads to a sustainable state, where the consumption of the agents decreases till reaching the resource reduction goal.

A sustainability scenario emerges - Scenario 2 in Figure 40 - where there is an overall resource consumption reduction. The reduction goal is reached, as shown in Figure 39.

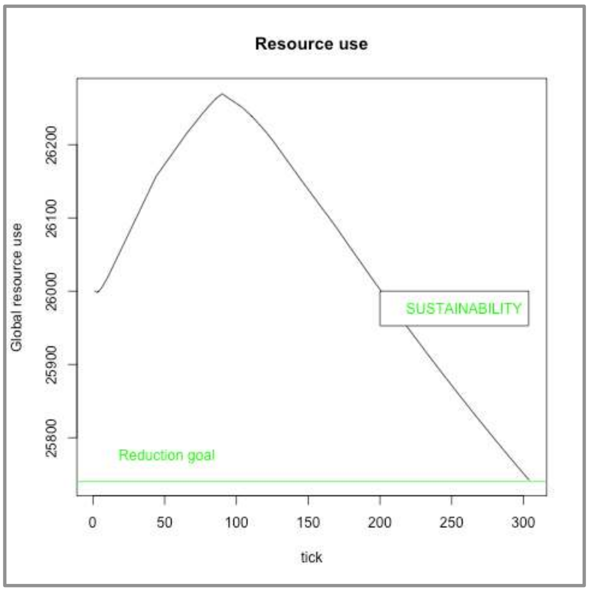


Figure 40 - Resource use in Scenario 2: sustainability

The only difference between the two initial configurations leading to Scenario 1 and to Scenario 2, as mentioned before, consists of one more evangelist agent in the agent set. This type of agent has a wider influence radius than the other types of agent.

In Figure 41 we can compare the time-series of the five different types of agents in the scenario 1 (on the left), and in the scenario 2 (on the right). We observe as a very small difference in initial condition can lead to a different dynamics in the whole system.

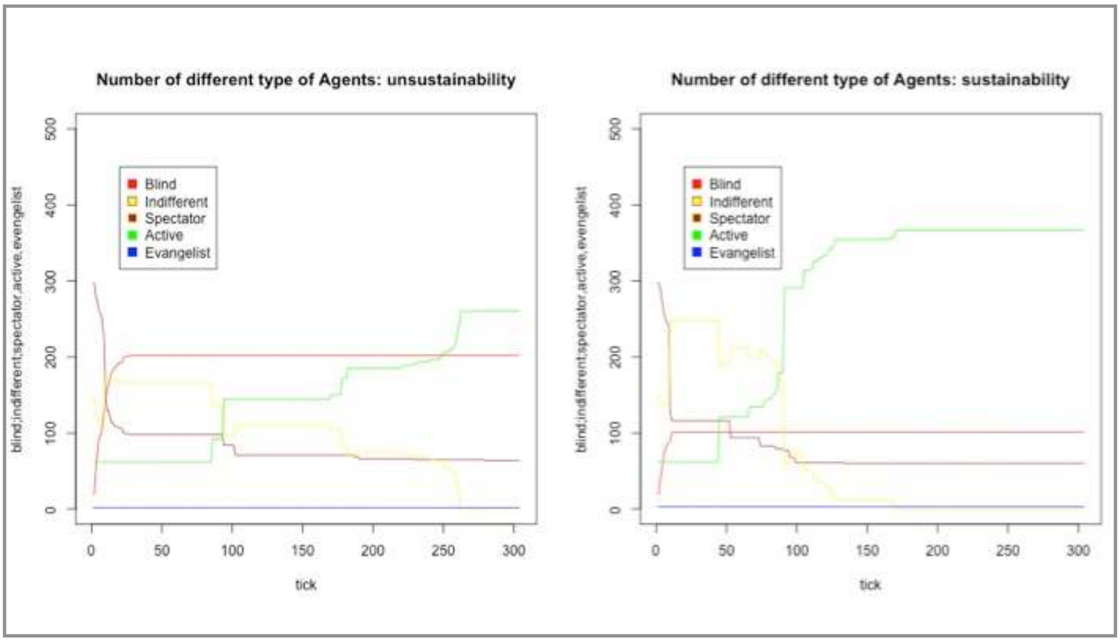


Figure 41 - Agent types distribution in unsustainable and sustainable scenarios

We can compare the two agent membership mechanisms leading to reach the overall reduction goal, i.e. leading to sustainability, and leading to unsustainability. We remark that a totally different dynamics is generated by the same behavioral consumption patterns of the agents and only one more influent agent, over a whole population of more than 500 agents.

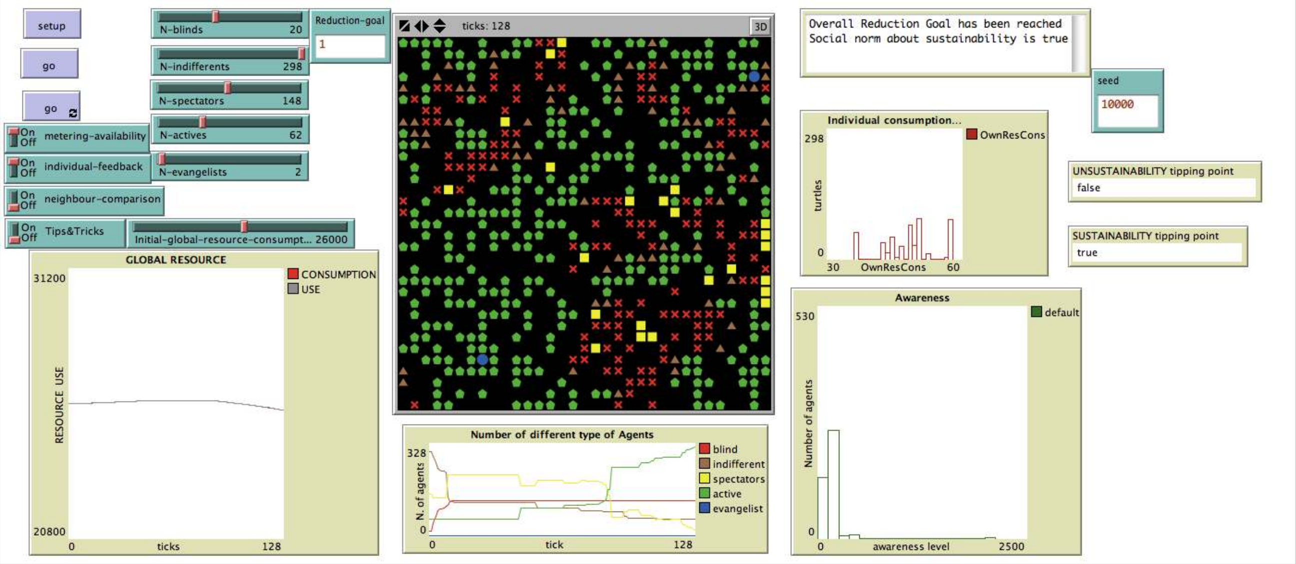
8.3 Scenario 3: empowering agents with smart metering functions

The role played by smart metering function can be described by an example.
The initial configuration of Scenario 1 has been defined supplying agents only with the metering function but without the other smart metering functions. We can see if giving agents with other smart metering function affect the overall system behavior. To add a smart metering function empowering agents with individual feedback about their historical consumption. we change this initial configuration by setting the feedback smart metering function to ON.

N-blinds	20
N-indifferents	298
N-spectators	148
N-actives	62
N-evangelists	2
Initial global resource consumption	26000
Overall reduction goal	1
metering-availability	ON
individual-feedback	ON
neighbour-comparison	OFF
Tips&Tricks	OFF

Table 8 – Initial Configuration of Scenario 3

This new Scenario 3 corresponds to Scenario 1 with feedback smart function. As showed in Figure 42, the overall emergent behavior changes and the system reaches the reduction goal.


N-blinds 20
N-indifferents 298
N-spectators 148
N-actives 62
N-evangelists 2
Reduction-goal 1
metering-availability On
individual-feedback On
neighbour-comparison Off
Tips&Tricks Off
Initial-global-resource-consumpt... 26000
seed 10000

```
Overall Reduction Goal has been reached
Social norm about sustainability is true
```

UNSUSTAINABILITY tipping point: false
SUSTAINABILITY tipping point: true

Figure 42 - Scenarios 3

The resource use of the scenario, as shown in Figure 43, leads to sustainability by reaching the reduction goal of 1% in 120 time units.

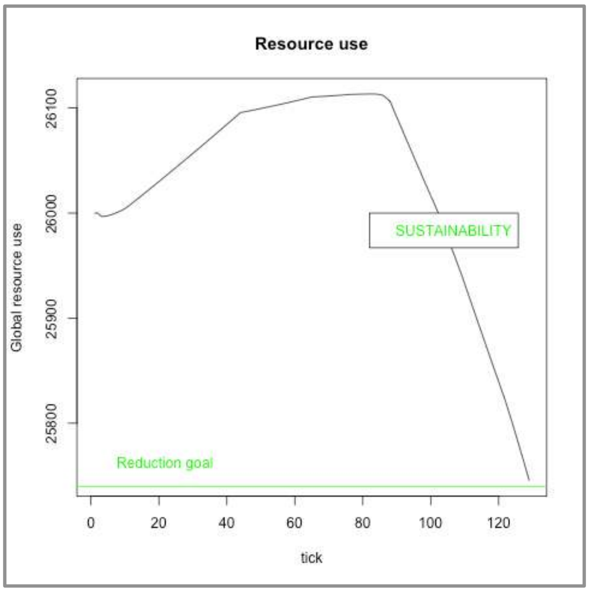


Figure 43 - Resource use in Scenario 3

As mentioned in previous chapter, an empirical definition of social norm widely used in the research area of global environmental challenge (Kinzing et al., 2013) establishes that social norm emerges after the system has reached a given tipping point. This tipping point may be as low as 10% of the population, if the minority is "consistent and inflexible" in its beliefs (Xie et al., 2011). In other words the existence of a significant portion of committed agents is an important feature.

8.4 Tipping point, reduction goal and social norm

In our system the agents that are "consistent and inflexible" in their beliefs" are the active ones and the evangelists, i.e. the green agents, but also the blinds.

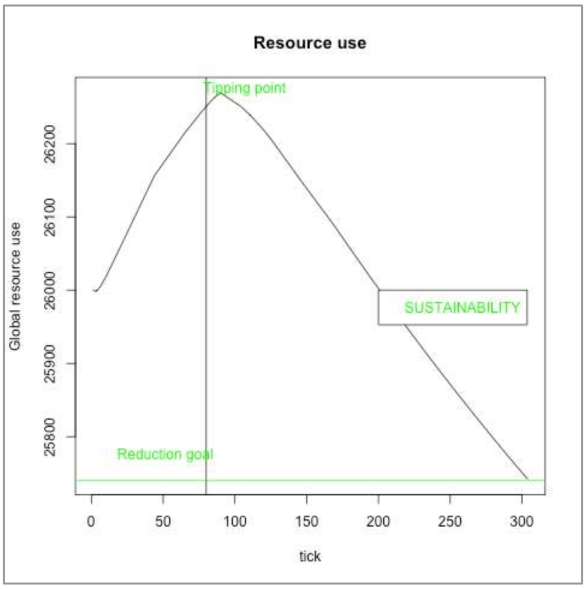


Figure 44 - Tipping point in Scenario 2

If we come back to the resource use in Scenario 2, we can observe, as showed in Figure 44, when the system reach the tipping point of 10% of green (actives and evangelists) agents that adopted a sustainable behavior.
The sustainability tipping point (STP) has been defined in Chapter 6 and 7 as "*a logical state variable that becomes true when the relative number of green agents with a negative delta individual consumption is greater than the 10% of the total number of agents and the total number of green agents with a positive reinforcement is greater than the total number of unaware agents with a negative reinforce*".
Because the tipping point is a logical variable its value can be true or false. What is interesting is the time when The STP became true. As value of the sustainability tipping point we associate the run number when it

become true. We will return on STP in Chapter 10. Such tipping point is the preliminary step for a sustainability social norm emergence. In Figure 45 we see the tipping point of Scenario 3.

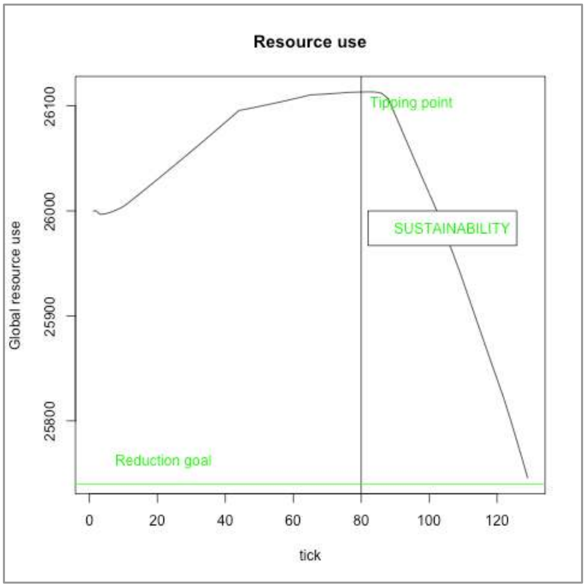


Figure 45 - Tipping point in Scenarios 3

We can observe that the tipping point is reached much earlier than the reduction goal. The reaching of the reduction goal is the effect of a long-term sustainability social norm. In all scenarios seed is set to 10000.

8.5 Stochastic relevance on model results

As introduced in Chapter 7, the initial position of agents is randomly assigned by the system, with as only constraint that on any cell of the grid there can be no more than one agent. We performed a set of experiments to test the sensitivity of the model to such a stochastic feature.

We replicated the three previous introduced initial configurations (see Table 6, 7 and 8), using 100 different seed values. The choice of replicating such experiments is driven by the consideration that they perfectly reproduce transition state situations, where a small change in initial conditions can change the finale state. We remember that:

- Configuration 1 leads to unsustainable consumption, but small changes, as only one more agent, are able to change the trend;
- In Configuration 2 we add one more evangelist (comparing Configuration 1) and this small change is able to change the final state, leading to sustainability;
- In Configuration 3 we replicate Configuration 1 but setting ON the feedback smart function and this small change is able to change the final state, leading to sustainability.

	CONFIGURATION1	CONFIGURATION 2	CONFIGURATION 3
N-blinds	20		
N-indifferents	298		
N-spectators	148		
N-actives	62		
N-evangelists	**2**	**3**	**3**
Initial global-resource-consumption	26000		
Overall reduction goal	1		
metering-availability	ON		
individual-feedback	**OFF**	**OFF**	**ON**
neighbour-comparison	OFF		
Tips&Tricks	OFF		
Seed: 100 random values			

Table 9 – Configurations of Set 1 of experiments on stochastic aspects (3x100 experiments)

The Set 1 of experiments on stocasticity is composed by 300 experiments, given by the combination of the three configurations for 100 different seed values.
Seed values and experiment results are supplied in Appendix 4, Table 11. We taken as references the configurations described in Par 8.1, 8.2 and 8.3, where seed is equal to 10000.
In Table 11 we put to 1 the value in a configuration column when the final state differs from the experiment n. 39 in Table 11 (with a seed value equal to 10000), that correspond to the scenarios described in Par 8.1, 8.2 and 8.3.
Looking at the results of Set1 of experiments we observe that:

- Configuration 3 always reached the same output of scenario 3, i.e. sustainability;
- Configuration 1 changes in 14% of case (i.e. reached sustainability instead of unsustainability)
- Configuration 2 changes in 45% of the case (i.e. reached sustainability instead of unsustainability).

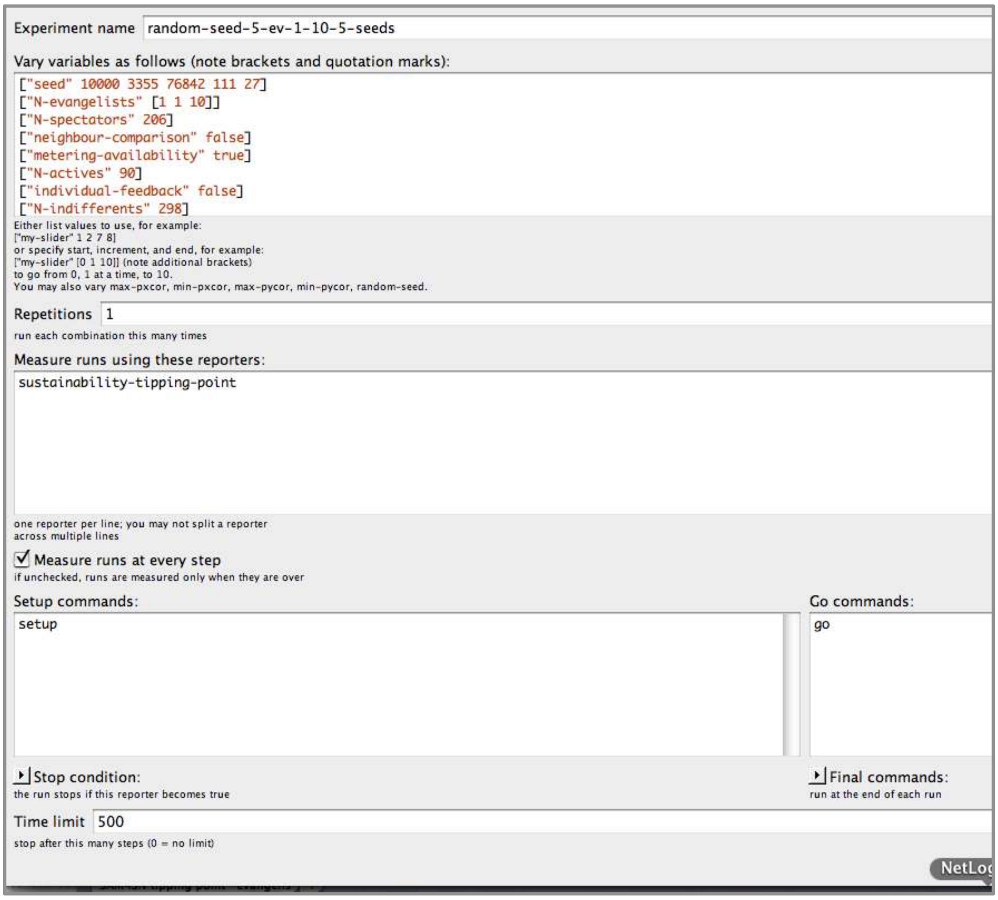
These results are reasonable because, as described above, Configuration 2 represents a critical situation, where a very small change in configuration of only one more agent (over an overall population of about 600 agents) can change the results of an experiment.
To better study such aspects we tried to explore if the transition to a configuration leading to sustainability happens if we add some more evangelists, and which is the variation interval in the number of evangelist agents.

We conducted a second set of experiments based on the Configurations of table 10.

Reduction-goal	1
N-actives	90
N-blinds	30
N-indifferents	298
individual-feedback	false
N-evangelists	**1,2,3,4,5,6,7,8,9,10**
N-spectators	206
Tips&Tricks	false
seed	10000, 3355, 76842, 111, 27
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 10 – Configurations of Set 2 of experiments on stochastic aspects (10x 5 experiments)

This Set 2 is composed by 50 experiments varying the number of evangelists from 1 to 10 and putting the seed value to 10000, 3355, 76842, 111, 27. We used *Netlogo BehaviourSpace* utility to perform this sets of experiment, as shown in Figure 46.



Experiment name: random-seed-5-ev-1-10-5-seeds

Vary variables as follows (note brackets and quotation marks):

```
["seed" 10000 3355 76842 111 27]
["N-evangelists" [1 1 10]]
["N-spectators" 206]
["neighbour-comparison" false]
["metering-availability" true]
["N-actives" 90]
["individual-feedback" false]
["N-indifferents" 298]
```

Either list values to use, for example:
["my-slider" 1 2 7 8]
or specify start, increment, and end, for example:
["my-slider" [0 1 10]] (note additional brackets)
to go from 0, 1 at a time, to 10.
You may also vary max-pxcor, min-pxcor, max-pycor, min-pycor, random-seed.

Repetitions: 1
run each combination this many times

Measure runs using these reporters:

```
sustainability-tipping-point
```

one reporter per line; you may not split a reporter across multiple lines

☑ Measure runs at every step
if unchecked, runs are measured only when they are over

Setup commands:

```
setup
```

Go commands:

```
go
```

Stop condition:
the run stops if this reporter becomes true

Final commands:
run at the end of each run

Time limit: 500
stop after this many steps (0 = no limit)

Figure 46 - Setting of Set 2 of experiments on stocasticity (50 experiments)

We verified a foreseen and acceptable variability in the SAM4SN behavior: within a variation interval of ± 1 unit of evangelists around the critical configurations (Configuration 1 and Configuration 2 i.e. the configurations with two or three evangelists) on an overall population of about 600 agents, the 50 experiments leads to coherent scenarios, independently form the seed parameters.

Passing from 1 to 10 evangelists with step 1, leads to 10 scenarios, under five different seed parameters.

In Appendix 4, where Figure 47 shows the results of experiments with seed equal to 10000, 3355, 76842 and Figure 48 shows the results of experiments with seed equal to 111, 27. Critical configurations, with two or three evangelists, are marked as green and pink (third and fourth columns) in Figures 47 and 48.

The SAM4SN behavior is responsive to the stochastic position of agents, but outputs are replicable within a small initial configuration variation interval.

Test files are available for experiments replication.

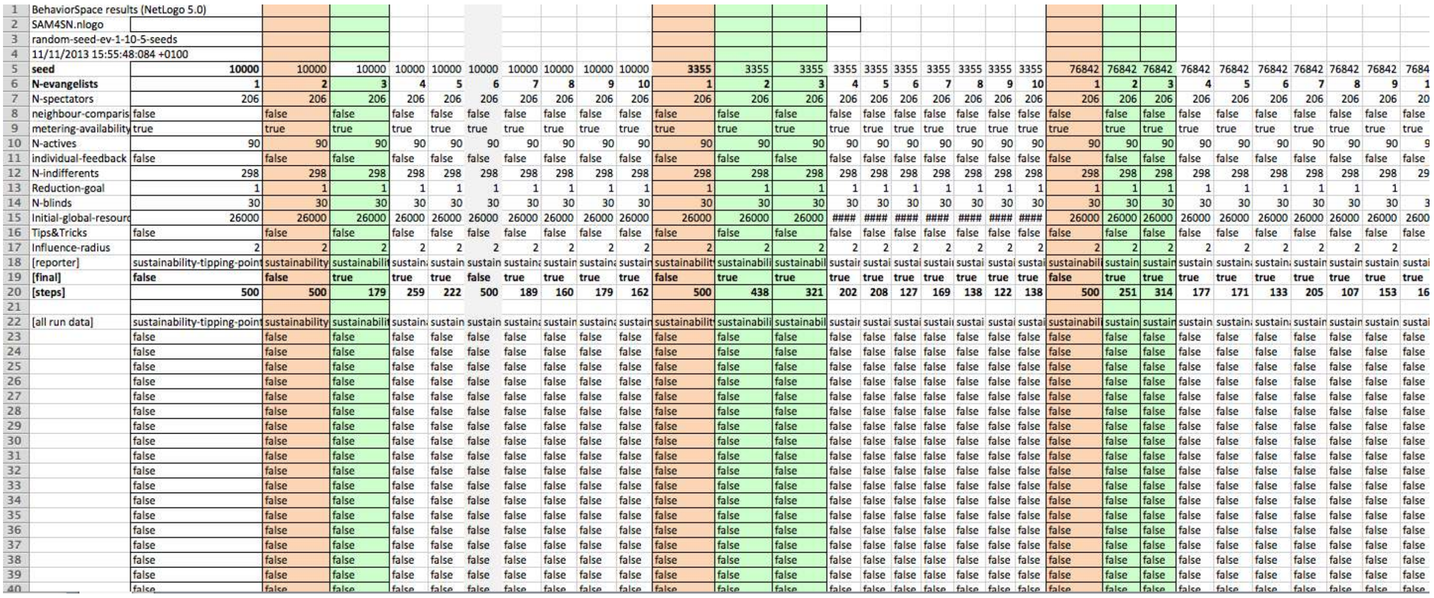
8.6 Conclusion

We described an ABM modeling awareness dynamic and reduction consumption mechanisms of households, with the aim to identify emerging patterns and scenarios leading to a reduction of the resource or leading to its overuse. Such goal can be reached in a sociotechnical ecosystem on the basis of individual behavior, social influence and social norm concepts. Stochastic behavior of SAM4SN is acceptable.

APPENDIX 4: Sets of experiments on stocasticity

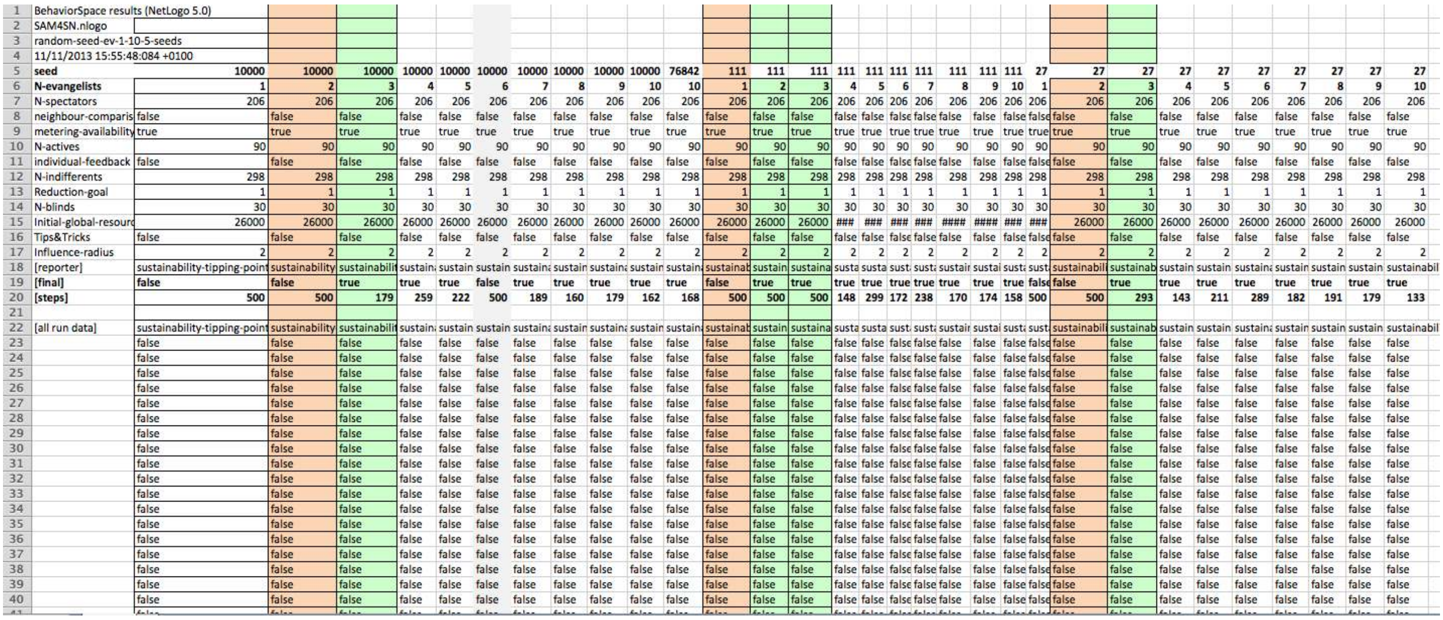
	RANDOM SEED VALUE	CONFIGURATION1	CONFIGURATION2	CONFIGURATION3
1	2			
2	3			
3	5			
5	10			
6	12		1	
7	15			
8	20			
9	23			
10	24			
11	29			
12	44		1	
13	55			
14	56			
15	89			
16	101			
17	120			
18	144		1	
19	189		1	
20	210		1	
21	322		1	
22	443		1	
23	444		1	
24	888		1	
25	898			
26	899	1	1	
27	1000			
28	1012			
29	1322			
30	1777			
31	1888			
32	2999		1	
33	3210		1	
34	3222			
35	3223	1	1	
36	6999		1	
37	8887		1	
38	8888		1	
39	**10000**			
40	10123			
41	11000	1		
42	11777	1	1	
43	12345		1	
44	12999		1	
45	16999			
46	17776		1	
47	17777			
48	29999			
49	43210		1	
50	47623			
51	50000			
52	69999	1		
53	70000		1	
54	101234		1	
55	112345		1	
56	123455		1	
57	123456		1	
58	147623		1	
59	300000		1	
60	476238			
61	476239		1	
62	543210		1	
63	622633	1		
64	765432		1	
65	988998		1	
66	1012345		1	
67	1622633	1		
68	1765432		1	
69	1988998		1	
70	4243444		1	
71	6226330			
72	6226331		1	
73	6543210			
74	7654320		1	
75	7654321			
76	8765432		1	
77	9889988			
78	9889989		1	
79	10123456			
80	14243444	1		
81	14243444	1		
82	18765432	1		
83	42434444		1	
84	42434445			
85	76543210			
86	87654320			
87	87654321	1	1	
88	98765432		1	
89	198765432	1	1	
90	876543210			
91	987654320			
92	987654321		1	
93	9876543210	1		
94	98765432101			
95	99999999999		1	
96	2E+11	1		
97	9.87654E+11			
98	1E+12			
99	9.87654E+12			
100	9.87654E+13			
	TOTAL FAILS	14	45	0

Table 11 – Results of Set1 of experiments on stocasticity



1	BehaviorSpace results (NetLogo 5.0)																														
2	SAM4SN.nlogo																														
3	random-seed-ev-1-10-5-seeds																														
4	11/11/2013 15:55:48:084 +0100																														
5	**seed**	**10000**	10000	10000	10000	10000	10000	10000	10000	10000	10000	**3355**	3355	3355	3355	3355	3355	3355	3355	3355	3355	76842	76842	76842	76842	76842	76842	76842	76842	76842	7684
6	**N-evangelists**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**
7	N-spectators	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	20
8	neighbour-comparis	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
9	metering-availability	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
10	N-actives	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	9
11	individual-feedback	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
12	N-indifferents	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	29
13	Reduction-goal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
14	N-blinds	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	3
15	Initial-global-resourc	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	####	####	####	####	####	####	####	26000	26000	26000	26000	26000	26000	26000	26000	26000	2600
16	Tips&Tricks	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
17	Influence-radius	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
18	[reporter]	sustainability-tipping-point	sustainability	sustainabilit	sustaina	sustain	sustain	sustaina	sustain	sustaina	sustain	sustainabilit	sustainabili	sustainabil	sustain	sustai	sustai	sustain	sustai	sustai	sustai	sustainabili	sustain	sustain	sustain	sustaina	sustaina	sustain	sustain	sustain	sustai
19	**[final]**	**false**	**false**	**true**	**true**	**true**	**false**	**true**	**true**	**true**	**true**	**false**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**false**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**
20	**[steps]**	**500**	**500**	**179**	**259**	**222**	**500**	**189**	**160**	**179**	**162**	**500**	**438**	**321**	**202**	**208**	**127**	**169**	**138**	**122**	**138**	**500**	**251**	**314**	**177**	**171**	**133**	**205**	**107**	**153**	**16**
21																															
22	[all run data]	sustainability-tipping-point	sustainability	sustainabilit	sustaina	sustain	sustain	sustaina	sustain	sustaina	sustain	sustainabilit	sustainabili	sustainabil	sustain	sustai	sustai	sustain	sustai	sustai	sustai	sustainabili	sustain	sustain	sustain	sustaina	sustaina	sustain	sustain	sustain	sustai
23		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
24		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
25		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
26		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
27		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
28		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
29		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
30		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
31		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
32		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
33		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
34		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
35		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
36		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
37		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
38		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
39		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
40		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false

Figure 47– Set 2 of experiments on stocasticity - Part I



1	BehaviorSpace results (NetLogo 5.0)																															
2	SAM4SN.nlogo																															
3	random-seed-ev-1-10-5-seeds																															
4	11/11/2013 15:55:48:084 +0100																															
5	**seed**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**10000**	**76842**	**111**	**111**	**111**	**111**	**111**	**111**	**111**	**111**	**111**	**111**	**27**	**27**	**27**	**27**	**27**	**27**	**27**	**27**	**27**	**27**
6	**N-evangelists**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
7	N-spectators	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206
8	neighbour-comparis	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
9	metering-availability	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
10	N-actives	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
11	individual-feedback	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
12	N-indifferents	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298	298
13	Reduction-goal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	N-blinds	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
15	Initial-global-resourc	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	###	###	###	###	####	####	###	###	26000	26000	26000	26000	26000	26000	26000	26000	26000
16	Tips&Tricks	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
17	Influence-radius	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18	[reporter]	sustainability-tipping-point	sustainability	sustainabilit	sustaina	sustain	sustain	sustaina	sustain	sustaina	sustain	sustaina	sustainab	sustain	sustaina	susta	susta	sust	sust	sustain	sustai	sust	sust	sustainabili	sustainab	sustain	sustain	sustaina	sustain	sustain	sustain	sustainabil
19	**[final]**	**false**	**false**	**true**	**true**	**true**	**false**	**true**	**true**	**true**	**true**	**true**	**false**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**false**	**false**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**
20	**[steps]**	**500**	**500**	**179**	**259**	**222**	**500**	**189**	**160**	**179**	**162**	**168**	**500**	**500**	**500**	**148**	**299**	**172**	**238**	**170**	**174**	**158**	**500**	**500**	**293**	**143**	**211**	**289**	**182**	**191**	**179**	**133**
21																																
22	[all run data]	sustainability-tipping-point	sustainability	sustainabilit	sustaina	sustain	sustain	sustaina	sustain	sustaina	sustain	sustaina	sustainab	sustain	sustaina	susta	susta	sust	sust	sustain	sustai	sust	sust	sustainabili	sustainab	sustain	sustain	sustaina	sustain	sustain	sustain	sustainabil
23		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
24		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
25		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
26		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
27		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
28		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
29		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
30		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
31		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
32		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
33		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
34		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
35		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
36		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
37		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
38		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
39		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
40		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false

Figure 48– Set 2 of experiments on stocasticity - Part II

9. SAM4SN VALIDATION

SAM4SN is an exploratory model that can be used as "a laboratory" to study socio-technical behaviors of people related to environmental sustainability. The validation approach has to be coherent with this consideration. After a short overview on ABM validation, the choice to perform a stakeholder validation is justified and the results are supplied.

9.1 Validation of Agent-Based Models

For researchers working according to the agent-based approach the validation of ABM is becoming one of the major points in the agenda (Tesfatsion, 2007; Fagiolo, Moneta, & Windrum, 2007). Since the empirical validation of ABM is still a brand new topic, at the moment there are only a limited number of contributions in the literature dealing with it, as summarized below.

Looking at the main methodological aspects, in the literature (Tesfatsion &. Judd, 2006; Bianchi, Cirillo, Gallegati, & Vagliasindi, 2007; Marks, 2007) we can find three alternative ways of validating computational models:

1. *Descriptive output validation*, matching computationally generated output against already available actual data. This kind of validation procedure is probably the most intuitive one;

2. *Predictive output validation*, matching computationally generated data against yet-to-be-acquired system data. The main problem concerning with this procedure is essentially due to the delay between the simulation results and the final comparison with actual data. This may cause some difficulties when trying to study long time phenomena. Predictive output validation must be considered an essential approach for an exhaustive analysis of a model meant to reproduce reality;

3. *Input validation*, ensuring that the fundamental *structural, behavioral and institutional* conditions incorporated in the model reproduce the main aspects of the actual system. This is also called *ex ante validation*.

We refer here to the work of Jannsen & Ostrom (2006) about empirical validation of Agent Based Models. Ostrom and Jannsen distinguish four different approaches to using empirical observation in combination with ABM:

- social laboratory;
- case study;
- survey research;
- census or statistical data.
-

Jannsen and Ostrom (2006) observe as given the empirical problems with data collection, and given too the explicit inclusion of cognitive, institutional, and social processes in ABMs, *in some cases no data even exist* to perform an empirical analysis.

When no data exist other criteria that Ostrom and Jannsen suggest to use to validate an ABM consist of answering some of these questions:

1. Is the model plausible, given our understanding of the processes?
2. Can we understand why the model is doing so well?
3. Did we derive a better understanding of our empirical observations?
4. Does the behavior of the models coincide with the understanding of the relevant stakeholders about the system?

These criteria - and in particular criterion 4 – have been followed in our validation activities, as below described.

9.2 SAM4SN Validation issue

Referring to the above described validation types - and relating them to our model - we can say that:
1. Prescriptive output validation is impossible because it is not available a suitable complete dataset for such kind of validation. Suitable data do not exist or are partially owned by utilities companies that do not supply them - even if for research purpose only - for privacy issues, because the data required consist of resource consumptions of households.

2. Predictive output validation is not the right one for the proposed model.

3. An (also if rough) ex-ante validation is the more suitable approach for our model.

9.2.1 SAM4SN ex-ante validation trial

The first step has been to look for a case study with related data set on behavioral changes toward more sustainable lifestyle and social influence of awareness mechanism- as depicted in our model. This is not a trivial issue for several reasons. Our model approach is original because it is strongly interdisciplinary. The mechanisms that it is trying and reproduce are socio technical mechanisms playing at different levels: environmental awareness spread, social influence and social norms, which are facilitated by smart metering functions.
The outcome is related to if, how and when such mechanisms lead to limited resource consumption reduction.
Overall it s difficult to find a limited-area case study aimed to study such complex eco and socio dynamics.
The only real empirical experience we can try to match with my models results was a behavioral changes program called "NW H2Home Smart". NW H2Home Smart is a BCP (Behavioral Change Program) about water consumption reduction that has been held in North Western Australia in 2011, by the Water Corporation of Western Australia and the School for environmental Science of the Murdoch University of Perth Department of environmental engineering. Such BCP aimed to increase environmental awareness of household, decreasing water consumption and increasing water recycling. Water is a limited resource in this geographic area because it is a desertification risk area and public authorities are trying to launch initiatives aiming to foster environmental awareness and related sustainable behaviors. As already said in the first part of the research, the limited resource can be energy, as well water, in the context of Global North households.
Main findings of such an empirical validation first trial have been satisfactory.
Looking at the final reports and overall results of the NW H2Home Smart program some positive findings are:
I. The model behind the NW H2ome Smart and the conceptual framework of SAM4SN are very similar, because both are based on categorization of household participant according to consumption patterns.
II. The overall organization of SAM4SN and of NW H2ome Smart are both based on:

- A categorization of agents in five types of different environmental awareness
- Reduction patterns by type
- Opinion leader's role
- Identification of main facilitators, by type, that leads to behavioral changes and reduction of consumptions.

The NW H2ome Smart program supplied us with a partial data set not suitable for an empirical validation of SAM4SN. Real individual consumption data of households are not available in a useful way.
A minimum sub-set of data allows only overall validation of SAM4SNmodel, consisting of a comparison of **results only at an aggregate level.**
Given a community of households in a given geographic area, such sub-set of data consists of:
- The overall initial water consumption
- The overall final water consumption.
- The time scale and global duration of the program (that supplied the smart metering basic tool).

The supplied dataset does not allow a complete ex-ante validation because initial individual water consumption data **are not usefully supplied** to compare with individual consumption over a given period and to evaluate the reduction.
For a an empirical validation of our model, we would need, at least, this set of information:

- Suitable profiling of households in a given area, able to typifying them;
- Individual initial water consumption of each household;
- Individual final water consumption of each household;
- The time step and global duration of a simulation.

The supplied profiling data did not allow us to assign our agents with an initial awareness level. Such assignment could be done by supplying users at the beginning of a project (launched by an utility company or by an environmental institution) with a questionnaire about their consumption patterns.

9.3 SAM4SN Stakeholder validation

As mentioned in section 1.2, the explicit inclusion of cognitive, institutional, and social processes in ABMs, leads often to empirical problems with data collection and in some cases, no data even exist (or are available) to perform a quantitative validation. As Ostrom and Jannsen suggest, alternative approaches can be used to validate an ABM when no data exist, as for example **relevant stakeholders opinion if the behavior of the models coincide with their understanding of the real system**.

We identified as significant stakeholders for validation:
- Istituto IRES (Istituto di Ricerche Economico sociali del Piemonte) di Torino
- The International ACM Conference on Management of Emerging Digital Ecosystem (MEDES2013), held in Luxembourg the 30th of October 2013.

We performed two validation sessions, one for each institution. All validation sessions have been performed by a questionnaire hand out to the audience.

The closed questionnaire is based on a 5-points Likert scale.

Items measured the level of disagreement or agreement on sentences related to the main features of the model:

- agent typing,
- agent behavior,
- social influence,
- social reinforcement.

In Appendix 5 the questionnaire for the stakeholder validation sessions.

9.3.1 MEDES 2013 stakeholder validation session

The validation has been performed in the "Digital ecosystem" session of MEDES2013. The answers have been supplied by all participants to the above mentioned conference session.

	Statement 1	Statement 2	Statement 3	Statement 4	TOTAL	
Strongly disagree	0	0	0	0	0	0
Disagree	0	0	0	1	1	0.02
Neither agree nor disagree	0	4	2	4	10	0.18
Agree	13	10	9	7	39	0.69
Strongly agree	1		3	2	6	0.11

Table 12 – MEDES2013 stakeholder validation results

The summary of the answers demonstrated a strong appreciation of the model: 80% agree or strongly agree (69% agree and 11% strongly agree), while only 18% neither agree nor disagree and only 2% disagree. Nobody strongly disagreed.

9.3.2 IRES PIEMONTE stakeholder validation session

The validation session has been performed at the research center of IRES Piemonte the 12th of November 2013 at Turin. Italy. Answers have been supplied by all participants to the seminar.

	Statement 1	Statement 2	Statement 3	Statement 4	TOTAL	
Strongly disagree	0	1	0	0	1	0.04
Disagree	1	0	1	0	2	0.08
Neither agree nor disagree	0	1	2	3	6	0.25
Agree	3	4	3	3	13	0.55
Strongly agree	2	0	0	2	2	0.08

Table 13 – IRES Piemonte stakeholder validation results

The summary of the answers demonstrated a good appreciation of the model: 63% agree or strongly agree (55% agree and 8% strongly agree), while 25% neither agree nor disagree, 8% disagree and only 4% strongly disagree.

9.3.3 Stakeholder validation overall results and comments

Stakeholder validation sessions confirmed, as main positive feedback, that the description of agent as strongly type based with awareness is a driving feature of the conceptual model. The most agreements are about statement1 – agent typing (95% of agree or strongly agree) and statement3 – social influence (75% of agree or strongly agree).

Statement4 – social reinforcement is the less uncertain with a 35% that neither agrees nor disagrees.

A 5% of answers to all statements are of disagreement or strong disagreement.

Several comments followed each session. Different type of comments came from Computer Scientists (Digital ecosystems of MEDES Conference) and from sociologists (IRES Piemonte). While computer scientists are strongly impressed from the complexity of the system, the sociologists are more concerned about economical related aspects (see preliminary assumptions in Chapter 5).

APPENDIX 5: Stakeholder validation questionnaire

Agent types

Statement 1. The categories of agents reproduce satisfactory the user segmentation.

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

Agent behaviors

2. The law of variation of individual consumption adequately covers the space of the parameters.

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

Social Influence

3. The representation of social influence on a local and global basis takes into account the main factors

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

Social reinforcement

5. *The representation of social reinforcement, which comes from the correlation between the trends of the individual with the collective behavior adequately, expresses the dynamics of user.*
6.

- Strongly disagree
- Disagree
- Neither agree nor disagree
- Agree
- Strongly agree

10. SENSITIVITY ANALYSIS OF THE ABM

The main objective of SAM4SN is to identify under which initial conditions the system leads to sustainable scenarios. **To reach the reduction goal, in the context of SAM4SN model, means to reach sustainability and both expressions are used as equivalent.**

We performed a local sensitivity analysis with the aim to understand how sensitive is the model to the value of main individual parameters.

We explored if the initial number of blind agents is a critical condition against the awareness diffusion dynamics, because too many blind agents prevent an awareness spread. We explored if a certain percentage of green agents (actives or evangelists) on the whole population is required to trigger a sustainable behavior.

We explored if and how much the consumption behaviour of the agents depends also from the availability of some smart metering functions, as we will see in a set of experiments.

We explored then if the "sustainability tipping point" (as defined in Chapter 6 and in Chapter 7) can be considered an "early signal" that the defined overall reduction goal will be reached

In other words we tried to verify **if the sustainability tipping point can be considered a qualitative monitoring indicator of sustainability.**

10.1 Committed agents density and sustainability constraints

We performed a set of experiments to test the dependence of the system behavior from the initial relationship between the number of green agents and of blind agents and trying to find some dependence among their initial number. We remember that for us **green agents are actives or evangelists** (see Chapter 7 for the formal definition of green agents).

We did a series of experiments to check if there is a correlation between the percentages of green agents on the whole population and the activation of a sustainable behavior and whether, and to what extent, the presence of blind agents is a constraint against such activation.

Each experiment consists of observing the behavior of SAM4SN **when the number of blinds is equal to that of the whole of actives and evangelists**.

The **series of experiments differ** in the density of population.

We performed **fives series of experiments, varying the density of population**:

- Very crowded population density
- Crowded population density
- Medium-crowded population density
- Scattered population density
- Very- scattered population density

Each series is composed by four sets of initial values, with three variants in the configuration for experiment (indicated in table 14 in yellow, turquoise and pink).

Reduction-goal	1
N-blinds	**x = (20,30,40,50)**
N-indifferents	**300**
N-spectators	**240**
individual-feedback	false
N-actives	**0, x/2, x**
N-evangeslists	**x, x/2, 0**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 14– Very crowded population density series

Reduction-goal	1
N-blinds	**x= (20,30,40,50)**
N-indifferents	**150**
N-spectators	**120**
individual-feedback	false
N-actives	**0, x/2, x**
N-evangeslists	**x, x/2, 0**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 15 – Crowded population density series

Reduction-goal	1
N-blinds	**x = (20, 30, 40, 50)**
N-indifferents	**74**
N-spectators	**60**
individual-feedback	false
N-actives	**0, x/2, x**
N-evangeslists	**x, x/2, 0**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 16 – Medium-crowded population density series

Reduction-goal	1
N-blinds	**x = (20, 30, 40, 50)**
N-indifferents	**37**
N-spectators	**30**
individual-feedback	false
N-actives	**0, x/2, x**
N-evangeslists	**x, x/2, 0**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 17 - Scattered population density series

Reduction-goal	1
N-blinds	**x = (20, 30, 40, 50)**
N-indifferents	**18**
N-spectators	**15**
individual-feedback	false
N-actives	**0, x/2, x**
N-evangeslists	**x, x/2, 0**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 18 - Very scattered population density series

We performed 5 x 4 x 3= 60 experiments. Table 19 is the global synopsis of the described 60 experiments. The **three configurations of each experiment** are defined as follows.

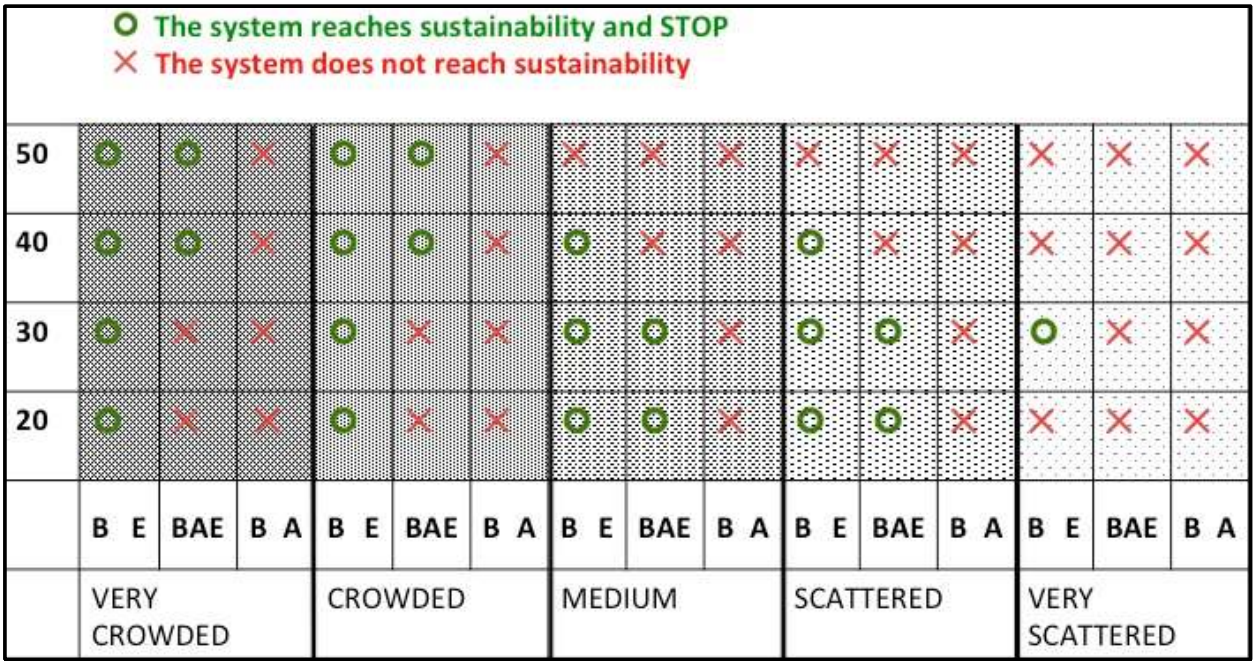
In the first configuration, we assigned the number of evangelists equal to that of the blinds (and therefore the active are 0). In Table 14 these values are indicated in yellow. This configuration is reported as **BE (Blinds Evangelists) Configuration** in Table 19.

In the second configuration we assigned the number of actives equal to that of the evangelists (i.e. the half of the blinds). In Table 14 these values are indicated in turquoise. This configuration is reported as **BAE (Blinds Actives Evangelists) Configuration** in Table 19.

In the third configuration we place the number of actives equal to that of the number of blinds (and therefore the evangelists are 0). In Table 14 these values are indicated in turquoise. This configuration is reported as **BA (Blinds Actives) Configuration** in Table 19.

Looking at the patterns in Table 19 we observed that in general the **BA Configuration is not sensible to the density** of the whole population. We can observe as it is always leading to unsustainability. We can so consider the density of blind agents on the whole population as a threshold against sustainability.

Looking at Table 19 from left to right (from more to less populated situations) other BE and BAE configurations are sensible to density: when density decreases, unsustainability is more probable.



○ The system reaches sustainability and STOP
✕ The system does not reach sustainability

50	○	○	✕	○	○	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕
40	○	○	✕	○	○	✕	○	✕	✕	○	✕	✕	✕	✕	✕
30	○	✕	✕	○	✕	✕	○	○	✕	○	○	✕	○	✕	✕
20	○	✕	✕	○	✕	✕	○	○	✕	○	○	✕	✕	✕	✕
	B E	BAE	B A	B E	BAE	B A	B E	BAE	B A	B E	BAE	B A	B E	BAE	B A
	VERY CROWDED			CROWDED			MEDIUM			SCATTERED			VERY SCATTERED		

Table 19 – Local sensitivity to density of population

If we look at patterns in Table 19 from top to bottom, we observe that such a phoenomenon is strongest when an absolute value of blinds is greater or equal to 40.

In Appendix 7 the plots of BAE Configuration for the series: very crowded, crowded, and medium crowded series (Figures 49, 50, 51).

All experiment files will be supplied on request, to allow replication and verification of experiments.

10.2 Committed agents and tipping points

If we come back to Chapter 8 we can observe, as showed in Figure 44 and in Figure 45, the sustainability tipping point as a potential indicator in configurations leading to sustainability.

The sustainability tipping point has been defined in Chapter 6 and 7 as "*a logical state variable that becomes true when the relative number of green agents (actives or evangelists) with a negative delta individual consumption is greater than the 10% of the total number of agents and the total number of green agents with a positive reinforcement is greater than the total number of unaware agents with a negative reinforce*".

Because the tipping point is a logical variable its value can be true or false. What can be interesting is to know when the sustainability tipping point becomes true. So as value of the sustainability tipping point we associate the run number when it becomes true.

The idea of a tipping point for environmental sustainability is used by Kinzig and colleagues (2013) and derives from theoretical works (Xie et al., 2011) about the role that committed agents have in reaching consensus. In particular the value of 10% of committed agents - as a critical value for opinion diffusion - has been introduced by Xie and colleagues (2011).

The notion of **committed agent** is implemented in SAM4SN, as well as the notion of *quasi-committed agent*.

In our model evangelist agents are strictly committed agents, because they are very determined in their belief. Their awareness cannot decrease, so they cannot change their type. When an agent becomes evangelist it will be forever.

Blind agents and active agents (see their description in Chapter 6 and 7) are "quasi committed" agents because their belonging to a type is very strong, if compared with other types of agent, like spectators and indifferents.

We introduced the notions of commitment and "quasi-commitment" as useful notions when linked to the concept of social reinforcement. Once a committed (evangelist) or quasi-committed agent (a blind or an active) is reinforced in his belief, this reinforcement is persistent and the agent remains reinforced as it was (positively or negatively), while not committed agents (spectators and indifferents) are responsive to positive or negative reinforcements. They reinforcement can be equal to 1 or to -1.

Looking at situations evolving toward sustainability, we can observe, as described in the next simulation experiments, that the sustainability tipping point (STP) is reached much earlier than the overall Reduction Goal (RG). So we can see the reaching of the RG as a long-term effect of a sustainability social norm.

We have already introduced in Chapter 8 some examples of experiment where the STP became true several runs before the system reached a sustainable behavior. If we will be able to demonstrate such property as a general property of STP, this will be a not trivial result, because the definition of STP is totally independent from the global reduction goal value and it depends only from the social reinforcement of a given percentage of committed or "quasi committed" agents.

An interesting property of SAM4SN would relay on **considering the STP** as a **sustainability real-time indicator**. STP could be seen as an "early warning" signal, able to anticipate the reaching of sustainability. We performed some sets of experiments to confirm or confute this hypothesis.

At first we performed one set of experiments to evaluate the magnitude order of the advance in reaching sustainability that the STP allows to foresee. Then we performed three sets of experiments to evaluate if the STP can be really considered as an indicator.

10.3 Sustainability tipping point use to forecast the achieving of the of reduction goal

To be a useful indicator the STP has to be able to supply some quantitative information about a future state of sustainability of the system. In our case it corresponds to know "how early" the STP becomes true before

the system reaches the sustainability (i.e. the reduction goal). This time interval is expressed in terms of run number of SAM4SN. We recorded the run when STP becomes true and we call it STP.
We recorded the run when RG has been reached and we call it RG.
Both STP and RG are expressed in term of the run numbers (from the start of simulation).
The difference between the RG and the STP represents the advance of the STP toward the reaching of the RG.
The relative advance of STP to RG is the ratio of the STP advance on RG. It gives a number between 0 and 1. We indicate it as STPRA (STP relative advance).
The Relative advance of STP on RG is an indicator, able to quantify how early the STP is on RG.
We evaluated the STPRA values on a set of 81 experiments, to find if and how much this potential indicator is significant in its amount.
Experiments are obtained on a basic initial configuration consisting of:

- Overall reduction goal of 1%;
- Initial consumption of 26000;
- 20 blind agents;
- Metering-availability and individual-feedback smart metering functions set to true;
- Neighbor-comparison and Tips&Tricks metering functions set to false.

The configurations of individual experiments are obtained by varying the initial number of other types of agent.

Reduction-goal (in %)	1
N-actives	**[20,30,40]**
N-blinds	20
N-indifferents	**[300,150,74]**
individual-feedback	true
N-evangelists	**[20,30,40]**
N-spectators	**[240, 120,60]**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	true

Table 20 - Configurations of initial state of a Set of 81 experiments on Sustainability Tipping Point and its relative advance on the reaching of the Reduction Goal

We recorded these data for all experiments:

CASE-NUMBER	STP(run number when STP become true)	Reduction Goal (run number when RG is reached)	STP Advance on RG	STP Relative Advance (STPRA)	Number of STPs

Table 21 – Data of each experiment

We observed as in all 81 experiments the system reached the sustainability (i.e the system stopped before the time limit of 800, so the RG is smaller than 800). In Appendix 6 you can find examples .
The amount of the STP relative advance is significant:

	MIN	1st Quartile	MEDIAN	MEAN	3rd Quartile	MAX
STPRA	0.02222	0.45450	0.68420	0.60280	0.79310	0.79310

Table 22 – Summary of STP Relative Advance (STPRA) in the Set of experiments of Table 20

Plotting as a histogram the 81 STPRA values we can have a better synopsis of the amount of such potential indicator.

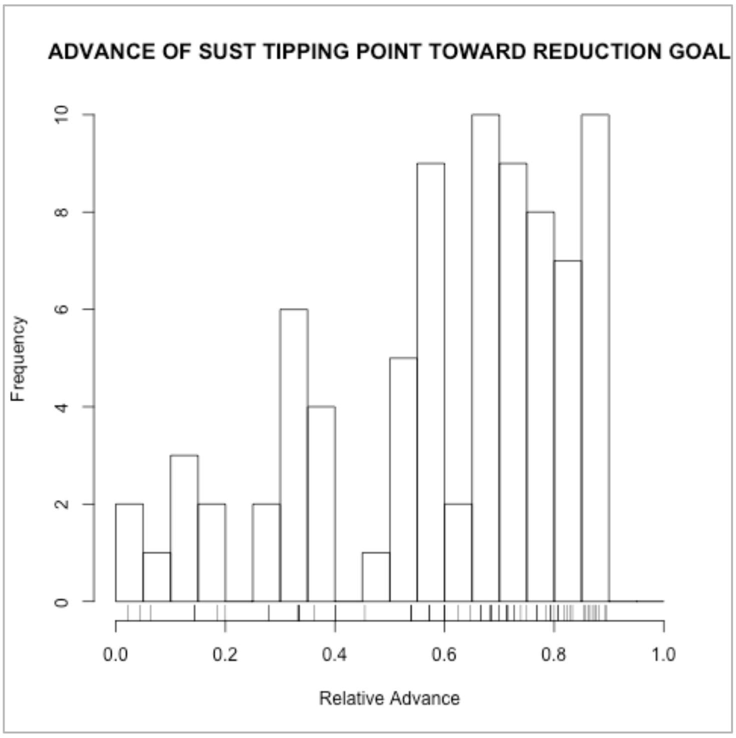


Figure 49- Distribution of STP Relative advance values

To be a useful indicator the STP has to be able to give also a quantitative, even if indirect, indication about a future state of the system.

10.4 Sustainability tipping point as an indicator

An *indicator* is a measure that is used to demonstrate change in a situation, or the progress in, or results of, an activity, project, or program. An indicator is a useful tool if it is reliable.
STP could be considered as a **qualitative monitoring indicator.**
To demonstrate if the STP is a reliable indicator and STPRA is able of anticipating reduction goal reaching, we have to demonstrate four conditions.

- Condition-1: The STP becomes *always true* when the system leads to sustainability.
- Condition-2: The STP becomes true *always before* the reaching of the sustainable state.
- Condition-3: The STP stays *always false* when the resource consumption trend is unsustainable.
- Condition-4: The STP becomes true *only once*.

We performed three sets of experiments to demonstrate such conditions. Each set is composed by 81 experiments.
Each set is obtained on a basic initial configuration, as in previous paragraph experiments set, consisting of:

- an overall reduction goal of 1%,
- an initial consumption of 26000,
- 20 blind agents

The configurations of each set of experiments depend on the configuration of the smart metering functions. The configurations of every 81 experiments of each set depend on the initial number of different types of agent.
We have to remember that smart metering functions has an impact on consumption patterns: simple metering availability and neighbor comparison affect the individual reduction goal, while feedback and suggestion affect the rate to reach such a reduction goal (see Chapter 7 for details).
As previously introduced in examples of Chapter 8, when no smart metering functions are available the system tends to stay in a unsustainable consumption state, never reaching the reduction goal. The availability of one or more smart metering functions facilitates the reaching of sustainability.

Set 1 of experiments is the same we used in previous paragraph, where both metering-availability and individual-feedback functions are set to true, while all other smart functions are set to false.

Reduction-goal (in %)	1
N-actives	[20,30,40]
N-blinds	20
N-indifferents	[300,150,74]
individual-feedback	**true**
N-evangelists	[20,30,40]
N-spectators	[240, 120,60]
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	**true**

Table 23 - Configurations of Set-1 of 81 experiments on Sustainability Tipping Point validation

In Set 2 of experiments only metering-availability function is set to true.

Reduction-goal (in %)	1
N-actives	**20,30,40**
N-blinds	20
N-indifferents	**300,150,74**
individual-feedback	false
N-evangelists	**20,30,40**
N-spectators	**240, 120,60**
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	**true**

Table 24 - Configurations of Set-2 of 81 experiments on Sustainability Tipping Point validation

Set-3 differs from Set-1 because all smart metering functions are set to false

Reduction-goal (in %)	1
N-actives	[20,30,40]
N-blinds	20
N-indifferents	[300,150,74]
individual-feedback	**false**
N-evangelists	[20,30,40]
N-spectators	[240, 120,60]
Tips&Tricks	false
seed	10000
neighbour-comparison	false
Initial-global-resource-consumption	26000
metering-availability	**false**

Table 25- Configurations of Set-3 of 81 experiments on Sustainability Tipping Point validation

We performed such three sets of experiments using *Netlogo BehaviorSpace* utility. We set as "time limit" for the experiment that the simulation stops after 800 runs, if the reduction goal is not reached before.

We observed the results of the three sets of experiments, in order to verify the four conditions required to consider the STP a reliable indicator.

We recorded the *run when the STP becomes true and we call it STP*.

If the STO becomes true and then false and again true, etc., it means that there are more STP, and it is against out theory that the STP is a reliable indicator of sustainability.

There are four possible merging scenarios for STP, as summarized in Table 25.

I) The system reaches the reduction goal and the STP become true only once. In other words there is sustainability and only one STP. The number of this kind of case is recorded in the second column.

II) The system never reaches the sustainability and the STP never becomes true. There is unsustainability and zero STP. The number of this kind of case is recorded in the third column of Table 25.

III) The system reaches sustainability and the STP becomes true several times. There is sustainability and more than one STP. The number of this kind of case is recorded in the forth column of Table 25.

IV) The system never reaches the sustainability and the STO becomes true one or more times. There is unsustainability and one or more STP. The number of this kind of case is recorded in the fifth column.

TABLE-number	SUST – one STP	UNSUST- no STP	SUST N.of STP>1	UNSUST N.STP> 0	ERRORS
TABLE-22 (+FB)	81	0	0	0	0
TABLE-23	65	0	16	0	16
TABLE-24 (NOMT)	0	79	0	2	2
TOTAL NUMBER	146	79	16	2	18

Table 26- Results of 243 (3 Set of 81) experiments on Sustainability Tipping Point validation

When the first or second scenarios happen (columns 2 and 3), the STP satisfies all the four conditions to be considered an indicator toward sustainability.

When the third or fourth scenarios happen, the STP does not satisfy the four conditions to be considered an indicator toward sustainability. The third situation fails to satisfy Condition-3 (STP stays always false when the resource consumption trend is unsustainable.). The fourth situation fails to satisfy Condition-4 (the STP becomes true only once).

We have to verify if (and to quantify how often) the STP fails to satisfy some of the four conditions required to be a reliable indicator.

Looking at the results of Set-1 of experiments (i.e. configurations in TABLE-22), we can observe as the system always reaches the RG, and STP becomes true only once.

Looking at the results of Set-2 of experiments (TABLE-23), we can observe as the system always reaches the RG, but only for 65 times the STP becomes true only once, while for 16 times there are more than one STP.

Looking at the results of Set-3 (TABLE-24) we can observe as the systems never reach sustainability and, as required, there is no one STP in 79 cases, while there are two exceptions where the STP fails.

Trying to quantify an evaluation on STP we can say that looking at the three sets of experiments as a whole, we can say that the STP behaves as a good indicators in 92.6% of the 243 experiments. In 7.4% of the total 243 experiments it leads to some errors: 0.8% are fully wrong indications, while 6.6 % of the results are only partially wrong, because what it is wrong is the quantitative evaluation of the advance of STP toward RG, while the kind of foreseen trend is correct.

Looking at the single set of experiments, we observe that in the first set of experiments the STP was always able to correctly anticipate the future state of the system. In the second set the behaviour of STP failed in 20% of the experiments. While in the third case there are 2.5 % of errors.

Trying to conclude, we can say that the STP relative advance can be considered a quantitative indicator able to reliably foresee in the all cases when the system will reach the reduction goal. On the total possible final scenarios, the STP error percentage is around 7% in average and in the worst case it can reach the 20%.

The availability of such an indicator can have several useful applications in decision-making (Bicking M, Troitzsch, & Wimmer).

All experiment files will be supplied on request, to allow verifying and replicating the experiment.

APPENDIX 6: SENSITIVITY ANALYSIS EXPERIMENTS

Experiments on density of population

The following figures refer to very crowded, crowded and medium crowded population densities.

Figure 50 – Configuration BAE of very crowded density population

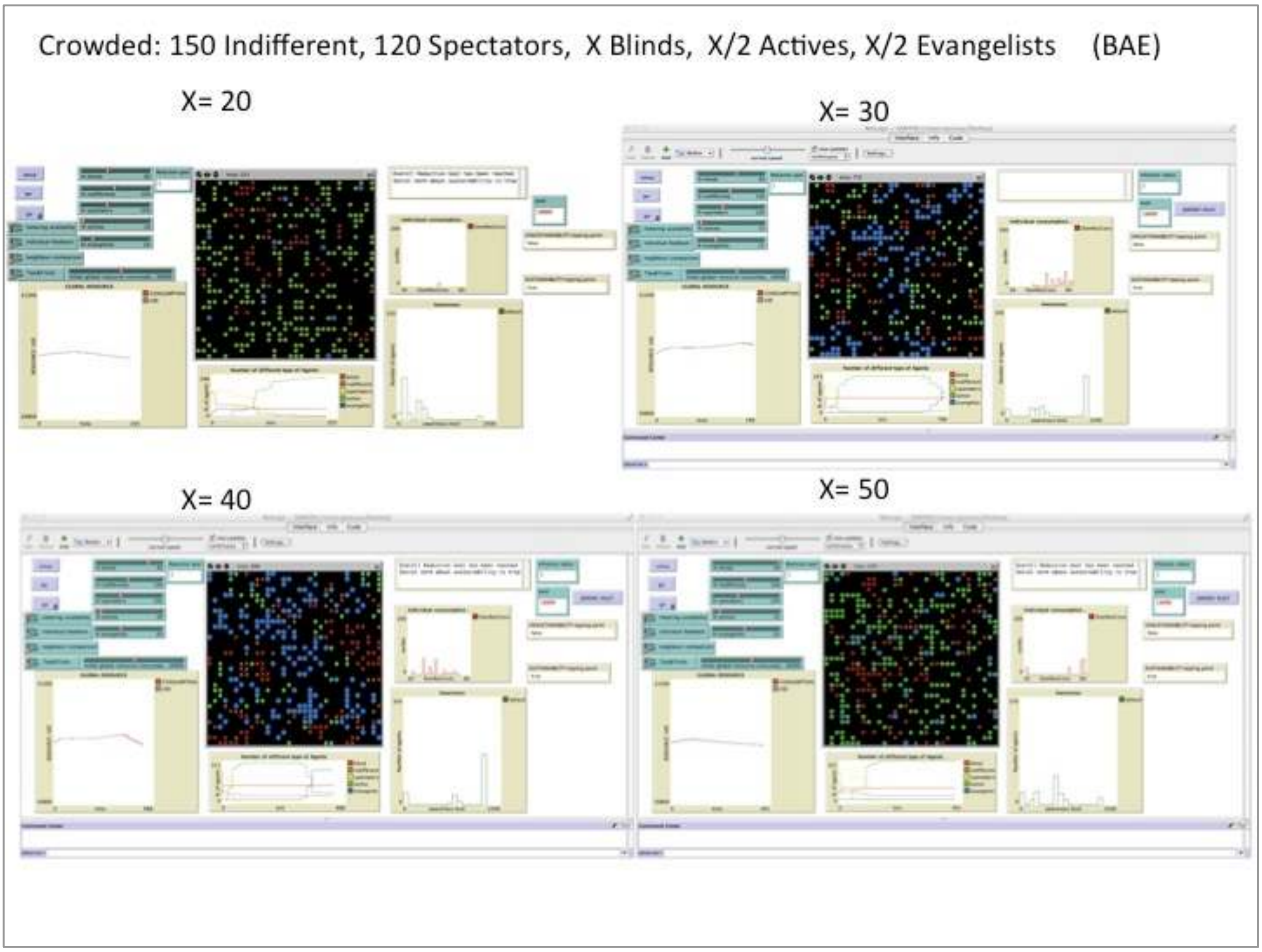


Figure 51 – Configuration BAE of crowded density population

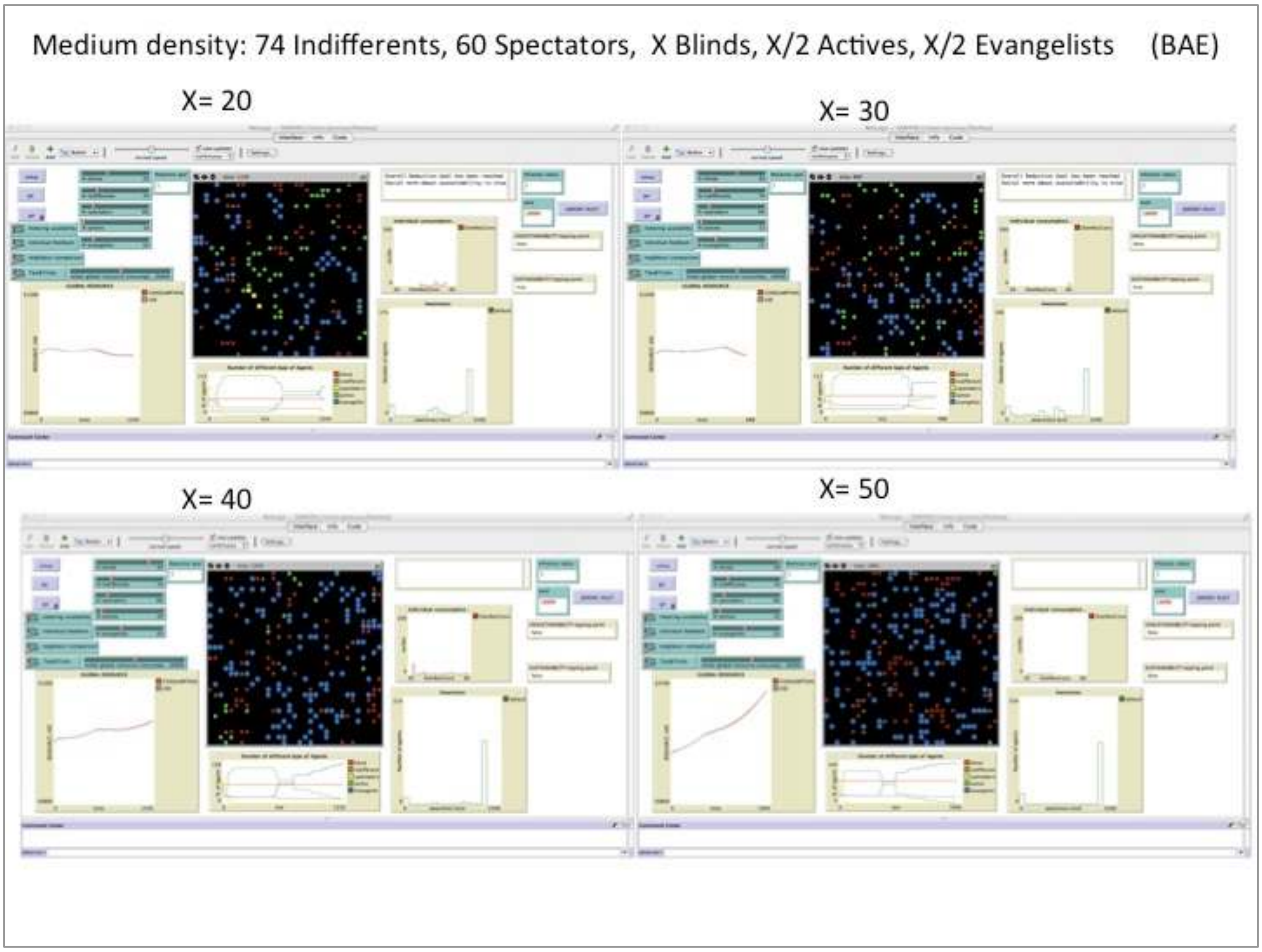
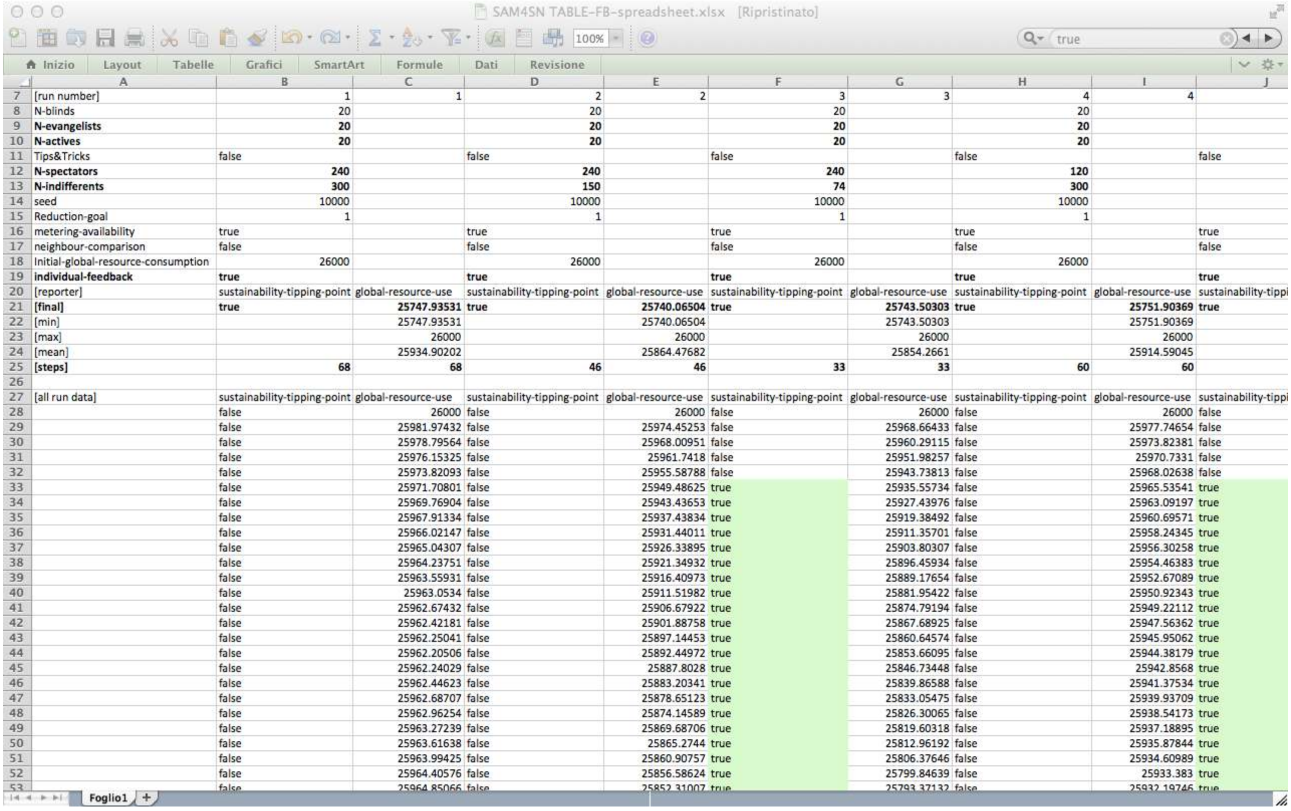


Figure 52 – Configuration BAE of medium density population

Sustainability Tipping Point Experiments

Relative advance of STP on Reduction Goal (STPRG)

In Figure 53 the implementation of experiments based on the Configurations of Table 20.



	A	B	C	D	E	F	G	H	I	J
7	[run number]	1	1	2	2	3	3	4	4	
8	N-blinds	20		20		20		20		
9	**N-evangelists**	**20**		**20**		**20**		**20**		
10	**N-actives**	**20**		**20**		**20**		**20**		
11	Tips&Tricks	false		false		false		false		false
12	**N-spectators**	**240**		**240**		**240**		**120**		
13	**N-indifferents**	**300**		**150**		**74**		**300**		
14	seed	10000		10000		10000		10000		
15	Reduction-goal	1		1		1		1		
16	metering-availability	true		true		true		true		true
17	neighbour-comparison	false		false		false		false		false
18	Initial-global-resource-consumption	26000		26000		26000		26000		
19	**individual-feedback**	**true**		**true**		**true**		**true**		**true**
20	[reporter]	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tippi
21	**[final]**	**true**	**25747.93531**	**true**	**25740.06504**	**true**	**25743.50303**	**true**	**25751.90369**	**true**
22	[min]		25747.93531		25740.06504		25743.50303		25751.90369	
23	[max]		26000		26000		26000		26000	
24	[mean]		25934.90202		25864.47682		25854.2661		25914.59045	
25	**[steps]**	**68**	**68**	**46**	**46**	**33**	**33**	**60**	**60**	
26										
27	[all run data]	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tipping-point	global-resource-use	sustainability-tippi
28		false	26000	false	26000	false	26000	false	26000	false
29		false	25981.97432	false	25974.45253	false	25968.66433	false	25977.74654	false
30		false	25978.79564	false	25968.00951	false	25960.29115	false	25973.82381	false
31		false	25976.15325	false	25961.7418	false	25951.98257	false	25970.7331	false
32		false	25973.82093	false	25955.58788	false	25943.73813	false	25968.02638	false
33		false	25971.70801	false	25949.48625	true	25935.55734	false	25965.53541	true
34		false	25969.76904	false	25943.43653	true	25927.43976	false	25963.09197	true
35		false	25967.91334	false	25937.43834	true	25919.38492	false	25960.69571	true
36		false	25966.02147	false	25931.44011	true	25911.35701	false	25958.24345	true
37		false	25965.04307	false	25926.33895	true	25903.80307	false	25956.30258	true
38		false	25964.23751	false	25921.34932	true	25896.45934	false	25954.46383	true
39		false	25963.55931	false	25916.40973	true	25889.17654	false	25952.67089	true
40		false	25963.0534	false	25911.51982	true	25881.95422	false	25950.92343	true
41		false	25962.67432	false	25906.67922	true	25874.79194	false	25949.22112	true
42		false	25962.42181	false	25901.88758	true	25867.68925	false	25947.56362	true
43		false	25962.25041	false	25897.14453	true	25860.64574	false	25945.95062	true
44		false	25962.20506	false	25892.44972	true	25853.66095	false	25944.38179	true
45		false	25962.24029	false	25887.8028	true	25846.73448	false	25942.8568	true
46		false	25962.44623	false	25883.20341	true	25839.86588	false	25941.37534	true
47		false	25962.68707	false	25878.65123	true	25833.05475	false	25939.93709	true
48		false	25962.96254	false	25874.14589	true	25826.30065	false	25938.54173	true
49		false	25963.27239	false	25869.68706	true	25819.60318	false	25937.18895	true
50		false	25963.61638	false	25865.2744	true	25812.96192	false	25935.87844	true
51		false	25963.99425	false	25860.90757	true	25806.37646	false	25934.60989	true
52		false	25964.40576	false	25856.58624	true	25799.84639	false	25933.383	true
53		false	25964.85066	false	25852.31007	true	25793.37132	false	25932.19746	true

Figure 53 - Dataset of experiments on STP relative advance on Reduction goal

In Table 27 a synoptic view of STP and STP relative advance (STPRA) values on Reduction Goal (RG)

CASENUMBER	STP(run number when become true)	Reduction Goal (run number when is reached)	STP Advance on RG	STP Relative Advance (STPRG)	Number of STP
1	44	69	25	0.362318841	1
2	44	47	3	0.063829787	1
3	6	34	28	0.823529412	1
4	44	61	17	0.278688525	1
5	6	41	35	0.853658537	1
6	6	21	15	0.714285714	1
7	44	61	17	0.278688525	1
8	6	31	25	0.806451613	1
9	6	16	10	0.625	1
10	44	54	10	0.185185185	1
11	6	48	42	0.875	1
12	6	35	29	0.828571429	1
13	6	57	51	0.894736842	1
14	6	36	30	0.833333333	1
15	6	21	15	0.714285714	1
16	6	51	45	0.882352941	1
17	6	24	18	0.75	1
18	6	15	9	0.6	1
19	44	55	11	0.2	1
20	6	44	38	0.863636364	1
21	6	29	23	0.793103448	1
22	6	48	42	0.875	1
23	6	31	25	0.806451613	1
24	6	20	14	0.7	1
25	6	56	50	0.892857143	1
26	6	21	15	0.714285714	1
27	6	14	8	0.571428571	1
28	44	45	1	0.022222222	1
29	6	29	23	0.793103448	1
30	6	21	15	0.714285714	1
31	6	42	36	0.857142857	1
32	6	21	15	0.714285714	1
33	6	13	7	0.538461538	1
34	6	33	27	0.818181818	1
35	6	15	9	0.6	1
36	6	9	3	0.333333333	1
37	44	46	2	0.043478261	1
38	6	30	24	0.8	1
39	6	20	14	0.7	1
40	6	44	38	0.863636364	1
41	6	19	13	0.684210526	1
42	6	13	7	0.538461538	1
43	6	29	23	0.793103448	1
44	6	14	8	0.571428571	1
45	6	10	4	0.4	1
46	6	46	40	0.869565217	1
47	6	26	20	0.769230769	1
48	6	19	13	0.684210526	1
49	6	31	25	0.806451613	1
50	6	19	13	0.684210526	1
51	6	13	7	0.538461538	1
52	6	28	22	0.785714286	1
53	6	15	9	0.6	1
54	6	9	3	0.333333333	1
54	6	9	3	0.333333333	1
56	6	19	13	0.684210526	1
57	6	15	9	0.6	1
58	6	22	16	0.727272727	1
59	6	14	8	0.571428571	1
60	6	9	3	0.333333333	1
61	6	18	12	0.666666667	1
62	6	10	4	0.4	1
63	6	7	1	0.142857143	1
64	6	26	20	0.769230769	1
65	6	19	13	0.684210526	1
66	6	15	9	0.6	1
67	6	23	17	0.739130435	1
68	6	13	7	0.538461538	1
69	6	9	3	0.333333333	1
70	6	18	12	0.666666667	1
71	6	11	5	0.454545455	1
72	6	7	1	0.142857143	1
73	6	26	20	0.769230769	1
74	6	18	12	0.666666667	1
75	6	14	8	0.571428571	1
76	6	22	16	0.727272727	1
77	6	13	7	0.538461538	1
78	6	9	3	0.333333333	1
79	6	17	11	0.647058824	1
80	6	10	4	0.4	1
81	6	7	1	0.142857143	1

Table 27 – STP Relative advance values of 81 experiment set

GLOBAL RESOURCE USE PLOT– Configurations of Table 20 (and Table 22)

In Figure 54 the global resource use plot of some cases of experiments based on the Configurations of Table 20 and Table 22. All 81 cases lead to sustainability (see the synoptic Table 26).

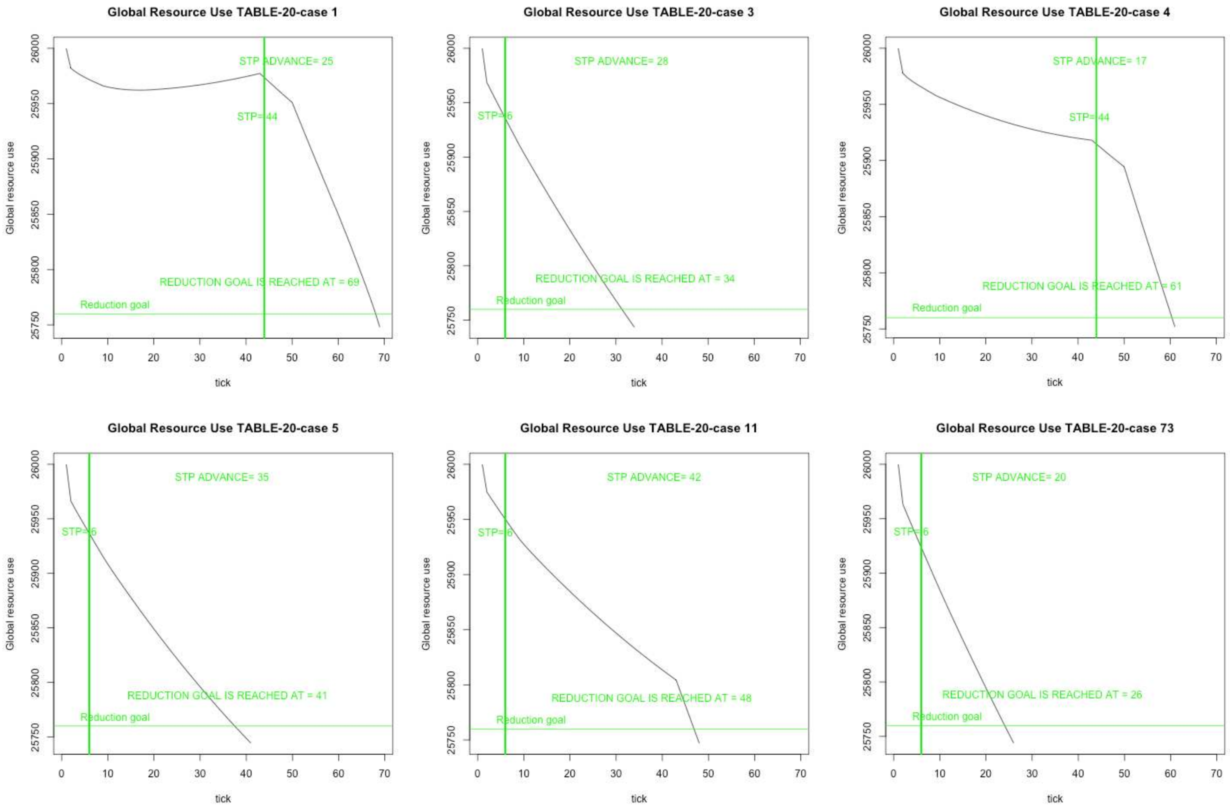
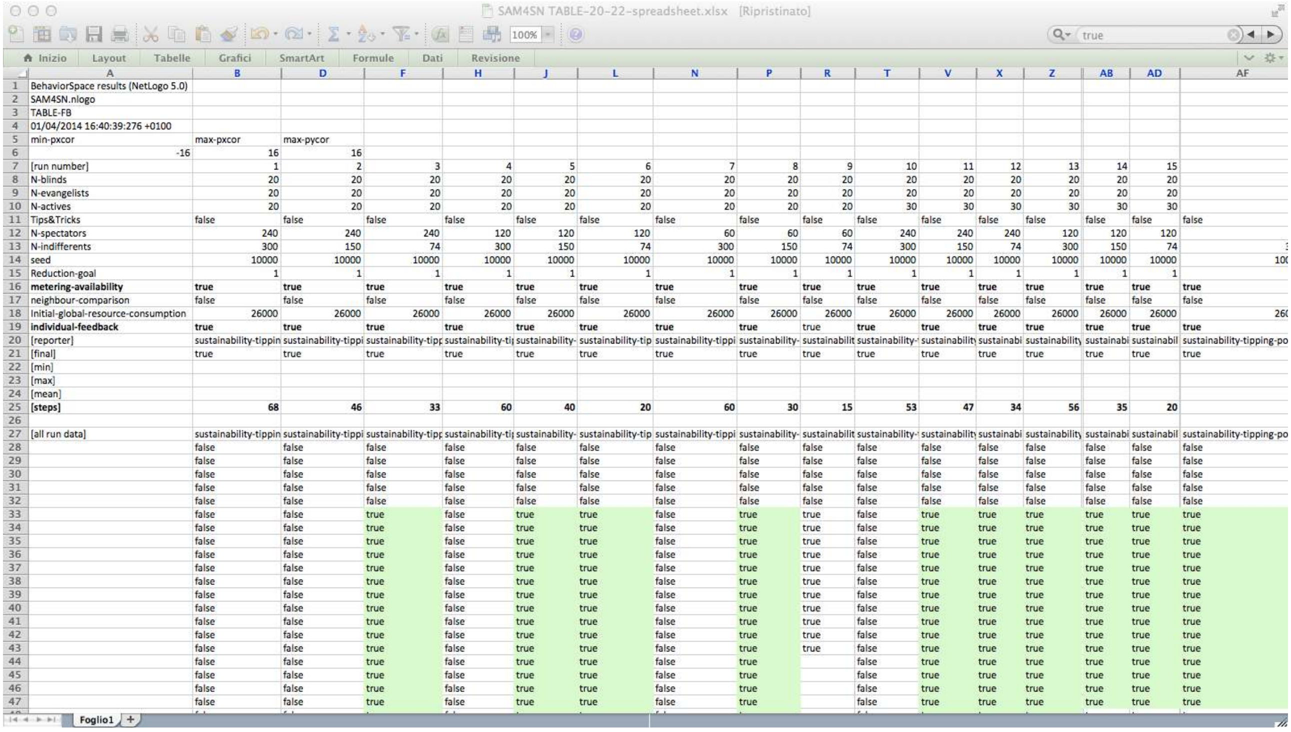


Figure 54 – Examples of global resource use in sustainable scenarios

Sustainability Tipping Point validation experiments

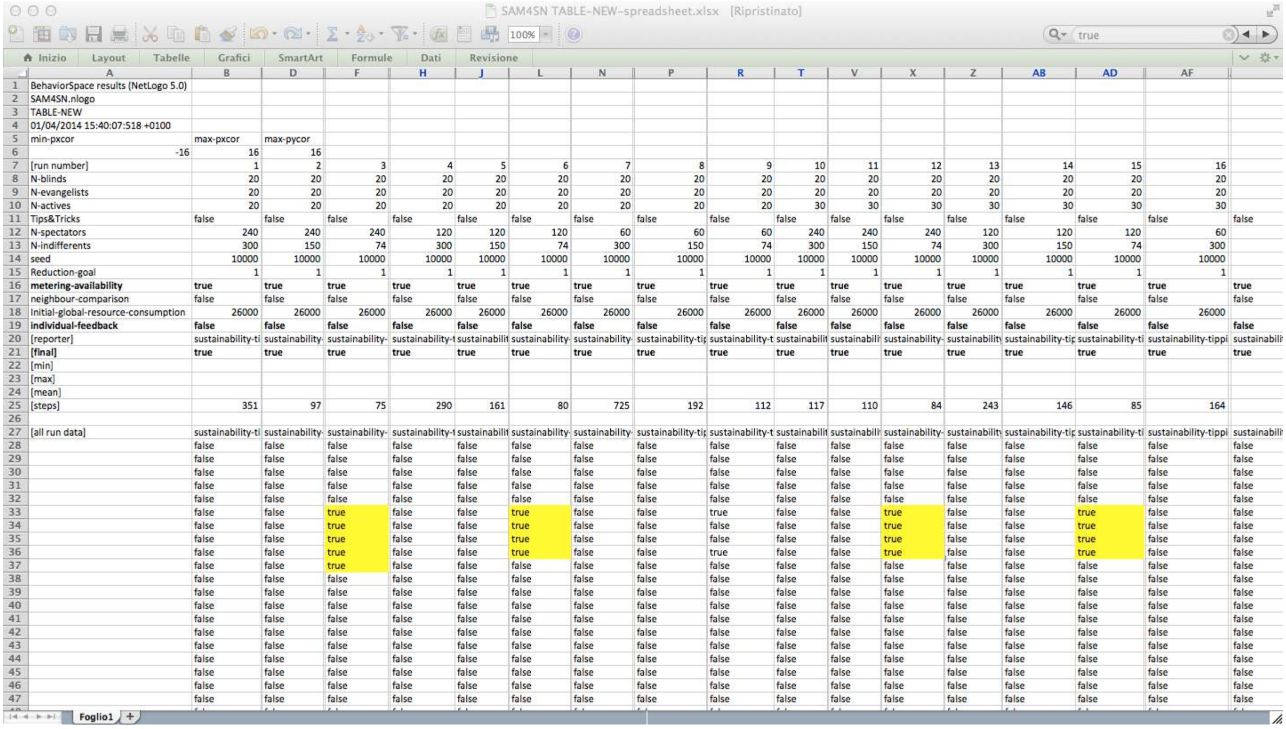
In Figure 55 the Set 1 of experiments on sustainability tipping point validation (81 experiments).



	A	B	D	F	H	J	L	N	P	R	T	V	X	Z	AB	AD	AF
1	BehaviorSpace results (NetLogo 5.0)																
2	SAM4SN.nlogo																
3	TABLE-FB																
4	01/04/2014 16:40:39:276 +0100																
5	min-pxcor	max-pxcor	max-pycor														
6	-16	16	16														
7	[run number]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
8	N-blinds	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
9	N-evangelists	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
10	N-actives	20	20	20	20	20	20	20	20	20	30	30	30	30	30	30	
11	Tips&Tricks	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
12	N-spectators	240	240	240	120	120	120	60	60	60	240	240	240	120	120	120	
13	N-indifferents	300	150	74	300	150	74	300	150	74	300	150	74	300	150	74	3
14	seed	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10
15	Reduction-goal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
16	**metering-availability**	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
17	neighbour-comparison	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
18	Initial-global-resource-consumption	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26
19	**individual-feedback**	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
20	[reporter]	sustainability-tippin	sustainability-tippi	sustainability-tipp	sustainability-ti	sustainability-	sustainability-tip	sustainability-tippi	sustainability-	sustainabilit	sustainability-	sustainability	sustainabi	sustainability	sustainabi	sustainabil	sustainability-tipping-po
21	[final]	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
22	[min]																
23	[max]																
24	[mean]																
25	**[steps]**	68	46	33	60	40	20	60	30	15	53	47	34	56	35	20	
26																	
27	[all run data]	sustainability-tippin	sustainability-tippi	sustainability-tipp	sustainability-ti	sustainability-	sustainability-tip	sustainability-tippi	sustainability-	sustainabilit	sustainability-	sustainability	sustainabi	sustainability	sustainabi	sustainabil	sustainability-tipping-po
28		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
29		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
30		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
31		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
32		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
33		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
34		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
35		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
36		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
37		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
38		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
39		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
40		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
41		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
42		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
43		false	false	true	false	true	true	false	true	true	false	true	true	true	true	true	true
44		false	false	true	false	true	true	false	true		false	true	true	true	true	true	true
45		false	false	true	false	true	true	false	true		false	true	true	true	true	true	true
46		false	false	true	false	true	true	false	true		false	true	true	true	true	true	true
47		false	false	true	false	true	true	false	true		false	true	true	true	true	true	true

Figure 55 - Set 1 of experiments on sustainability tipping point validation

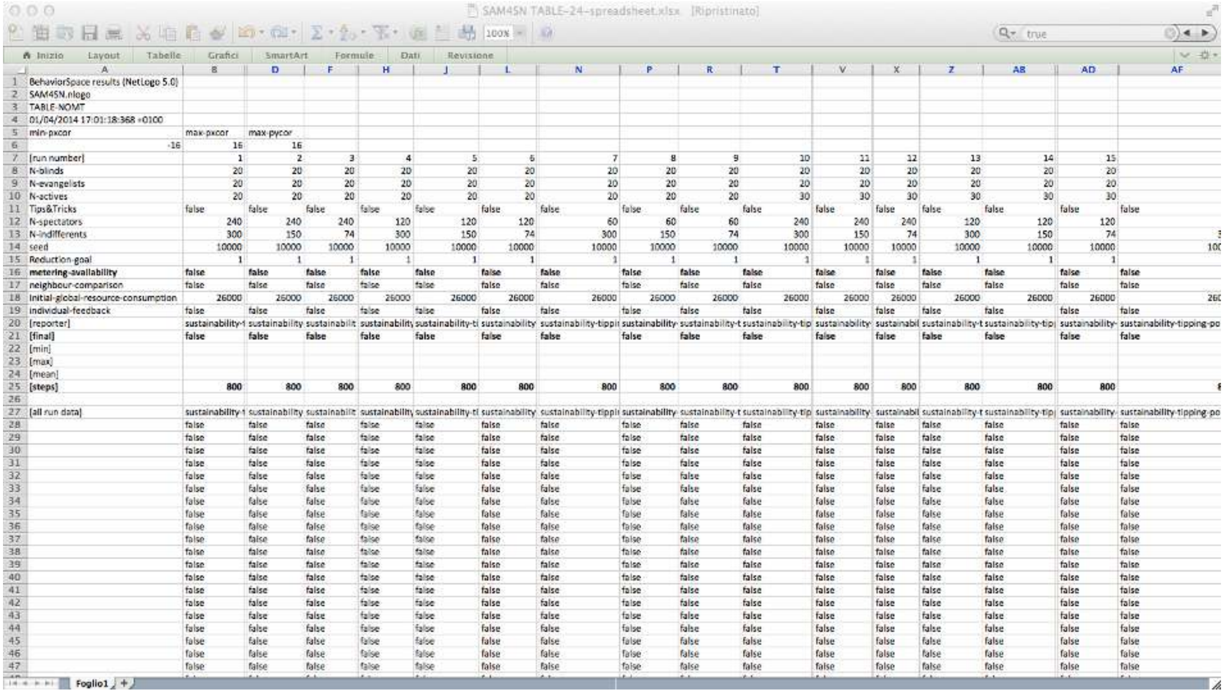
In Figure 56 the Set 2 of experiments on sustainability tipping point validation (81 experiments)



	A	B	D	F	H	J	L	N	P	R	T	V	X	Z	AB	AD	AF	
1	BehaviorSpace results (NetLogo 5.0)																	
2	SAM4SN.nlogo																	
3	TABLE-NEW																	
4	01/04/2014 15:40:07:518 +0100																	
5	min-pxcor	max-pxcor	max-pycor															
6	-16	16	16															
7	[run number]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
8	N-blinds	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
9	N-evangelists	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
10	N-actives	20	20	20	20	20	20	20	20	20	30	30	30	30	30	30	30	
11	Tips&Tricks	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
12	N-spectators	240	240	240	120	120	120	60	60	60	240	240	240	120	120	120	60	
13	N-indifferents	300	150	74	300	150	74	300	150	74	300	150	74	300	150	74	300	
14	seed	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	
15	Reduction-goal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
16	**metering-availability**	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
17	neighbour-comparison	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
18	Initial-global-resource-consumption	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	
19	**individual-feedback**	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
20	[reporter]	sustainability-ti	sustainability-	sustainability-	sustainability-t	sustainabilit	sustainability-	sustainability-	sustainability-tip	sustainability-t	sustainabilit	sustainabili	sustainability-	sustainability	sustainability-tip	sustainability-ti	sustainability-tippi	sustainabili
21	**[final]**	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
22	[min]																	
23	[max]																	
24	[mean]																	
25	[steps]	351	97	75	290	161	80	725	192	112	117	110	84	243	146	85	164	
26																		
27	[all run data]	sustainability-ti	sustainability-	sustainability-	sustainability-t	sustainabilit	sustainability-	sustainability-	sustainability-tip	sustainability-t	sustainabilit	sustainabili	sustainability-	sustainability	sustainability-tip	sustainability-ti	sustainability-tippi	sustainabili
28		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
29		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
30		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
31		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
32		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
33		false	false	true	false	false	true	false	false	true	false	false	true	false	false	true	false	false
34		false	false	true	false	false	true	false	false	false	false	false	true	false	false	true	false	false
35		false	false	true	false	false	true	false	false	false	false	false	true	false	false	true	false	false
36		false	false	true	false	false	true	false	false	true	false	false	true	false	false	true	false	false
37		false	false	true	false	false	false	false	false	false	false	false	false	false	false	false	false	false
38		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
39		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
40		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
41		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
42		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
43		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
44		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
45		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
46		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
47		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false

Figure 56 – Set 2 of experiments on sustainability tipping point validation

In Figure 57 the Set 3 of experiments on sustainability tipping point validation (81 experiments).



	A	B	D	F	H	J	L	N	P	R	T	V	X	Z	AB	AD	AF
1	BehaviorSpace results (NetLogo 5.0)																
2	SAM45N.nlogo																
3	TABLE-NOMT																
4	01/04/2014 17:01:18:368 +0100																
5	min-pxcor	max-pxcor	max-pycor														
6	-16	16	16														
7	[run number]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
8	N-blinds	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
9	N-evangelists	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	
10	N-actives	20	20	20	20	20	20	20	20	20	30	30	30	30	30	30	
11	Tips&Tricks	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
12	N-spectators	240	240	240	120	120	120	60	60	60	240	240	240	120	120	120	
13	N-indifferents	300	150	74	300	150	74	300	150	74	300	150	74	300	150	74	
14	seed	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	
15	Reduction-goal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
16	**metering-availability**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**
17	neighbour-comparison	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
18	initial-global-resource-consumption	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	
19	individual-feedback	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
20	[reporter]	sustainability-t	sustainability	sustainabilit	sustainability	sustainability-ti	sustainability	sustainability-tippi	sustainability-	sustainability-t	sustainability-tip	sustainability-	sustainabil	sustainability-t	sustainability-tip	sustainability-	sustainability-tipping-po
21	**[final]**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**	**false**
22	[min]																
23	[max]																
24	[mean]																
25	**[steps]**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	**800**	
26																	
27	[all run data]	sustainability-t	sustainability	sustainabilit	sustainability	sustainability-ti	sustainability	sustainability-tippi	sustainability-	sustainability-t	sustainability-tip	sustainability-	sustainabil	sustainability-t	sustainability-tip	sustainability-	sustainability-tipping-po
28		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
29		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
30		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
31		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
32		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
33		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
34		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
35		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
36		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
37		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
38		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
39		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
40		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
41		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
42		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
43		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
44		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
45		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
46		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
47		false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false

Figure 57 - Set 3 of experiments on sustainability tipping point validation

GLOBAL RESOURCE USE PLOT– Configurations of Table 23

In Figure 58 the global resource use plot for some cases of experiments based on the Configurations of Table 23. The presented examples lead to sustainability (see the synoptic Table 26).

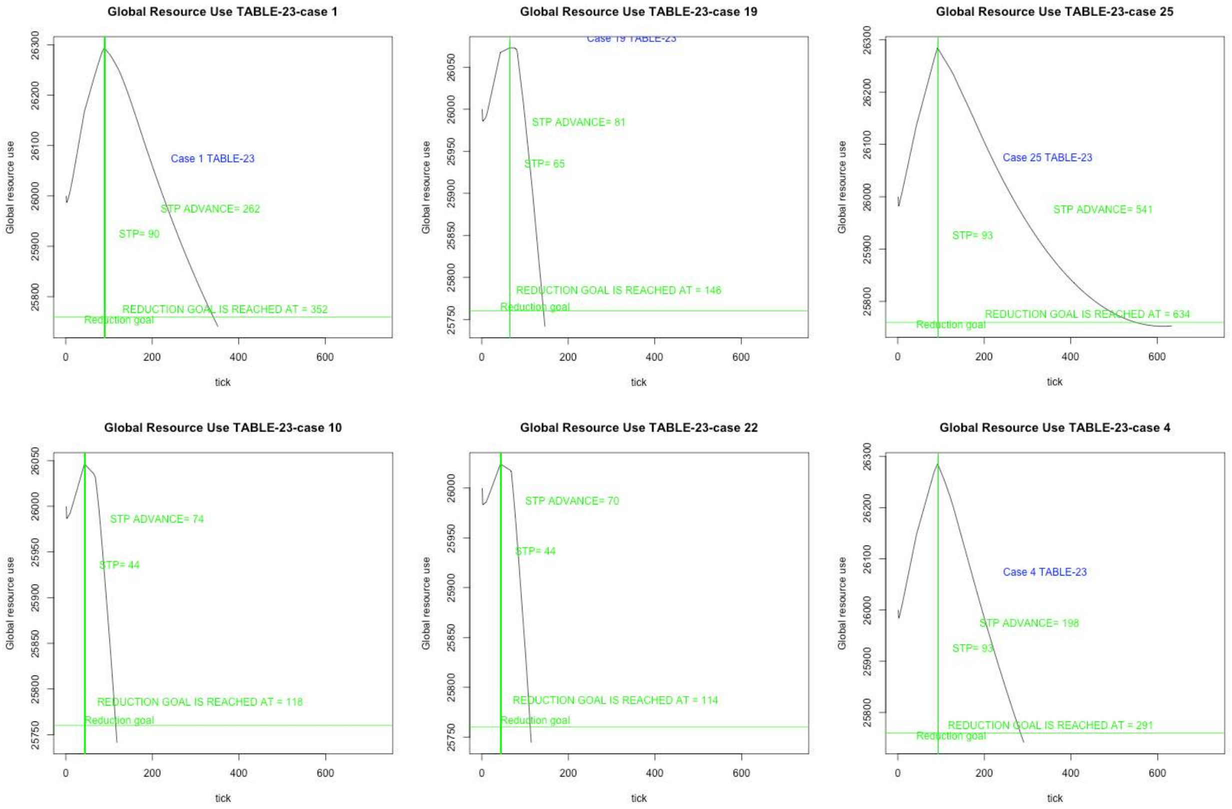


Figure 58 – Examples of global resource use in sustainable scenarios

In Figure 59 the global resource use plot for some cases of experiments based on the Configurations of Table 23. The presented examples are about critical configurations, leading to sustainability, and there is more than one STP (see the synoptic Table 26).

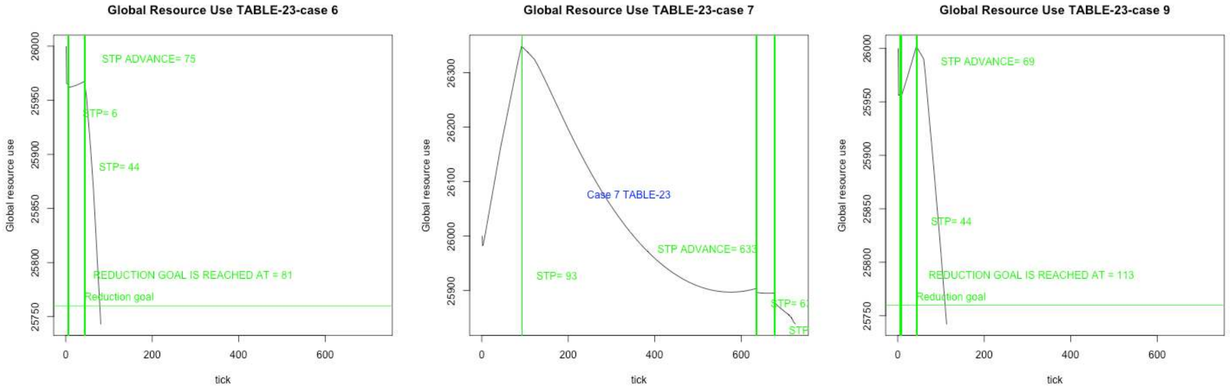


Figure 59 – Examples of global resource use in critical scenarios leading to sustainability

GLOBAL RESOURCE USE PLOT– Configurations of Table 24

In Figure 60 the global resource use plot for some cases of experiments based on the Configurations of Table 24. The presented examples lead to unsustainability (see the synoptic Table 26).

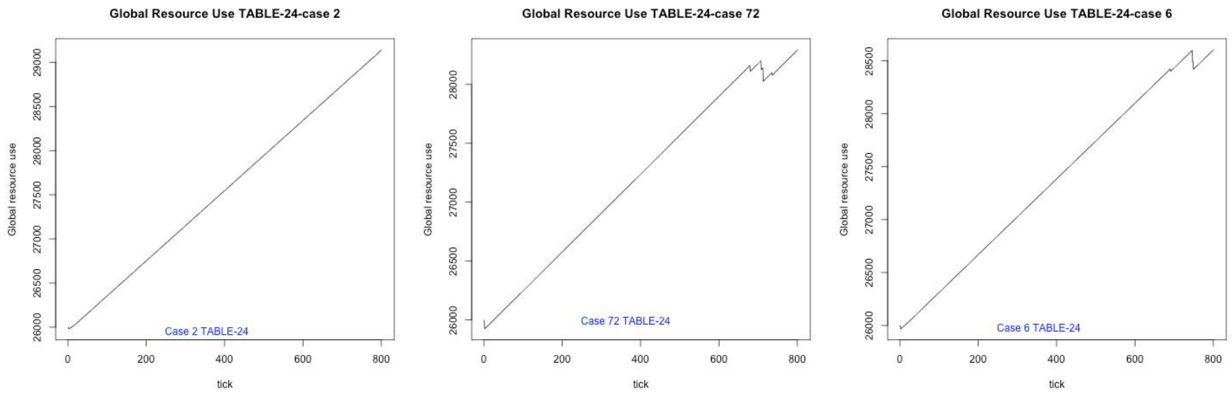


Figure 60 – Examples of global resource use in unsustainable scenarios

11. MAIN FINDINGS

Using the proposed model under different initial conditions leads to different outcomes. Some scenario leads to overuse of the resource, while in other scenarios this does not happen because the social mechanism has a positive effects and sustainable behavior emerges.

Some emergent phenomena has been observed about the reaching of a sustainable consumption:

1. The initial number of blind agent is a critical condition against the awareness diffusion dynamics, because too many blind agents prevent the awareness spread.

2. A certain percentage of green agents (actives or evangelists) on the whole population is required to trigger a sustainable behavior. Such a percentage depends also on point 4.

3. From the difference of only one unit in the number of committed agents (i.e. blinds or evangelists) the sustainability can derive or cannot derive.

4. The relevance of smart metering functions is significant for reaching or not sustainability. Because we taken as assumption that these functions impacts on individual consumption, the SAM4SN allows to quantify their impact.

5. The time to reach sustainability is affected by availability of smart metering functions.

6. Last but not least, the more interesting observed result is the property of the sustainability tipping point, as defined in Chapter 7, to foresee the trend in the overall consumption behaviour and to predict if and when the system will achieve the overall reduction goal.

STP can be considered as a new qualitative monitoring indicator of reduction goal reaching. We have seen that its behaviour as indicator is reliable in most cases, with an average error percentage of 7 %.
We derived the STP relative advance (STPRA) toward the overall reduction goal and we found that such advance is significant, because its value is around the 60% in average.
Because the sustainability tipping point and the overall reduction goal are totally independent this result is not trivial. From this consideration we can estimate the potential interest of such an indicator. Considering the STP an indicator of an emergent social norm toward sustainability could help us in estimating “if and how long after” a given target will be reached.

The purpose of the analysis of STP is related to its potential use in decision-making.
STP and STPRA can help decision makers to establish which initial configuration of different types of agent leads to sustainability and the required number of committed agents to enable a social norm. To consider the initial commitment of agents as a constraint to reach an overall objective is an approach for several kind of campaigns or initiative based on social norm effects.

A decision maker can pivot on that idea, for example, with pilot programs to support group of people to become more proactive and committed on a given cause. On the opposite he can evaluate that a strong initial commitment against such cause will counter any effort toward it.
In policy-making it can be useful to better distribute effort and resources in environmental sustainability programs, while for a utility company the STP can be valuable to predict trends of decrease in resource consumption.

12. FUTURE DEVELOPMENT AND CONCLUSION

The research activities described in this PHD are suitable for several further developments, both in theoretical both in application terms.
We developed an ABM of awareness dynamic and reduction consumption mechanisms of households, with the aim to identify emerging patterns and scenarios leading to a reduction of the resource or leading to its overuse.
SAM4SN has been implemented in NetLogo5. It will be released as free software with related documentations and added to the OpenABM model library, allowing its sharing for future developments and improvements.

SAM4SN has been developed to study the sustainability issues in terms of need to reduce the consumption of a limited resource. Sustainability is reached when a given overall goal of reduction is reached and we applied SAM4SN to the broad and popular area of household energy consumptions.
A further immediate opportunity is to apply SAM4S again in the context of household energy consumption, but in real environmental ICT-based policy programs from the beginning, allowing building a real dataset to initialize the model. In such kind of policy-based programs the STP can be an useful tool for policy makers to better understand, for example, the areas of a political intervention where to allocate more resources or less resources. The sustainability tipping point can give decision makers a support to understand if a sustainability social norm is emerging in a given area.
Continuing to stay in a household consumption field, SAM4SN is a suitable ABM to study other limited resource, as for example water consumption in domestic field. For utilities companies SAM4SN could be a tool to explore how and when to invest on smart metering functions development.

SAM4SN is a tool to explore and better understand the classes of phenomenon related to sustainability issues in terms of reduction of consumption of a limited resource in a broad sense. The basic elements that are mandatory to apply the SAM4SN approach in sustainability issues in any contexts are:

- the limited resource to be reduced;
- the reference institution where the resource is used and where a specific awareness can spread;
- the limiting factor on which to play

We started our research introducing a conceptual framework for ICTs and sustainability. In Chapter 1 we supplied an example about the need of awareness from software developers to avoid environmental impact of cloud computing, and in particular from the computing power that is supplied from cloud computing. In Chapter 2 we supplied an example of rebound effects depending on a lack of awareness from software developers. We described them because they are two not trivial examples of the complex relationship between ICT and sustainability, demonstrating how environmental awareness of stakeholders can be an effective approach to manage such issues.
In both examples we identified the three above listed basic elements. As reference institution we can be consider the software developers community, the resource to be reduce is energy in the first case or material in the second case, as the limiting factor we identified the social norm in such informal institution.
As computer scientists we hope that SAM4SN will be adapted and used in such context.

Our overall research contribution consists of bridging the gap between different disciplines related to the ICT and sustainability field. We think that increasing the number of “active consumers” the general framing of energy consumption can change and reach a good mix of efficiency and sufficiency.
Such goal can be reached in a dimension based on the concepts of individual behavior, informal institution and social norm.

SAM4SN can be used as a virtual laboratory where to perform experiments on such mechanisms and concepts. Acknowledging consumers as truly actives entails that they can take part in the construction of the solution. A direct recommendation is then to allow consumers to have unrestricted access to their own consumption data. A further recommendation is to allow them, on a voluntary basis, to relax some privacy-based constraints toward a dimension of social reputation. More generally a trend toward environmental sustainability entails that consumers should always have access to their own data, to make effective the notion of appropriation. We can refer to consumers as well as to users or citizens. In all cases the main idea of our research is that the environmental awareness is an individual feature affecting the whole sustainability mechanism.

A conclusion of our specific research can be attempted by saying (Terna, 2013) that "Complexity as a tool to understand reality, comes from a strong theoretical path of epistemological development; to be widely accepted, however, it still requires a significant step ahead of the tools we use to make computations about this a class of models, with sound protocol, easy interface, learning tools, computational facilities…but it also requires a deep and humble acceptation of the idea that each of us is as far from understanding and controlling the environmental and socio technical system as an ant is with respect to the anthill".

REFERENCES

Axelrod, R. (2007). Simulation in the social sciences. In J.P. Rennard (Ed.), *Handbook of research on nature inspired computing for economic and management* (pp. 90–100). Hershey: Idea Group.

Bianchi, C., Cirillo, P., Gallegati. M., & Vagliasindi, P. (2007). Validating and Calibrating Agent-Based Models: A Case study. *Computational Economics, 30*, 245–264.

Bicking M., Troitzsch K.G., & Wimmer M. (2010). Regulatory Impact Assessment: Modelling and Simulation to Facilitate Policy Choices. In Andreas Ernst, Silke Kuhn (Eds.) *Proceedings of the3rd World Congress on Social Simulation WCSS2010*. Kassel, Germany.

Biswas, S., & Sen, P.(2009). Model of binary opinion dynamics: Coarsening and effect of disorder. *Phys. Rev. E* 80, 027101.

Casti, J.L. (1992). *Reality Rules:II. Picturing the world in Matematics – The frontier*. (pg. 379-402; 387-389). New York: Wiley- Interscience publication.

Fagiolo G., Moneta, A., & Windrum, P. (2007). A Critical Guide to Empirical Validation of Agent-Based Models in Economics: Methodologies, Procedures, and Open Problems. *Computational Economics, 30*(3), 195–226.

Griskevicius, V., Tybur, J, & Van den Bergh, B. (2010). Going green to be seen: Status, reputation, and conspicuous conservation. *Journal of Personality and Social Psychology, 98*(3), 392-404

Harris, G. (2002). Integrated assessment and modelling: an essential way of doing science. *Environmental Modelling & Software, 17,* 201–207.

Haefner, J. W. (2005). *Modelling biological systems: Principles and applications* (2nd ed.). New York: Springer.

Janssen, M. A., & Ostrom, E., 2006. Empirically based, agent-based models. *Ecology and Society, 11*(2), 37.

Y. Liu et al., (2008). Linking science with environmental decision making: Experiences from an integrated modelling approach to supporting sustainable water resources management. *Environmental Modelling & Software, 23*(7), 846-858.

Lu, Q., Koriss, G., & Sztmanski, B.K. (2009), The Naming game in Social Networks: Community Formation and Consensus Engineering. *J Econ Interact Coord, 4*, 221-235.

Kinzig, A.P., Ehrlich, P.R., Alston L.J., Arrow, K., Barrett, S., Buchman, T.G., Daily, G. C., Levin, B., Oppenheimer, M., Ostrom, E., & Sahari D. (2013). Social Norms and Global Environmental Challenges: the Complex Interaction of Behaviors, Values, and Policy. *Bioscience, 63* (3), 164-175.

Marks, R.M. (2007). Validating Simulation Models: A General Framework and Four Applied Examples. *Computational Economics, 30*, 265–290.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent-based models - ODD + D, an extension of the ODD protocol**.** *Environmental Modelling & Software, 48*, 37-48.

Railback, S.F., & Grimm, V. (2011). *Agent-based and Individual Based Modelling*. Princeton, New Jersey: Princeton University Press.

Terna, P. (2013). A complex lens for economics, or: about ants and their anthill. *SpazioFilosofico2013*.

Tesfatsion, L. (2007). Website on Validation of ACE: http://www.econ.iastate.edu/tesfatsi/empvalid.htm

Tesfatsion, L., & Judd, K. (2006). *Handbook of computational economics 2*. Amsterdam: North Holland.

Troitzsch, K. (2004). Validating simulation models. In: *Proceedings 18th European Simulation Multiconf* (pp. 98–106). SCS Europe.

Wesley Schultz, P., Nolan, J.M., Cialdini, R.B., Goldtsein, N.J., & Griskevicius, V. (2007). The Constructive, Destructive, and Reconstructive Power of Social Norms. *Psychological Science 18* (5), 429-434.

Windrum, P., Fagiolo, G. & Moneta, A. (2007). Empirical Validation of Agent-Based Models: Alternatives and Prospects. *Journal of Artificial Societies and Social Simulation 10*(2), 8 http://jasss.soc.surrey.ac.uk/10/2/8.html

Xie, J., Sreenivasan, S., Korniss, G., Zhang, W., & Lim, C., Syzmanski, BK. (2011). Social consensus through the influence of committed minorities. *Physical Review E* 84, 01130, 1-8.

List of figures and tables

LIST OF PUBLICATIONS

Damiani E., Sissa, G, (2013). An Agent Based Model of environmental awareness and limited resource consumption. In *MEDES '13 Fifth International ACM Conference on Management of emerging Digital Ecosystem, Luxemburg, October 29-31*(pp.54-59). NY: ACM New York.

Sissa, G. (2013). An awareness based approach to avoid rebound effects in ICTs. In L. M. Hilty, B. Aebischer, G. Andersson, & W. Lohmann (Eds), *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability*, ETH Zurich: Zurich. DOI: http://dx.doi.org/10.3929/ethz-a-007337628.

Sissa, G. (2013). Longer Use, Better Use: How to Avoid Software Induced Hardware Obsolescence. In P. Ordóñez de Pablos (Ed.), *Green Technologies and Business Practices: An IT Approach* (pp. 163-174). Hershey, PA: Information Science Reference. doi:10.4018/978-1-4666-1972-2.ch009

Sissa G. (2012). An Agent Based approach for sustainable ICT services toward environmental sustainability. In: *Digital Ecosystems and Technologies (DEST 2012), 6th IEEE International Conference* (pp. 254-259). IEEE.

Sissa, G. (2011). Public policies on ICTs for dematerialisation: how to plan, monitor and assess the outcomes. *Notizie di POLITEIA, 104*, 67-78.

Lopez J.C, Natvig, L., & Sissa, G. (2011). Green ICT: the information society commitment for environmental sustainability. *CEPIS UPGRADE, XII* (4), 2-5.

Lopez J.C, Natvig, L., & Sissa, G. (Eds.). (2011). Green ICT: Trend and Challenges. Monographic issue *CEPIS UPGRADE, XII* (4).

Sissa, G. (2011). Utility computing: green opportunities and risks. *CEPIS UPGRADE, XII* (4), 16-21.

Sissa, G. (2011). A model to assess the net environmental impact of ICT-based services. In: *Data-Driven Process Discovery and Analysis SIMPDA 2011* Edited by: Karl Aberer Ernesto Damiani Tharam Dillon

Sissa, G. (2011). Assessment criteria for policy on ICT and climate change. In W. Pillman, S. Shade, & P. Smits (Eds.), *EnviroInfo 2011 – 25th Symposium Informatics for Environmental Protection, 1* (pp. 253-260). Aachen: Shaker Verlag.