ICT 4 Climate Change Adaptation

Systemic and Generative Perspectives & Tools

Paul Shabajee & Chris Preist
Department of Computer Science
University of Bristol
Bristol, UK
paul.shabajee@bristol.ac.uk

Malcolm Fairbrother & John-David Dewsbury
School of Geographical Sciences
University of Bristol
Bristol, UK

***Abstract*— The predicted manifestations of global climate change are diverse and extensive. Information and Communications Technologies (ICTs) offer great potential to enable and enhance climate change adaptation projects, programmes and activities. As yet these roles have received relatively little systematic consideration. In this paper we outline the nature of climate change adaptation contexts and present a set of prototype tools that aim to enable the identification and exploration of opportunities for ICTs to play positive roles across the full spectrum of climate change adaptation contexts. The tools are both generative and systemic—generative in enabling the creative identification of potential adaptation roles for ICTs, of all kinds, and systemic in providing a means of taking into account the complex interactions between the key elements of any climate change adaptation context. Further because of their systemic nature they can be iteratively applied enabling adaptive responses to the inevitable change within any climate change adaptation project. The paper provides an illustration of the generative use of the tools and finally explores key limitations in the initial work leading to suggestion for further development.**

***Index Terms*— Climate change, climate change adaptation, ICT, complexity, ICT 4 development**

I. Introduction

The direct predicted manifestations of global climate change are diverse and extensive. They include: increases in extreme weather events such as torrential rainfall or severe heat waves; extended periods of drought; changes in seasonal patterns; glacial melting; sea level rise; ocean acidification; temperature changes in water-bodies and changes in geographical ranges of flora and fauna, including crops [1][2].

The consequences of these manifestations for humans and natural ecosystems are highly variable and context-specific. For example, increases in the occurrence and intensity of extreme weather events such as intense rainfall can lead to a wide range of acute impacts, such as localised and regional flooding, coastal inundation, and infrastructure damage. These in turn may lead to immediate consequences such as loss of life, injury, interruption of food and energy supplies, and communication disruption, all of which require disaster recovery actions and remediation. In addition, they may have medium- to long-term impacts such as heightened requirements for expensive flood defences, the degradation of ecosystems or farmland, the displacement of peoples, changes in business model viability and insurability, etc.

ICTs (information and communication technologies) have great potential to enable and enhance climate change adaptation projects, programmes and activities. While there has been considerable work in the domains of ICT for Development (ICT4D e.g., [3]–[5]) and ICT for climate change mitigation (e.g.,[6]), as yet there has been relatively little consideration of the potential of ICTs to play a role in climate change adaptation (see [7]–[9].)

In this paper we present a set of conceptual models derived from a review of relevant literatures and current practices, and informal interviews [10]. Together they aim to enable the proactive identification and exploration of opportunities for ICTs to play positive and effective roles across the full spectrum of climate change adaptation contexts. They also provide a means of understanding how relatively small changes in contexts (e.g. geographical location, availability of regulatory infrastructures, socio-economic status and structure of a community, skills availability and access to expertise) can open up, and close down, climate change adaptation application opportunities for different forms ICT.

The features are designed to enable the tools to be used in the initiation, design, planning and longer-term evolution of ICT4Adaptation projects and initiatives. They aim to be able to support continual and adaptive identification and enhancement of roles of ICT for climate change adaptation and broader sustainable development goals.

II. Climate Change Adaptation Context

A typical definition of climate change adaptation is given by [1]: *"Adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change."*

Adaptation can take place at the level of individuals, households, communities, and whole societies. Their capacity to adapt in order to cope, and indeed thrive, both with increased risks of acute shocks and with the longer term impacts of climate change can be thought of in terms of a related set of concepts:

- Resilience: Ability to resist, absorb, accommodate and recover from a shock.
- Vulnerability: Propensity to suffer harm from exposure to external shocks and stresses.

- Adaptive capacity: Preconditions necessary to enable adaptation, including social and physical elements, and the ability to mobilize these elements.

For more detailed exposition of these concepts see Ospina and Heeks [11], Nelson et al. [12], Smit and Wandel [13], and Smit and Pilifosova [1].

TABLE 1: BASES FOR CHARACTERIZING AND DIFFERENTIATING ADAPTATION TO CLIMATE CHANGE (FROM [1])

General Differentiating Concept or Attribute	Examples of Terms Used
Purposefulness	Autonomous ↔ Planned Spontaneous ↔ Purposeful Automatic ↔ Intentional Natural ↔ Policy Passive ↔ Active Strategic
Timing	Anticipatory ↔ Responsive Proactive ↔ Reactive Ex ante ↔ Ex post
Temporal Scope	Short term ↔ Long term Tactical ↔ Strategic Instantaneous ↔ Cumulative Contingency Routine
Spatial Scope	Localized ↔ Widespread
Function/Effects	Retreat - Accommodate - Protect Prevent - Tolerate - Spread - Change – Restore
Form	Structural - Legal - Institutional - Regulatory - Financial – Technological
Performance	Cost - Effectiveness - Efficiency - Implementability – Equity

In sustainable development terms, climate change presents specific challenges, such as the need for efficient and effective disaster recovery, and demands proactive adaptation measures to mitigate risks and, if possible, to benefit from climate change-induced long-term trends and associated acute shocks.

However, climate change also both multiplies and amplifies existing development challenges and associated vulnerabilities [14]. The vulnerability and adaptive capacity of a community to cope with climate change impacts is in large part dictated by the community's broader development context; positive development status is broadly reflected in higher adaptive capacity, if not adaptive practice [9]. Hence climate change adaptation can be considered part of the larger sustainable development context.

It is useful to note that the term *development* is used differently in different research contexts. For example, in the context of ICT4D (ICT for Development), development generally refers to developing countries and communities, and in particular 'poor and marginalized' peoples in such contexts [4]. Whereas what we call ICT4Adaptation (ICT for Climate Change Adaptation) applies to sustainable development in the contexts of both developing and developed countries and communities. That said, ICT4D is closely analogous to what we call ICT4Adaptation and there are many lessons to be learnt from ICT4D.

There are a myriad of forms of climate change adaptation that are highly contextual. The very large extent of this range is illustrated by Table 1, from Smit and Pilifosova [1]. For example, possible responses to Climate Change impacts (function/effects in Table 1). include *retreating* from an impact, *accommodating* changes, *protecting* against change or efforts at *preventing* changes, etc. Responses may be more or less spontaneous or purposeful, proactive or reactive, localized or widespread, etc. Any particular response or set of responses can be thought of as being made up of a set of states shown in the table.

III. ICT & CLIMATE CHANGE ADAPTATION

ICTs increasingly play ubiquitous, pervasive and critical roles in virtually all aspects of human life. They provide the infrastructures, tools, and contexts ranging from highly personal and intimate communications between individuals and their social circles all the way through to those on which global trade, knowledge exchange, and diplomacy rely. As such, ICT is a fundamental factor in virtually any sustainable development context; indeed, it may provide the data and analytical tools needed to identify the existence of a development issue. For example, satellites, sensor networks, and climate modelling systems helped identify climate change as a phenomenon itself. Alternatively, ICT may 'simply' enable infrastructures and systems on which development initiatives rely such as mobile communications, or may be a key component of a project itself.

In a review and analysis of literatures relevant to ICT4Adaptation (see for example [2], [4], [5], [7], [9], [11], [12], [15]), we identified a diverse range of current and potential roles for ICTs in the contexts of adaptation. Some of these are directly related to meeting challenges associated with climate change, such as:

- provision of early warning systems for extreme weather
- sharing knowledge of adapted farming practices
- awareness raising of climate-related risks
- co-ordinating disaster recovery information
- supporting consultation and participation in developing adaptation policies
- provide training in flood management
- sensor networks providing data to aid adaptation decision making
- gathering and analysing information for vulnerability assessments

The majority relate to broader development goals: providing adaptation outcomes through improving resilience, reducing vulnerability and improving adaptive capacity. Many examples involve a complex mix of changes enabled by ICT and consequent changes in local and national socio-economic and political contexts. For example, improving access to market information, enabling more effective political advocacy, sharing of farming practices and empowering local communities and individuals though disintermediation and improving institutional transparency.

Box 1 gives an illustrative example of existing flood alerting services from the UK Environment Agency, which uses a range of ICT-based channels to provide warnings of flood risks to communities, business and individuals. The Environment Agency is responsible for delivering sustainable flood and coastal erosion risk management solutions across

Box 1: Examples of UK Environment Agency Flood Alert Services

- Web pages providing risk identification service and guidance and advice on flood risk and how to prepare for potential flooding (http://www.environment-agency.gov.uk/homeandleisure/floods/)
- Floodline Warnings Direct service that residents and businesses at risk of flooding can sign up to in order to get alerts by land-line telephone, mobile phone and e-mail (https://fwd.environment-agency.gov.uk/app/olr/home).
- Alert web-widgets (http://www.environment-agency.gov.uk/homeandleisure/floods/137543.aspx) that enable 3rd parties such as local government and news agencies provide up-to-date warning information on their own websites.
- Live data on river levels from monitoring stations (http://www.environment-agency.gov.uk/homeandleisure/floods/riverlevels/default.aspx)

England and for overseeing the delivery of solutions by Local Authorities and Internal Drainage Boards. In this role they provide a range of flood warning information services to householders and business using a variety of ICT channels. Figure 1 shows an example of one of their flood warning web services that enable 3rd party web sites, such as those run by local authorities and community groups, to include up-to-date flood warning information. Such services enable users to prepare for acute flood risks proactively. These ICT-based services complement other alerting systems, e.g. mobile loud hailers.

Understanding how effective such measures are and how best to provide such alerts is a complex issue – see for example [16]. Many issues arise in relation to the ICT solutions, e.g. ensuring those without direct access to the ICTs are alerted.

Underpinning many of these applications and potentials are a range of what might be thought of as requirements or sometimes pre-requisites for a potential application of a specific ICT; for example, necessary and robust infrastructure, access to appropriate ICTs, appropriate and enforced regulation, bodies of reliable knowledge, long term commitments to maintain and develop systems, and existence of trusted brokers.

These pre-requisites emphasize the issue that ICT-based applications must function within a diversity of contexts within which Climate Change Adaptation must take place, from highly economically developed nations and communities through to those struggling under multiple acute and chronic development pressures in poorer nations. Different ICTs have different characteristics, such as technical, economic, political and social pre-requisites, and specific features or affordances that mean they are suited to particular roles in particular contexts, e.g. basic mobile phones have characteristics that make them more viable for providing an effective means of communication in many poorer developing world contexts than smart-phones or desktop computers.

This mapping of the relationships between ICT characteristics/affordances and adaptation context is critical in understanding the many roles that ICT may play in adaptation in any practical situation. Given that one of the core goals of this research is to identify potential applications of ICT for climate change adaptation, it is necessary to develop a means of identifying or at least understanding the mappings between ICTs and concrete adaptation contexts.

FIGURE 1 - EXAMPLE OF FLOOD WARNING WEB-SERVICE PROVIDED BY THE ENVIRONMENT AGENCY IN ENGLAND

In recent years a number of frameworks have been developed that aim to help frame and systematise the assessment and conceptualisation of ICT4Adaptation activities including Ospina and Heeks [9], Souter et al [17] and Karanasios, et al. [18]. For example, Ospina and Heeks' e-Resilience framework [9] builds on the concept of livelihood systems to emphasize ICTs' potential for reducing climate change vulnerability through building resilience. In addition, there have been a number of reports and researchers actively drawing together concepts, knowledge and early case-studies, such as Kalas and Finlay [14] and Ospina [19] as well as broader reviews of the more transformational use of ICTs in developing world contexts [15].

Our work builds on and extends ideas within this prior work. We present three related conceptual models which (i) relate technological interventions to different stages of climate impact; (ii) categorise the components and contexts of potential ICT systems of intervention; (iii) provide a framework and informal taxonomy for categorising ICT interventions for adaptation. These models are designed to be *generative* in that they are intended not only to categorise existing applications but also to stimulate thinking about potential new applications.

IV. PERSPECTIVES AND CONCEPTUAL MODELS

A. Causal Chains of Climate Change

The first and highest level model is illustrated in Fig 2. The impacts of climate change can be thought of as a set of interlocking causal chains. Starting with a primary impact (e.g. changes to weather patterns), leading to physical consequences, generally on a fairly large scale, which in turn lead to human and ecosystem level impacts and on to consequences for individuals and communities.

Figure 2 illustrates a specific example of such a causal chain. Driven by the primary impact of 'changes in weather patterns' that may eventually lead (in this example) to loss of income and food sources at the community level, which

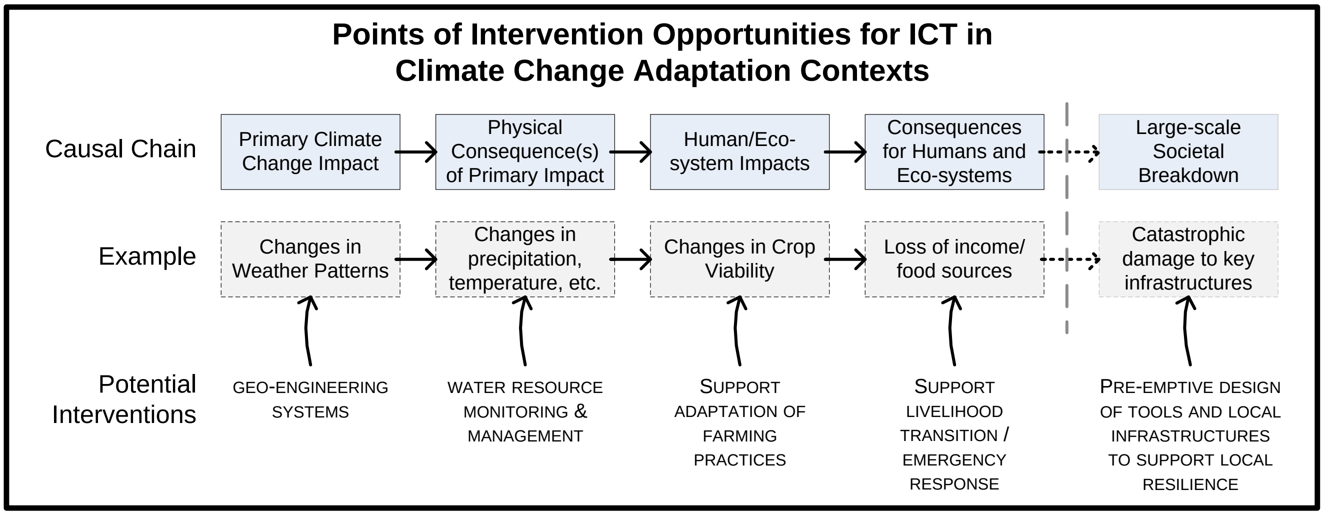

FIGURE 2- MODEL OF INTERPLAY OF FACTORS IN IDENTIFYING ADAPTATION OPPORTUNITIES FOR ICTS

may have acute consequences (e.g. requiring emergency response) and/or chronic consequences, requiring longer term adaptation.

This perspective shows that there are opportunities for adaptation interventions (of any kind) at different stages in those causal chains. The most pre-emptive is at the level of reducing or mitigating the primary cause or impact, all the way through to the most reactive response where an acute emergency must be responded to.

At the extreme end of this set of causal chains is the latent potential for very large-scale disruption, due, for example, to cumulative localised impacts on food supply or combinations of climate change and wider environmental and societal factors such as financial or potential energy crises. Tomlinson et al. [20] argue that ICT can and should have a pre-emptive role in helping prepare to cope with potential wide-scale societal collapse that may be caused by climate change or indeed any other cause.

ICTs can have potential roles to play at all points in the chains shown in Fig 2. The potential interventions on the bottom row are examples taken from our literature review of potential roles that ICT can play. For example, the use of automated sensor networks in water resource management underlie the flood alert services (illustrated in Box 1) and the use of social networking services in helping disseminate information about and support the use of new farming practices (see for example [19]).

We note later in this paper that ICTs often bring with them unintended consequences and one set of potential interventions to improve a given situation might be to adapt, re-think or even remove existing ICTs from a context.

As with any model it is a simplification. When using it, it is important to be aware of implicit limitations. For example the principle behind the perspective, that of *causal chains,* is problematic (see for example [21]). In any real-world context, even in physical non-human elements of the system, the interlocking set of 'causal chains' are both richer and more complex than a simple linear representation like that of Fig 2. can possibly contain. In addition, alone, it does not bring an awareness of the possible range of interventions that ICT may provide.

However, this perspective provides an important and useful prompt to highlight and remember that interventions can, and may need to be made at any stage, and possibly more than one, in a given adaptation context. In addition, in combination with the other two perspectives and models described below, it highlights the need to take account of changes and interactions between multiple levels in any adaptation context.

B. ICT Ecosystems

A second perspective relates to ICTs themselves. Fig 3 illustrates the very large scope of 'ICT' and the components of what can be thought of as an ICT ecosystem. This perspective derives from the realization that, in any real-world adaptation context, a particular ICT is *always* both a collection of other ICTs and part of a larger interacting system of ICTs.

For example, a mobile phone is composed of processor chips, screen, keyboard, aerial, microphones, etc. It requires an operating system and application software to manage the hardware and interactions with the user. It is also *dependant* for its function on the existence of mobile telecommunications infrastructures and other ICTs that can receive and do something useful with the data received from the original mobile phone, be that another mobile phone of a business colleague or an SMS (Short Message Service) based information service.

Figure 3 includes technical standards, regulation, and policy and in addition the existence of viable and sustainable business models. It may be debatable whether these are ICTs or even technologies themselves, however their roles as components in the ICT ecosystem are critical. Differences in the nature and degree of these will significantly determine the form and viability of an ICT eco-system in any particular context.

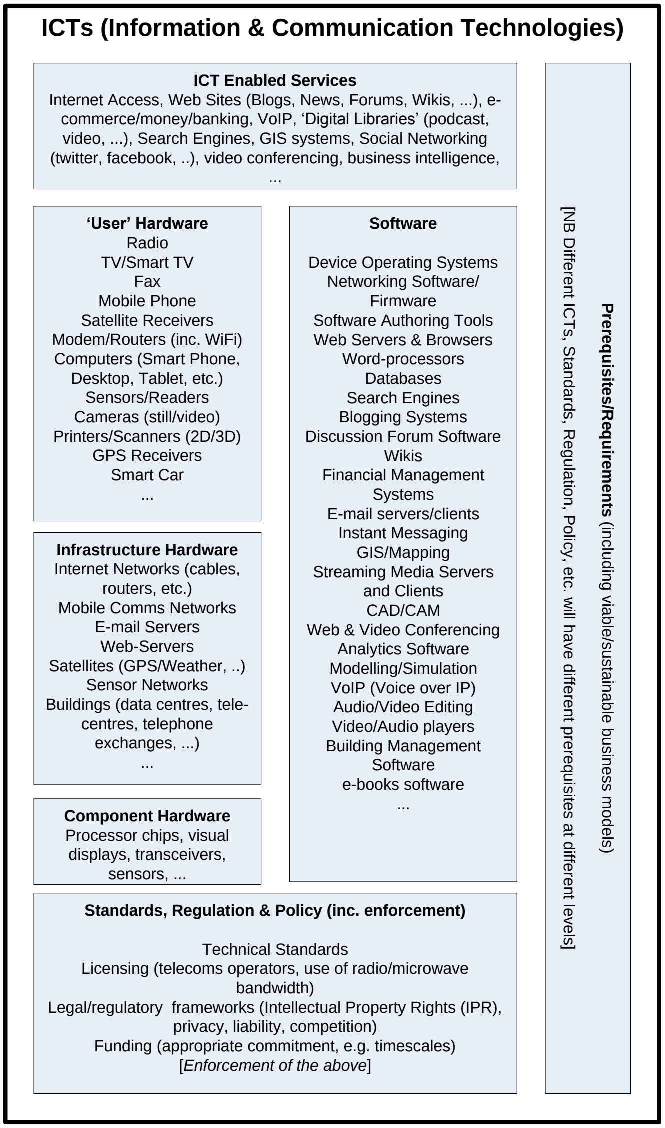

FIGURE 3 - CONCEPTUALISING THE COMPONENTS OF AN ICT ECOSYSTEM

The ecology perspective applies at all scales of what might be thought of as ICTs. For example the concept of so-called smart cities [22], which, broadly speaking, embodies a vision of ICTs providing highly detailed, rich and integrated information infrastructures for cities that enable more efficient and effective use of resources, thereby contributing to climate change mitigation and meeting adaption needs. A 'smart city' would be a very large-scale integrated ecosystem of many of the ICTs outlined in Fig 3.

There are many other ways of categorising ICTs. For example, [4] notes the importance of conceptualizing ICT in an ICT4D context and makes a distinction between ICTs for 'information capture', 'information storage' and 'information sharing/communication' including both hardware and software in each category. He also notes other frameworks, including that of Hamelink [4], who also distinguishes 'processing technologies' and 'display technologies'. Once again these categories are not taxonomies of ICTs but components of composite ICTs that manifest as particular devices, software or solutions generally within a larger set of ICT enabled systems.

An important aspect of the ecosystem metaphor is that it highlights change and evolution as well as inter-dependency. As technologies and their wider context changes (social, economic, environmental, etc.) the impacts of those changes propagate through the ecosystem. Importantly *new ICTs* co-evolve with other factors, and can be thought of as competing for niches (application domains, market share, etc.) within that larger eco-system.

An awareness of *inter-dependencies* is helpful in assessing the appropriateness of any particular technology in a given context. In addition, by making interdependencies explicit it can play a role in risk assessment processes, especially in conjunction with the other models described in this section, by helping to identify risks associated with ICT4Adaptation systems. Those may be simple, such as helping to identify key points of failure in an application 'eco-system', or complex, such as in helping understand unintended systemic behaviours that may evolve over time due to systemic interactions.

However the eco-system metaphor breaks down quickly if pushed too far. For example, while the Internet or World Wide Web can be thought of as technologies in such an ecosystem, they are also global scale technological platforms on which other technologies exist, develop and themselves co-evolve in that 'environment' – however it may not be helpful to think of many aspects of these or other ICTs using an ecological metaphor. In addition the nature, mechanisms, and rate of change are significantly different to that of natural ecosystems.

C. Identifying ICT Enabled Adaptation Opportunities

Finally, we present a conceptual model of factors that together can help categorise ICTs in adaptation contexts, and can be used generatively to explore new possibilities. This model is built on the previous two models, and ideas from other conceptual frameworks identified in the literature scan, particularly Ospina and Heeks [9], Souter et al. [17], and Karanasios, et al. [18]. The model provides a perspective on the relationships between key factors in any climate change adaptation context, combined with characteristics of ICTs and their potential roles to help identify potential ICT for Adaptation opportunities.

The model is illustrated in Fig 4. The four factors are:

- Application context: the characteristics of a specific community, infrastructure available, economic, and political context, etc.
- Application domain, e.g. agriculture, water resource management, emergency response, etc.
- Potential role(s) of ICT4Adaptation, e.g. improving access to information, resource monitoring, enabling community engagement, etc.
- Characteristics, requirements, and affordances of particular ICTs characterised in Fig 3., e.g. cost, necessary infrastructures and user skills, maintainability, portability, etc.

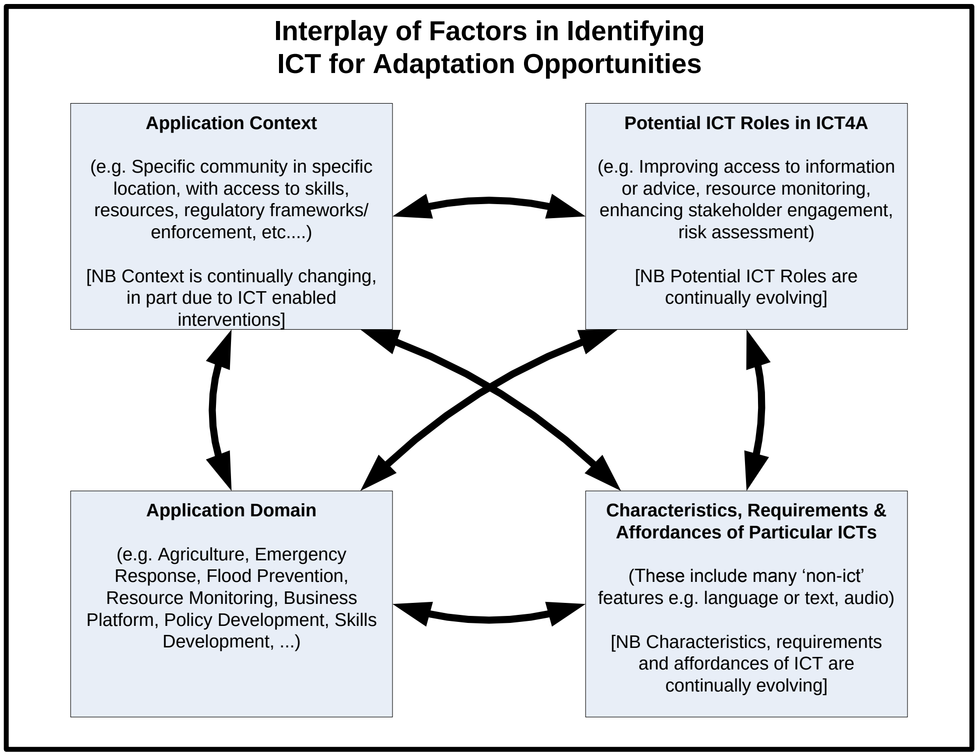

FIGURE 4 - MODEL OF INTERPLAY OF FACTORS IN IDENTIFYING ADAPTATION OPPORTUNITIES FOR ICTS

The factors are shown inter-linked by arrows. The arrows illustrate that the factors are inter-dependant; a change in one may drive change in the others.

For example, a change in application context, such as a change in access to skills within a community, may well add new potential roles for ICTs that were previously unavailable. It may mean that previously *irrelevant* characteristics of ICTs become relevant and may change the detailed nature of targeted application domain or possibly change prioritisation of which domain(s) are targeted.

The model is both systemic and generative. Systemic in that any single change in any factor may have knock on impacts on other factors, as described above, which may in turn themselves have knock on impacts, quite possibly feeding back to the original factor. It is generative, of potential opportunities for ICT4Adaptation, in that by specifying a set of options or contexts for a given factor or factors, e.g. specifying an application context and application domain will constrain the range of choices for potential ICT roles and the ICTs (because of their characteristics, requirements and affordances), leading to, and hopefully stimulating, the identification of potential opportunities in that constrained context.

D. A Model for Scenario and Adaptive Planning

This same conceptual model can be used to support a specific project in considering wider, systemic implications as it progresses. This is because contexts continually change. For example, the outcomes of the adaptation project itself change the context – e.g. new skills become or new technologies become available and/or innovative practices develop, costs change and funds become available, etc. Use of the model can then help identify new opportunities for ICT, enabled by such changes. Knock on impact such as those noted above will occur continuously throughout a project in any adaptation context. Including those within the model then drives identification of new possibilities.

Pre-emptive use of the model could be used as part of longer term scenario based planning activities. For example, by starting with a particular project and its intended (and potential unintended) outcomes. The model could be used to investigate how those various outcomes might open up new opportunities for ICT (and other) adaptation activities.

This awareness could then be used to map a range of potential on-going adaptation programme trajectories (possible paths) contingent on the actual outcomes of the project at any stage as they are implemented and evolve in practice.

E. Illustrative Generative Use of the Model

Table 2 gives some illustrative examples of possible values, dimensions or spectra for each of the various factors. In practice it is likely that the starting points or constraining factors would be the application context and application domain. Here we illustrate the generative nature of the model by starting with a range of application contexts and domains.

One common differentiating factor in the application context is 'developed'/'developing' nation context. This distinction is potentially problematic for a number of reasons,

TABLE 2 - EXAMPLES OF 'STATES' OF THE HIGH LEVEL FACTORS IN FIGURE 4

Application Context	**Potential Roles of ICT**
• 'Developed'/Developing Country • Rural/Urban • ICT Infrastructure Available • Levels ICT 'Literacy' • Levels of literacy/numeracy • Homogeneous/Heterogeneous community • Sub-community (e.g. farmers)/'public community' • Political and regulatory environments	• Information/Advice/Sharing • Resource/Situation Monitoring • Enhanced Stakeholder Engagement • Risk Assessment • Enabling Accountability & Transparency • Community Empowerment – open engagement, crowd-sourcing, etc. • Supporting Distributed Communities • Simulation of future scenarios
Application Domain	**Characteristics, Requirements & Affordances of Particular ICTs**
• Farming/Agriculture • Water Resource Management • Business/Livelihood • Education & Training • Health • Settlement/Displacement • Disaster Preparedness, Response, Management and Recovery • Empowerment of communities and social change	• Enable/support 1:1; 1:Many; Many:1; Many:Many communication • Presentation of information Video/Audio/Text/Visualisation • Persistent/Transitory • Sensor/Activator • Individual 'push'/ Collective • 'Push'/'Pull' of information • Interaction modalities (keyboards, voice, etc.) • Quality of interaction/communication possible • 'Smart'/'Dumb' (e.g. degree of processing, analysis, etc.) • Contextual Awareness (e.g. location)

but it is generally used as a proxy for a more specific set of contexts, e.g. availability of infrastructures, levels of poverty, health indicators, access to education, scale and types of businesses, scales of social welfare systems, etc. Another key differentiating contextual dimension is urban/rural. Here we used variations of these two application context factors, with a primary focus on the 'developed'/ 'developing' distinction, to illustrate how the model can help identify potential roles for ICT in Adaptation.

In order to illustrate the use of the model, we focus on two (arbitrary) application domains: i) reducing health risks from changes induced by climate change, and ii) planning for mitigation of increased occurrence of acute impacts of climate change (such as extreme weather). Finally, we chose two categories of potential role for ICT: i) monitoring for policy development and ii) support of people affected by acute impacts.

This set of 2 (application contexts) x 2 (application domains) x 2 (potential ICT roles) gives us a set of eight possible combinations. Table 3 shows an example of potential ICT4Adaptation applications.

The examples in Table 3 illustrate the generative nature of the framework, showing both the diversity of potential applications and also how common components, such as mobile device based alerting systems, can have multiple roles. There are existing incidences of some of these examples in place or under development; however, the point here is to show how the matrix provides a framework to identify potential ICT for Adaptation applications.

V. DISCUSSION AND FURTHER WORK

ICTs have great potential for enabling and amplifying benefits from climate change adaptation programmes, activities, behaviors in a quite literally unimaginable number of ways – in large part because new technologies, uses of technologies and their contexts of use continually co-evolve. This paper reports on work that aims to provide a set of ways to help identify and explore latent opportunities for the use of ICTs in as wide a range of climate change adaptation contexts as possible.

The conceptual models presented in this paper explicitly expose the very large 'design space' of opportunity for the use of ICTs in diverse ICT4Adaptation contexts. They do this by highlighting the opportunities for intervention at multiple levels and by opening up awareness of particular ICTs as [always] part of a larger eco-system of technologies and other contextual factors. In doing so they draw explicit attention to the potential benefits and risks associated with those inter-dependencies. The third model described provides a means of realizing and understanding the complexity of the interactions between four key groups of factors in any particular context. Those being: i) application context, ii) application domain, iii) potential role(s)

TABLE 3 – ILLUSTRATIVE EXAMPLES OF POTENTIAL ICT4ADAPTATION APPLICATIONS:
I.E. IDEAS STIMULATED BY THE USE OF THE MODEL OUTLINED IN FIGURE 4

	Application Context	**Application Domain**	**Example ICT Role**	**Example of Potential ICTs, Outline of Intervention Idea**
1	Industrialised nation (UK). Rural & Urban. Medium-term adaptation to change in climate leading to increased ranges of animal species.	Health - risks of increase in number of mosquito borne diseases.	Monitoring of occurrence and range of mosquitoes.	ICT-based system for integration of data and statistics from range of distributed sources, at different scales. For example, health authorities, central and local governments, community/crowdsourced (automatically, e.g. via Twitter, and systematically via explicit recruitment). Example technologies, Web 2.0/Linked Data.
2	Industrialised nation. Rural. Medium term adaptation to increased risks of disruption due to natural disasters, e.g. flooding, forest fires, landslides.	Planning for mitigation of acute impacts. Support of displaced peoples in period (possibly extended) after an acute impact.	Short- and medium-term accommodation and integration of displaced people into nearby communities.	Suite of services that support emergency service workers in placing displaced people within nearby communities, e.g. register of displaced peoples and ‘match making’ with volunteers who offer support, e.g. temporary accommodation (within the community), physical and support resources.
3	Industrialised nation. Urban. Short- to long-term adaptation to increased risks of extreme temperature variations.	Health – reducing risks to people who are vulnerable to extremes of temperature.	Identification and support of vulnerable people	System to support local community workers/leaders to identify people, e.g. elderly, those who live alone, etc., who are vulnerable to acute impacts of climate change, e.g. extremes of temperature. Including system to identify and co-ordinate support needed at time of impact.
4	Non-industrialised nation. Rural. Medium-term adaptation to increased risk of flooding.	Planning for mitigation of acute impacts. Identification of flood risk areas.	Modelling and monitoring flood risk for policy development.	Use of crowdsourced data from mobile phones (volunteers or paid people from communities) to monitor water levels at specific times. Requests for measurements to be made can be sent out as alerts. Enabling systematic collection of data at experimentally and analytically useful times.
5	Non-industrialised nation. Urban. Medium-term adaptation to increased risk of flooding.	Planning for mitigation of acute impacts. Identification of flood risk areas.	Modelling and monitoring flood risk for policy development.	Same as 4. With possible additions of specific focus on drainage blockages and localised flows as well as water levels.
6	Non-industrialised nation. Urban.	Health – increased risk of severe respiratory illnesses (acute asthma/severity of chronic lung disease) due to increased incidence of poor air quality.	Provision of information alerts.	Provision of alerts to vulnerable people and relevant authorities using various ICTs, e.g. mobile phones, e-mail, etc. of times and degree of risks of poor air quality. Could also crowdsource instances of acute impact on individuals to help increase effectiveness of response.
7	Non-industrialised nation.	Health – risks associated with occurrence of unfamiliar illnesses due to changes induced by climate change.	Provision of health advice e.g. unfamiliar illnesses due to climate change impacts.	Dissemination of guidance via community radio, community video, community news services (e.g. web/text based). Provision of alerts via same and text messages at times of acute occurrence or risk.
8	Industrialised nation.	Planning for mitigation of acute impacts on logistics (e.g. food deliveries) due to extreme weather events.	Modelling and monitoring of logistics systems, identification of vulnerabilities.	Modelling (e.g. agent-based, event-based modelling), of logistic systems under range of scenarios to identify risks and help design resilient systems and/or contingency measures, e.g. local food stores, etc.

of ICT4Adaptation, and iv) characteristics, requirements, and affordances of particular ICTs.

Perhaps even more helpfully the model provides a means of 'taming' that complexity and systematically, yet creatively, exploring the design space of potential opportunities in a concrete way. Finally, taken together the perspectives and models take account of and make explicit the fundamentally important recognition that adaptation contexts continuously change and so provide a means of identifying ways to dynamically adapt to those changes.

There are aspects of ICT4Adaption that are not yet integrated into the models presented here. Firstly, the design, manufacture and use of ICT is itself a source of greenhouse gases (GHG), a cost that must be included in any meaningful assessment of its potential benefits in other ways.

Secondly, the models presented in this paper are primarily focused on the understanding and identification of *positive* roles that ICT might play in climate change adaption. There are many ways in which ICTs may have direct or unintended negative impacts. For example the very ubiquity of and dependence on ICT itself brings with it significant potential for fragility in the face of acute climate change impacts, e.g. failures in ICT infrastructure could themselves lead to amplification of climate change impacts, such as disruption of food supplies and other logistically vital services (see for example [20]).

Further, as noted above, the systemic nature of the many factors that affect any particular ICT4Adaptation intervention mean that there will, in all probability, be unintended consequences of any ICT4Adaptation project. Those consequences may be *beneficial* or *detrimental*, these are terms that are themselves are problematic, since, in any particular ICT4Adaptation context the complexity of the situation means that what is beneficial from one individual's, group's or system's, perspective may be detrimental from another.

Any comprehensive assessment of ICT4Adaptation should include these kinds of issues. It seems possible that the tools developed here can be further extended to help with these forms of analysis. For example, through conducting pre-emptive analysis of interactions between factors it may be possible to identify unintended consequences of an intervention, thereby more effectively helping to identify risks and further opportunities. This would provide a means to explore and prioritise both benefit and detriment associated with various scenarios. We argue that studying such systemic inter-relationships is vital for a meaningful and successful understanding of ICT4Adaption activities. ICTs themselves can potentially provide improved means for making such assessment and prioritisation processes more inclusive.

While the focus of the examples presented has been largely at the level of communities, as illustrated in Figure 2, there are many possible points of intervention at different scales from global to personal. There is significant opportunity to further explore and develop the uses of the models at different and multiple-simultaneous scales, to generate many more opportunities for ICT4Adaptation.

Finally there are many significant and problematic practical issues with the use of ICTs for adaptation, for example, associated with digital exclusion [16, p. 56] and sustainable implementation [23]. Including such practical issues is important in any ICT4Adapation project and should be included in any development of this work.

The issues raised above, along with the opportunities for development, provide a rich vein for future improvement of this work. In addition they contribute to this paper's aims of contributing to the broadening and deepening of the growing ICT4Adaptation literature and in particular debate about how best to identify and bring to realization the potentials of ICTs for climate change adaptation across the whole spectrum of adaptation contexts.

As yet there have not been opportunities to utilize and evaluate this set of perspectives and tools in practical ICT 4 Adaptation contexts. However, we are seeking opportunities to do so in partnership with others and so to practically evaluate and further develop the ideas and tools.

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VII. References

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