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Abstract: To assess the potential impact of ICT on environmental sustainability in the European Union within a time horizon until 2020, we developed a System Dynamics model. In our contribution we make a critical, retrospective evaluation of the model with regard to the requirements and expectations of the project commissioners and of experts involved in the modeling and simulation process. The issues addressed are problem adequacy, validity, transparency, communicability and receptivity of the model. We conclude that modeling approaches that better support a modular model design than System Dynamics does would lead to better results regarding these requirements, and that a modeling language based on a more domain-specific ontology than System Dynamics would be needed to create models that are communicable and have an adequate epistemic connectivity to the scientific and political discourse.

Keywords*:* System Dynamics; environmental modeling; socio-economic modeling; prospective studies; information and communication technologies; sustainable development

1. INTRODUCTION

Information and Communication Technologies (ICTs) have a great potential to support sustainable development. However, most of the ICT-related trends, such as the trend towards pervasive computing or policies for 'the information society', are currently not exploiting this potential. On the contrary, there is some risk that ICT will become counterproductive with regard to environmental sustainability (see e.g. Hilty et al., 2005; Köhler and Erdmann, 2004; Kräuchi et al., 2004; Widmer et al., 2005). Systematic approaches to develop ICT and its applications in view of the goal of sustainable development are therefore essential.

In a project commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission’s Joint Research Centre, the authors developed a System Dynamics model to assess the potential impact of ICT on environmental sustainability in the European Union within a time horizon until 2020. The final goal of the project was to formulate policy recommendations based on new insights about the relative relevance of ICT application fields for environmental sustainability.

In this paper we give a short overview of the modeling and simulation methodology used, identify the requirements and expectations towards the model, and retrospectively evaluate the outcome of the modeling and simulation process with regard to these demands.

2. SYNOPSIS OF THE METHODOLOGY

The methodology applied in the project consisted of eight steps, which in practice were not executed in strict sequential order because of various interdependencies. A short description of each of these steps is given. The reader who is interested in further details is referred to the original reports (interim reports accessible online at http://cleantech.jrc.es/pages/ct8.htm, final report at http://fiste.jrc.es/pages/detail.cfm?prs=1208).

2.1 Screening for relevance

In a first step, the economic sectors and ICT applications with the greatest impact on environmental sustainability were identified. As a reference, the six environmental indicators that were developed in response to the conclusions of the European Council in Gothenburg (June 2001) and reported to the Spring European Council in March 2002 were taken:

- greenhouse gas emissions
- energy intensity of the economy
- volume of transport to gross domestic product
- modal split of transport
- urban air quality
- municipal waste collected, landfilled and incinerated

2.2 Data collection

The second step consisted of collecting existing data about environmental impacts of ICT in the selected sectors and for the identified application types. An extensive literature search was done to identify:

- trends in ICT development
- trends in ICT penetration and application (focusing on the types of applications identified)
- available data in the field of environmental effects of ICT.

All data that were later fed into the model (i. e. used to set model parameters or to initialize model variables) are referenced in the fourth interim report (Hilty et al. 2004).

2.3 Scenario building and validation

Acknowledging the complexity and uncertainty of future developments, scenario methodology was applied to assess the future impact of ICT on environmental sustainability. Three plausible scenarios describing alternative future courses of ICT until 2020 were created, taking the complex interactions of economic, social and ecological factors and variables into account.

The scenario-development process identified the most important factors likely to influence the development and use of ICT in the future. This process was mainly based on expert interviews. Out of these factors, the most uncertain ones (classified as highly unpredictable) were used to create the difference between the three scenarios 'Technocracy', 'Government First' and 'Stakeholder Democracy'. Table 1 shows a condensed characterization of the scenarios.

Table 1: Main characteristics of the three scenarios (Erdmann et al., 2005)

Uncertain Factor	**'Technocracy' Scenario (A)**	**'Government first' Scenario (B)**	**'Stakeholder democracy' Scenario (C)**
Technology Regulation	Incentives for innovation	Government intervention	Stakeholder approach
Attitudes towards ICT	Moderate, conservative	Open and accepting	Highly accepting
ICT in business	High level of cooperation	High level of competition	Between A and B
Attitudes towards the environment	Moderate / controversial	High awareness and interest	High awareness and interest

2.4 Model building

The model building step consisted in defining the main parts and variables of the conceptual model, characterizing their basic causal interrelations, refining the conceptual model and implementing it. Figure 1 shows the simplified conceptual model structure which resulted from the decomposition of the system under study into subsystems and served as a blueprint for the model. The external variables on the input-side represent the external factors identified in the scenario-building and validation steps. The indicators on the output-side quantify the impact on environmental sustainability.

The conceptual model structure basically allows for modeling the following effects of ICT on the environment:

- ICT is used (submodel 'ICT use').
- ICT supports energy supply management or energy demand management (submodel 'Energy').
- ICT changes transport by offering virtual forms of mobility and by supporting traffic management (submodel 'Transport')
- ICT changes the production of goods and services by supporting 'virtual goods', i.e. services meeting needs that otherwise would be satisfied by material goods. It also changes the business processes that are used to supply all types of goods and services by enabling e-business (submodel 'Goods and Services').
- ICT supports waste management (e.g. by enabling more 'intelligent' recycling systems) and contributes to the waste stream by its hardware, i.e. it creates electronic waste (submodel 'Waste').

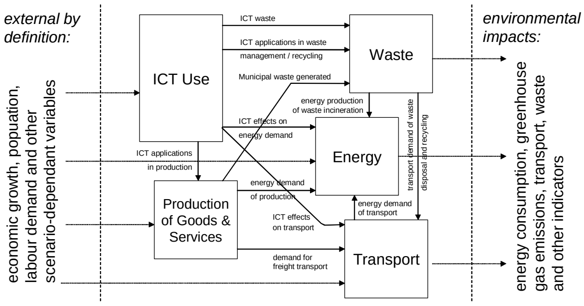

Figure 1: Simplified conceptual model structure (Erdmann al., 2004)

Each submodel was refined using causal loop diagrams. The submodels were then integrated into one comprehensive model, which was refined to a System Dynamics model and implemented using the Powersim Studio 2003 simulation system. The overall model included more than 3000 variables, among which 85 % were auxiliary variables mainly required for data handling, simulation control and output presentation purposes. Running the model required 60 Megabytes of RAM and 21 seconds CPU time for a simulation run of 20 years length on an Intel Pentium M processor with 1.6 GHz clock rate.

2.5 Model validation

A model validation workshop with 10 international experts in the field of 'ICT and environment' was held on September 18, 2003, at the Swiss Federal Laboratories for Materials Testing and Research (Empa) in St.Gallen, Switzerland. In a first step, the participants discussed the input data (values for external variables and for parameters) presented by the project team. This step was introduced to deal with the uncertainty of a large part of the input data. If the experts agreed on a parameter, it was assumed to be confirmed. Larger error margins were assumed, if the estimates of the experts showed relevant deviations. Second, the participants were asked to estimate the results for the environmental indicators for the year 2020 relative to the levels of 2000 for each scenario. In a third step, the simulation results shown were discussed in groups and in the plenary. The aim of this step was to collect arguments for and against the plausibility of the results and identify potential errors in the model.

2.6 Simulation

To account for the uncertainty of the parameters, sub-scenarios that exploit parameter uncertainty to maximize or minimize the environmental indicators were created. These were called 'worst case' or 'best case' sub-scenarios, respectively. Given an environmental indicator, all parameter values are selected within their min/max boundaries in such a way that the indicator is maximized or minimized. Energy was selected as the leading indicator for this optimization. A third sub-scenario was created by just setting each parameter to the average of its min and max values, called the 'mean' sub-scenario.

Since the goal of the project was to identify and quantify *the impact of ICT* on environmental indicators, the possibility was introduced to 'freeze' the ICT development and application in all sectors on the level of the year 2000 for the purpose of comparison.

The experimental design for the simulation has therefore three dimensions:

- Scenario (A, B or C);
- Sub-scenario (worst case, mean, or best case, using total energy demand as a leading indicator);
- 'ICT as expected' or 'ICT freeze' (dynamic development of ICT according to the respective scenario vs. ICT frozen at the level of 2000).

This design results in 3x3x2=18 values that have to be calculated for each output variable.

2.7 Evaluation of results

The model output was evaluated with regard to the specific questions the simulation study was intended to answer, e.g. which applications of ICT are most relevant regarding their (positive or negative) environmental effects.

2.8 Policy recommendations

Finally, the results were interpreted in the context of the given political framework and policy recommendations were formulated.

3. REQUIREMENTS AND EXPECTATIONS TOWARDS THE MODEL

Two categories of demands towards the model are distinguished: Requirements explicitly defined and addressed by the project commissioners or the project team, and expectations of the experts involved in reviewing the modeling and simulation outcome. Whereas for the requirements there is documented evidence, the expectations at least partly reflect the subjective perception of the experts involved.

3.1 Requirements

The project was commissioned by the IPTS to explore qualitatively and to assess quantitatively the ways in which ICT can influence future environmental sustainability, taking reference to the six indicators that were developed in response to the conclusions of the European Council in Gothenburg. The scope of the study covered three kinds of effects, with an emphasis on understanding the second and third:

- impacts and opportunities created by the physical existence of ICT and the processes involved (first oder effects);
- impacts and opportunities created by the ongoing use and application of ICT (second order effects);
- impacts and opportunities created by the aggregated effects of large numbers of people using ICT over the medium to long term (third order effects).

The objectives of the modeling and simulation part of the project were defined in Hilty et al. (2004) as:

- to refine and quantify the scenarios developed by creating a simulation model of the impact of ICT on environmental sustainability;
- to estimate the model parameters based on the data collection step, on additional literature reviews and expert consultation;
- to provide input for the evaluation and policy recommendation steps by identifying the factors that have most influence on the environmental indicators.

These requirements are strongly related to the following issues:

- problem adequacy of the approach;
- model and input data validity;
- validity of simulation results.

The issue of problem adequacy considers the appropriateness, possibilites, and limitations of the modeling and simulation approach with regard to the problem investigated. Model and input data validity addresses the question of whether or not the causal mechanisms and data considered in the model are sufficient to answer the questions at issue and consistent with empirical evidence. And, finally, validity of simulation results refers to the adequacy of the simulation experiments by which these results were produced, also regarding uncertainty issues.

3.2 Expectations

The model and its simulation results were discussed at the model validation workshop mentioned above and at a later workshop addressing the findings of the project, which was held at the Visions of the Information Society (VIS) conference on November 4, 2005 in St. Gallen. One of the main expectations of the participants – as perceived by the authors – was to learn about the key drivers and causal interrelations determining the impacts of ICT on environmental indicators by comparing their own subjective perceptions with the structure and behaviour of a model that had been implemented under systematic consideration of theoretical knowledge and empirical data.

Such expectations are, in particular, related to the following issues:

- simulation model transparency;
- communicability of model structure and simulation results;
- receptivity of model and simulation results by the target audience.

The issue of transparency is concerned, among others, with the accessibility of the assumptions the simulation model is based on and the retraceability of the simulation outputs to the assumptions. Communicability addresses the possibility to present model characteristics and simulation results in a comprehensible form. Receptivity considers uptake of the results by the scientific community or the policy makers.

4. EVALUATION OF COMPLIANCE WITH REQUIREMENTS AND EXPECTATIONS

In this section we present a *self-critical, retrospective* evaluation of the outcome of the modeling and simulation process with regard to the issues that were identified in the previous section as being related to the explicit or implicit requirements and expectations towards the model. Due to space restrictions, we can only present a rough outline of this evaluation.

4.1 Problem adequacy

The problem addressed in the project is the potential environmental impact of new ICT applications within a defined time horizon. A main prerequisite for the quantification of this impact is an adequate representation of the structure and behaviour of the 'real system' investigated.

Depending on the ontology underlying the specific modeling approach chosen, there are different ways to represent and quantify a 'real system'. The System Dynamics approach is to model causal interrelations between variables that have been identified as governing system behaviour. This approach seems appropriate when considering environmental sustainability at a policy level: Every ICT application typically has an effect on more than one variable, and these effects can reinforce or counterbalance each other.

One of the potential benefits of causal modeling with System Dynamics is that many causal relationships, which may never have been considered before, can be included. Stating them explicitly, instead of leaving them in the sphere of implicit assumptions, makes them more accessible for scientific and political discourse, which in turn can create new insights.

However, a System Dynamics model usually is based on a multitude of heterogeneous concepts and assumptions that considerably influence the simulation outcome. This e.g. holds for the concept of elasticities and the so-called 'constant travel time hypothesis' implemented in our model. The elasticities, which are based on estimated values, determine the extent of rebound-effects, i.e the induction of demand by efficiency improvements. The 'constant travel time hypothesis', which states that the average time people spend for traveling is almost constant, largely determines passenger transport trends.

The many assumptions that had to be made and the lack of data that would be needed to quantify all causal relationships represented in the model may be criticized. However, this is not an argument against System Dynamics: Ignoring a causal relationship is no less an assumption than introducing one without having enough data to exactly quantify it. Yet, the undamped consideration of causal relationships may lead to another limitation: The rising complexity of the model itself. High model complexity renders a model intransparent and binds cognitive resources, which may induce a (reductionist) *methodological lock-in effect* hampering the *epistemological alertness* necessary for a scientific or policy discourse.

4.2 Model and data validity

Model and data validity were tested by involving independent experts into the modeling and simulation process (see 2.5). Among others, the following actions were taken in reaction to the model validation workshop (Hilty et al., 2006):

- allow for a shift of energy consumption from the industrial to the domestic and service sector, if and only if the former decreases by a product-to-service shift;
- introduce a level variable for e-waste to account for the fact that there is a stock of ICT at the beginning of the simulation that will become waste after a certain delay, depending on the average useful life of the equipment.

4.3 Transparency

Like many other System Dynamics models, our model is a heterogeneous mixture of theoretical concepts, practical heuristics, empirical data and experience-based assumptions. This makes the model itself complex and difficult to comprehend for those who were not actively involved in the modeling process. One of the lessons learned from the model validation workshop was that it is very difficult for the experts to interpret the results of the entire, monolithic model, i.e. to retrace the simulation output back to the relevant structural elements or cause-and-effect relationships. As a consequence, we tried to restructure the model *a posteriori* by isolating parts (modules) having a weak interaction with the rest, and discussed them separately wherever possible.

4.4 Validity of simulation results

Validation is referred as the process, where models or model components are compared against observational data and/or theoretical knowledge. Because, for epistemological reasons, a model can generally never be verified but only falsified, model validation can in principle continue ad infinitum. If the model survives a test, it is perceived as more valid and reliable than before. If it is falsified, the model is revised and newly validated. In this project there was no room for many such validation cycles. To create the best possible results, some pre-validated input from the scenario phase was used, and a number of experts were asked to review the modeling and simulation outcomes (see 2.5). Nevertheless, many uncertainties regarding the quantititave parameter values remained.

With regard to uncertainty management, two types of uncertainty have to be distinguished: (1) Things that cannot be known because they depend on future policies and other open developments; and (2) things that could be known, but are not known (exactly) because of incomplete knowledge. The first type of uncertainty has been accommodated in the scenario-creation process, and the second type by giving the model parameters minimum and maximum values (error boundaries) and by creating best-case and worst-case scenarios based on these boundaries.

4.5 Communicability

The communicability of a model, including its underlying concepts and assumptions, is a necessary prerequisite to understand and discuss its simulation outcomes and to gain new insights. This is particularly true for a model conceived as a heuristic tool for creating policy recommendations. Communicability is directly related to model transparency, which, as stated above, was limited by model complexity. As a consequence, the task of communicating the model to the experts involved usually remained unfinished in face-to-face situations like the workshops and had to be postponed until during reviews of the project reports.

4.6 Receptivity

The application of a simulation model as a heuristic tool ideally requires that the model ontology is common to the model user and that epistemic connectivity to the scientific or policy discourse is given. Whereas the model ontology was common to only a few experts involved, the epistemic connectivity to the discourse should have been given by involving the experts into the modeling and simulation process from the beginning of the project. However, model complexity, to a certain degree, impeded the stimulation of scientific and policy discourse through common insights.

5. CONCLUSIONS

The requirements and expectations towards the modeling and simulation process could not all be fulfilled in the course of this project. In particular, rapidly increasing model complexity hampered the communication of the model to the involved experts, which is a main prerequisite to stimulate the scientific and policy discourse by common insights. The ontology provided by System Dynamics can be too general to guide the modeling process into the direction of communicable models. This drawback, which may be typical for a systemic-modeling approach, might be overcome by approaches that support a modular model design better than System Dynamics does. More specific modeling languages, common in other fields, might be necessary to model the socio-economic and socio-technical issues we treated in this project. It will be a great challenge to define an adequate ontology of a modeling language for this domain – an ontology that would create the epistemic connectivity to scientific and political discourse in the field.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Erdmann, L., Hilty, L.M., Goodman, J., Arnfalk, P., The future impact ICT on environmental sustainability, Synthesis Report, Institute for Prospective Technology Studies (IPTS), Sevilla, 2004. http://fiste.jrc.es/pages/detail.cfm?prs=1208

Hilty, L.M., Wäger, P., Lehmann, M., Hischier, R., Ruddy, T.F., Binswanger, M., The future impact of ICT on environmental sustainability, Fourth Interim Report, Refinement and quantification, Institute for Prospective Technological Studies (IPTS), Sevilla, 2004. http://cleantech.jrc.es/pages/ct8.htm

Hilty, L.M., Köhler, A., Schéele, F., Zah, R., Ruddy, T., Rebound effects of progress in information technology, *Poiesis & Praxis: International Journal of Technology Assessment and Ethics of Science* (11) 1-20, 2005.

Hilty, L.M., Arnfalk P., Erdmann L., Goodman J., Lehmann M., Wäger P.A., The Relevance of Information and Communication Technologies for Environmental Sustainability - a Prospective Simulation Study, *Environmental Modelling and Simulation*, 2006. Accepted for publication.

Köhler, A., Erdmann, L., Expected environmental impacts of pervasive computing. Human and *Ecological Risk Assessment* 10 (5), 831- 852, 2004.

Kräuchi, P., Wäger P.A., Eugster M., Grossmann G., Hilty L.M., End-of-Life Impacts of Pervasive Computing, *IEEE Technology and Society Magazine* 24 (1), 45-53, 2004.

Wäger, P.A. and Hilty, L.M., A Simulation System for Waste Management – From System Dynamics Modelling to Decision Support, Proceedings of the 1st Biennial Meeting of the International Environmental Modeling and Software Society (iEMSs), Lugano, 24-27 June, IDSIA, 2002, 174-179.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., Global perspectives on e-waste, *Environmental Impact Assessment Review* 25 (5), 436-458, 2005.