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Sustainability through Computation

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Overview

This chapter describes how computation can support individuals, groups, and societies in living sustainably. By sustainability, we refer primarily to the Earth's capacity to support human, animal and plant life while sustaining our planet's existing climate and biodiversity. We argue that measuring a system's sustainability by characterizing status quo, quantifying the effects of an intervention, and comparing decision alternatives will lead to greater overall sustainability. The chapter first discusses why it is difficult to obtain measures about sustainability. On the one hand, sustainability is a complex issue, drawing on multiple disciplines. On the other hand, sustainability may be described at varying levels of scale, each with a very large number of variables, assumptions, and interactions. Next we turn to computation and discuss its use in analyzing sensed data and simulating sustainability. We describe strategies for computing sustainability and for handling multiple models, simulations, and parameters. Finally, we present several visions for using computing and simulation to improve sustainability. Pursuing these visions will help us effectively deal with our exponential population growth and also, we argue, help improve sustainability.

Introduction

Sustainability is a problem of scale. As the human population has increased exponentially in a short period of time, we face new challenges. Suddenly it has become important to calculate Earth's total *biocapacity*: the biological capacity of an area of land or water to generate resources and to absorb waste. Biocapacity can be weighed against our *ecological footprint*: the measure of the demand that human activity puts on the biosphere. But even if these limitations can be measured [1], the question of how to develop insights, plan actions, and mitigate damage to our shared life support system remains. Meanwhile, our economic system promotes unbounded growth under the assumption of a limitless supply of resources to be consumed independent of any consequences. Furthermore, our infrastructure is designed to separate production from usage obfuscating true environmental costs and leading to a personal sense of limitless abundance.

Sustainability is also a problem of complexity. Environmental systems and subsystems have a level of complexity that makes causal relations difficult or impossible to find. Moreover, many of the variables change dynamically and many are yet to be discovered. The more we learn about the world and our place in it, the more complexity we find at any spatial and temporal scale. Exploring this unfolding web of complexity results in an unprecedented level of uncertainty about the mechanisms and relations in the organic and inorganic physical processes that support our existence. This uncertainty has prompted many questions. At a personal level, we may wonder what natural, mechanical, and business processes are required to supply the water we drink, the food we eat, and the air we breathe. At a global level, we may ask to what limits our planet can be pushed, beyond which natural systems can no longer provide what we desire from them. Fundamentally, our uncertainty about the stability or fragility of Earth's ability to support life has resulted in a global discourse on a strategy of sustainability. The concept of sustainability is the common-sense response to great uncertainty: when an outcome is impossible to predict because of complexity, one may hope that reducing interference with natural systems may increase the overall stability of the system, based on the assumption that natural systems are maximally stable from millions of years of natural optimization. If we can reduce uncertainty by reducing human impact on the environment while we continue to learn and understand more about the systems involved, we hope to be able to extend our timeframe for survival and even prosperity.

This chapter argues that an important tool to address scale and to study complexity is *computational modeling*; mathematical models representing the behavior of a complex system by computer simulation. To test a number of hypotheses, a simulation can be created for each scenario. The outcomes of these simulation experiments can support decision-making. The unique challenge of modeling the sustainability problem is the multiscale and multidisciplinary nature of the global environmental and economic processes involved. Quantifying sustainability issues, and tracking them over time, will help to calibrate the simulations further developing the models that generate emergent complexity in the effort to improve the resemblance to observed behaviour. Next we explain why sustainability must be studied at many scales and where the complexity of measuring and modeling sustainability lies. Then we discuss how computational modeling may be applied to sustainability and present some visions for how to make modeling and simulation impact thinking about and acting towards sustainability.

Sustainability

The use of physical resources is central to the topic of sustainability. As resources are extracted from the environment, transformed into products and services, and consumed, a number of effects and side-effects occur that impact the environment in a myriad of ways. We discuss efforts to measure these impacts at a global level as well as at the level of an individual product. We describe how these vast differences in scale contribute to the complexity of determining causes from their effects and we provide examples of multiscale issues.

To address the great complexity of large natural systems, a sustainability strategy can be adopted to minimize impact. The impact of human intervention on the planet has often been expressed with the metaphor of a *footprint*. The properties of a footprint include the type and amount of (a) original resources together with the process of extraction of those resources, (b) production resources (consumed and wasted) together with the process of production, (c) resources used for distribution together with the process of distribution, (d) resources required during the use period, and (e) wasted/recyclable resources together with the process of disposal and/or reuse (see Figure 1).

By understanding and measuring our environmental and ecological footprint, we can work toward reducing it thereby reducing uncertainty of whether or not we are permanently damaging our current or future environment. To characterize the size and nature of various ecological footprints, the full product lifecycle must be considered. Both products and by-products, that is, resources used in production as well as side effects produced such as waste and emissions, contribute to these footprints.

To better account for resources used, a simple taxonomy of types and sources of resources is helpful. Natural resources may be considered to be *renewable* or *non-renewable*. Renewable resources can be *replenished* at the same rate as they are consumed. For example, water, trees and other plants are generally considered to be renewable resources as they can be replaced by equivalent natural resources within a human timescale. Also, water is considered to be renewable since water table levels can be maintained. However, care must be taken in these generalizations as conservation and resource management must control the *rate* of consumption to ensure renewal. That is, if a forest is completely cut down, important parts of the ecosystem including animals and other plants will be destroyed. Planting thousands of trees after a clear-cutting may not be possible if the ground properties cannot sustain such a large simultaneous resource drain. Also, even if a forest could be regrown, it would not be considered to be renewable if it would take longer than a human lifetime to restore the forest.

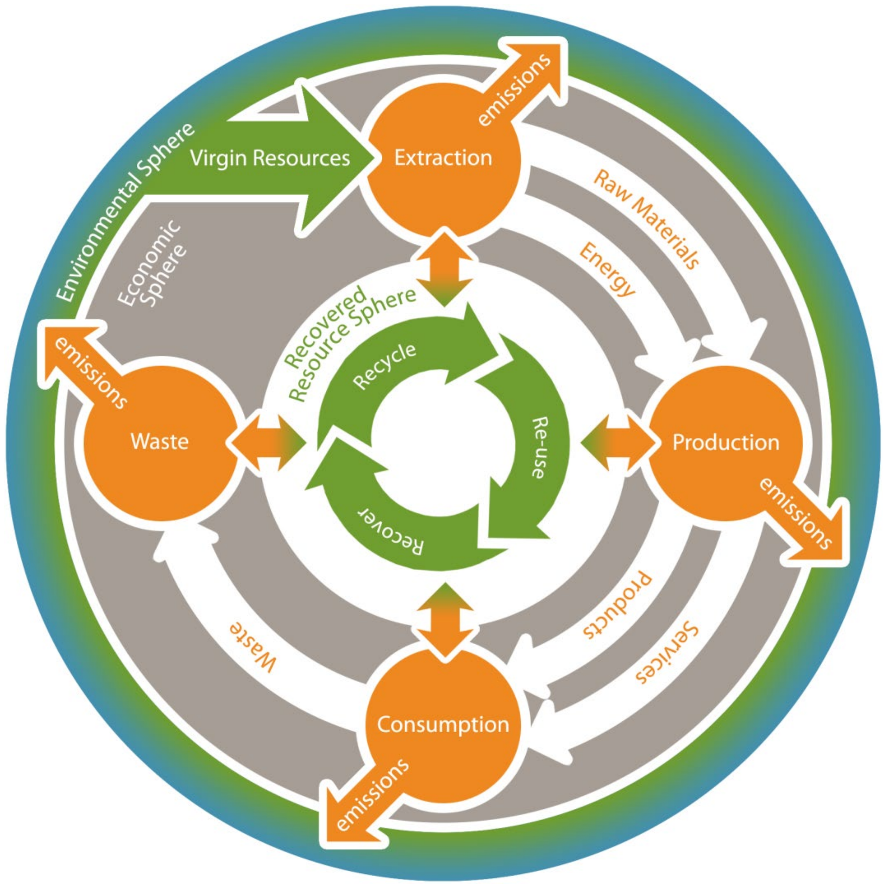

Figure 1: Resource transfers and cycles from the Environmental Sphere into the Economic Sphere. Extending the conservation of resources in the inner Recovered Resource Sphere will minimize the need for additional virgin resources (adapted from [2]).

Some natural resources are often included in the category of renewables but are essentially infinite and could be called *constant* resources: the sun, the earth and the moon which can be utilized for solar energy, geothermal energy, wind power, wave power and tidal energy. *Non-renewable resources* cannot be replenished at the same rate as they are consumed. So-called fossil fuels such as oil, coal and natural gas were created by natural processes over geological timescales and so, once they have been consumed, they are effectively gone. Unfortunately, the consumption of these non-renewable resources creates harmful emissions in large quantities.

In addition to the categorization of resources as renewable or non-renewable, it is helpful to differentiate *recovered* resources from *virgin* resources. When natural resources are first extracted from the environment, they are considered to be virgin. But when resources (natural or man-made) are recovered after they have been used and can be re-used in production instead of virgin resources, they are considered to be recovered resources (see Figure 1).

Humanity's rate of consumption of virgin resources can be reduced by the re-use of objects and materials, and by the recovery of materials and the recycling of those recovered resources into new useful objects. Once virgin resources have been removed from the environmental sphere and have entered the economic sphere, our level of sustainability will be increased if we delay additional virgin resource extraction by increasing the duration that these materials are maintained within the inner cycle of use, recovery, and re-use (see Figure 1).

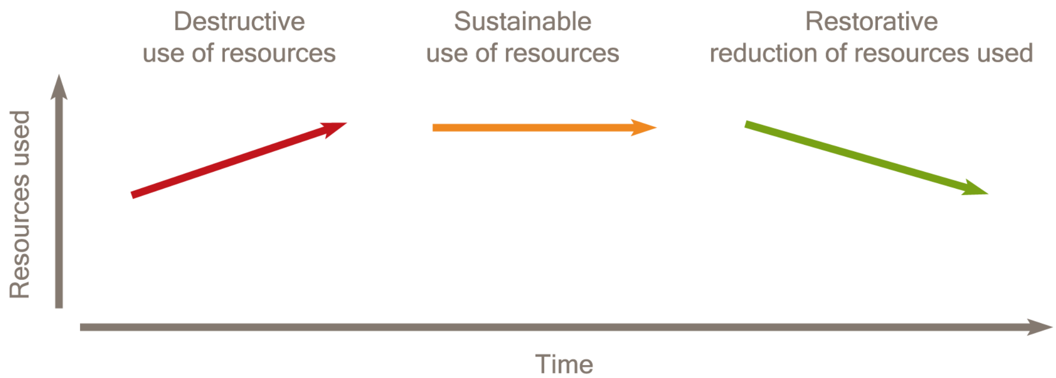

Figure 2: (left to right) Destructive trend where more resources are used than are returned in a reusable form. Sustainment trend where the quantity of resources used for production and consumption is fixed. Restoration trend where more resources are returned to the environment, as usable input, than are consumed.

While the quantity of resources used will fluctuate, the desired trends would move from destructive to sustainable to restorative levels of consumption (see Figure 2). A destructive trend is defined as a growing footprint of consumption of virgin and non-renewable resources. Currently, since we are in a destructive trend, our collective challenge is to both decrease our use of virgin and non-renewable resources and increase our use of recovered and renewable resources. A sustainable trend would start when only recovered, renewable, and constant resources are being consumed at renewable rates. Finally, a restorative trend would be defined as a negative footprint where absolute quantities of recovered and renewable resources are being reduced and the remaining quantity could be returned to natural systems in a usable form.

Therefore, we define *sustainability* as the reduction of our footprint toward a sustainable trend of resource usage.

Environmental Footprint

Footprints include both products (the amount of resources consumed) and pollution (the amount of waste and emissions produced). Atmospheric, land-based and water-based pollution (see Figure 3) all affect each other but are often discussed independently. Atmospheric pollution is the most popular topic of public discourse and is often casually referred to as a *carbon footprint* but is intended to describe carbon dioxide (CO_2) and other harmful emissions reported in CO_2-equivalent (CO_2e) units. Land use footprints are not yet generally discussed but are as important as a carbon footprint as these factors are all related. For example, the destruction of virgin rainforest, to grow cattle for instance, is a large and serious problematic use of land that permanently damages biodiversity as well as natural carbon dioxide consumption and oxygen production. *Water footprints* have also been studied (www.waterfootprint.org). Of course, natural water cycles are also an integral part of carbon and land-use footprints. As with the atmosphere, water may seem to be an infinite resource but the renewal rate of ground water can be anywhere from days to centuries so careful conservation is required to ensure local ecosystem preservation.

Figure 3: Human impact on the environment can be classified into a number of interacting areas: land, the water table, (open) water, and the atmosphere.

Problematic human impact on natural systems has been examined by the United Nations Environment Programme (UNEP) Sustainable Consumption and Production Branch [3]. This group works to define metrics to better understand the current global resource imbalance between consumption and production and its potential cost to environmental stability. Three dangers are specifically called out as primary factors to consider: Global Warming Potential, Land Use Competition, and Human Toxicity. Within these factors, ten categories of resource use are defined: plastics, coal, natural gas, crude oil, biomass, animal products, crops, iron and steel, other metals, and minerals. While each of the three factors has its own dominant problem category, a combined value reflects how these factors affect the environment. To help support decision-making, a weight is chosen for each category based on its overall estimated environmental impact, resulting in one general *environmental footprint*, expressed as an Environmentally-weighted Material Consumption indicator (right-hand column in Figure 4).

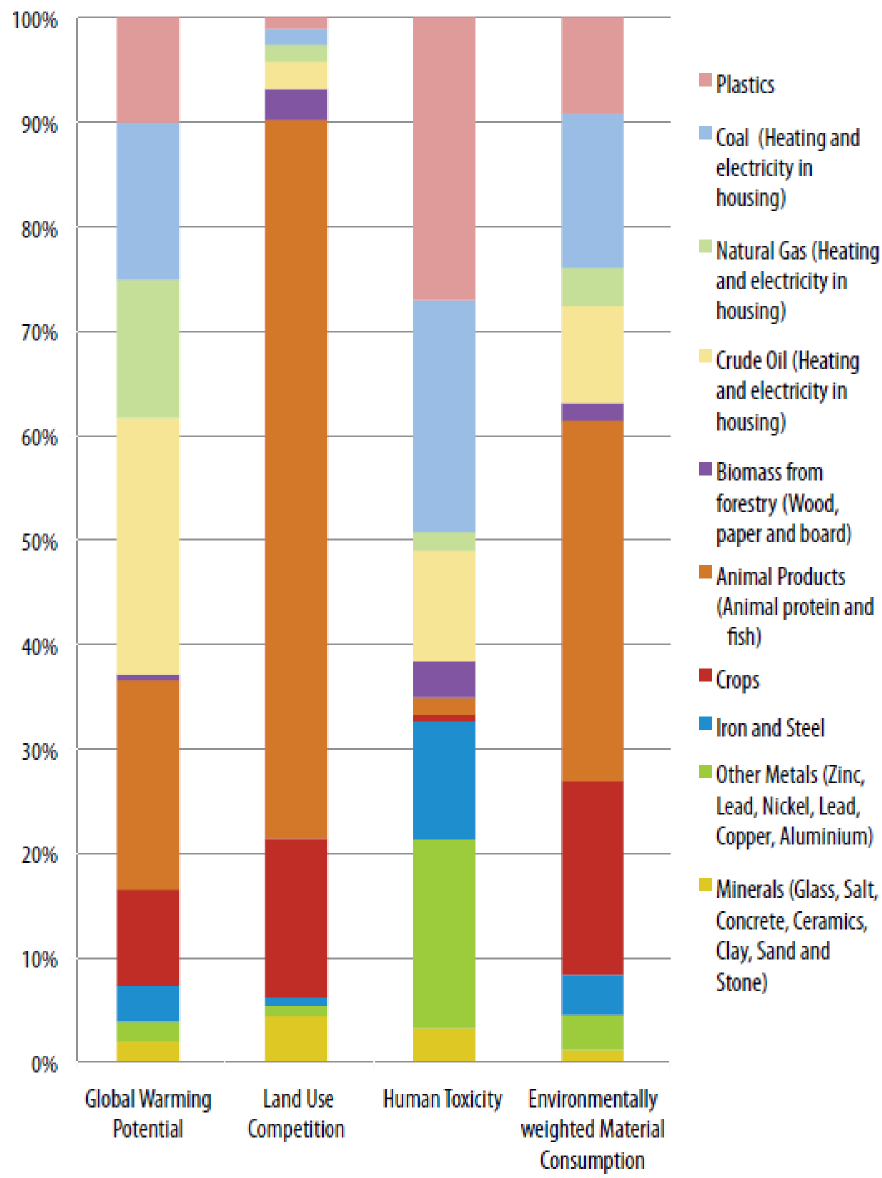

Figure 4: Environmental damage indicators as reported by the United Nations Environment Programme (UNEP) Sustainable Consumption and Production Branch [3].

Our environmental footprint, caused by material consumption expressed by this indicator, is led by Animal Products (34.5%), Crops (18.6%), and Coal (14.8%). Animal Products stand out as the primary global environmental problem, larger than Crops and Coal combined, because of the massive amounts of resources that are consumed in producing the 294.7 million metric tons of meat from (roughly 58 billion) land and aquatic animals that are killed each year for food [4]. This consumes a large portion of the global water and food supply.

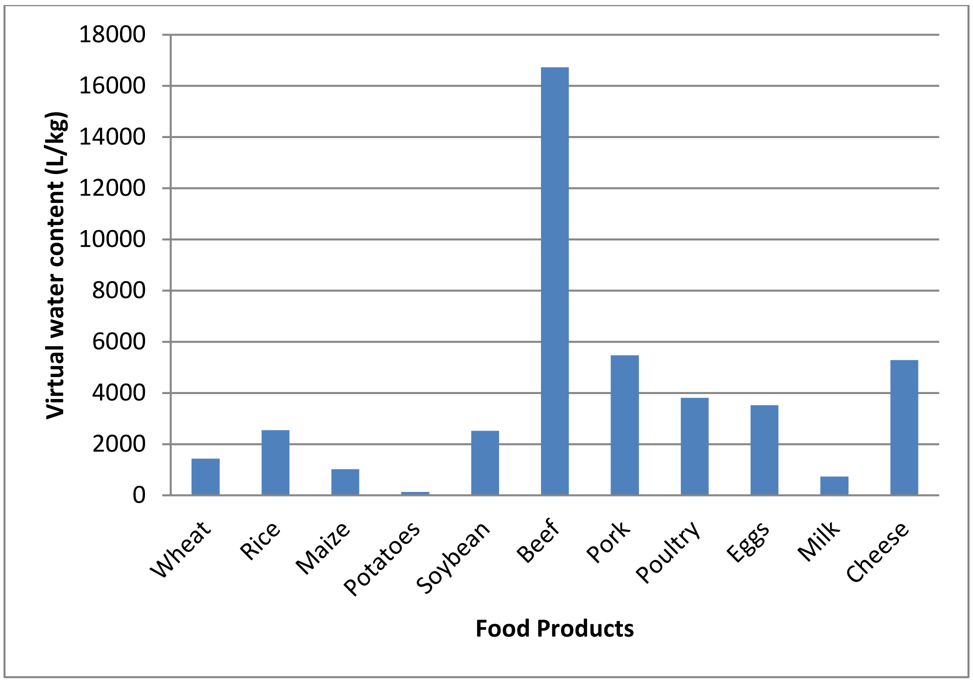

Figure 5: Comparative water demand from everyday food products (L/kg) [5: Table 4.1]

As shown in Figure 5, unexpected water demands for everyday food products shows how the consumption of water resources is not inherently obvious [5]. For example, the production of one kilogram of beef consumes 16726 L of water while the same amount of potatoes only uses 132L. These numbers show how practices, such as factory farming, can destabilize the water table for an entire region. To better measure the water footprint and to capture these hidden environmental costs, the concept of *virtual water* was introduced by Tony Allen in 1993 [5]. This term describes the amount of water consumed in the production process of an agricultural or industrial product. This can also be an important political issue when trade considers the export or import of water-intensive products. For example, the production of a 32-megabyte computer chip of only 2 grams requires 32 kg of water [5]. A general lack of transparency in resource consumption in the supply chain of products adds significantly to the complexity discussed earlier.

In terms of Global Warming Potential, Greenhouse Gas (GHG) emission reports from the United States Department of Energy [6] and the Livestock's Long Shadow report from the United Nations Food and Agriculture Organization [7], find that the three primary causes of anthropogenic GHGs are Buildings (48%), Animal Products (18%), and Transport (14%). Typically, transport is believed to be the climate change culprit even though buildings –or rather the energy utilized for heating, cooling, and lighting buildings– are the dominant air pollution problem (see Figure 6). This could be thought of as a multiscale problem as buildings are often the largest man-made structures on Earth, yet directly and indirectly emit gases that cause nano-scale chemical reactions that destroy our atmosphere.

Figure 6: The power generation currently utilized to supply heating, cooling, and lighting to buildings causes more GHG pollution of the atmosphere than any other category. Photo of Shanghai (Azam Khan 2010).

Greenhouse gases include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs). These substances interact in ways that are difficult to predict. The most dangerous of these is CFCs as they destroy ozone. Unfortunately, when exposed to ultraviolet light, CFCs release a free Chlorine (Cl) atom that reacts with O_3, breaking it into O and O_2. This starts a chain reaction where a single Cl atom can break down 100,000 O_3 molecules (see Figure 7) [8]. Although ozone itself is a GHG, it also acts as a protective layer around the Earth preventing ultraviolet radiation from damaging life on the surface of the planet. The ozone layer is relatively thin and is sensitive to disturbances.

To make matters worse, the lifetime of some GHGs can be quite significant. For example, methane (CH_4) has a lifetime of about 10 years [9], N_2O has a lifetime of 114 years, and some CFCs can last from 45 years to 1700 years [10].

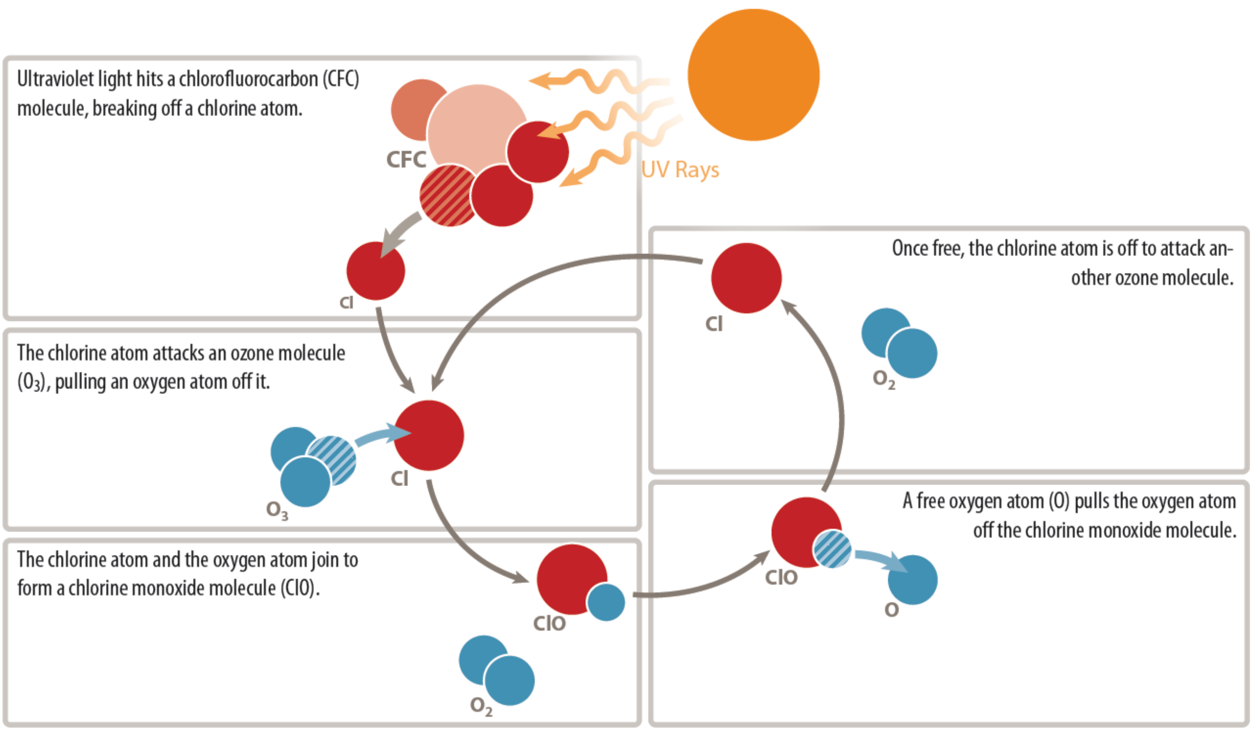

Figure 7: The ongoing destruction of ozone in the stratosphere by chlorine atoms derived from the breakdown of CFCs in the atmosphere. (Diagram by Michael Glueck.)

The discovery that ozone destruction would continue for some time, despite the total cessation of CFC emissions into the atmosphere, motivated a global resolution to ban the production of CFCs worldwide at the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer. The hope was that the ozone layer would recover in about 60 years by 2050. However, in 2011, a massive ozone hole was still observed over the southern hemisphere (see Figure 8).

Methane is about 20 times more effective than CO_2 at trapping heat in the atmosphere. It primarily stems from enteric fermentation in ruminant animals (37%), such as cows and sheep [7]. Nitrous oxide is considered to be 296 times more dangerous than CO_2 and, as with methane, the main global source of N_2O is animals (65%), such as cows and pigs [7]. The animal waste (220 billion gallons of waste each year in the U.S.; over 830 billion liters [12]) from factory farms is typically collected in “lagoons” (see Figure 9).

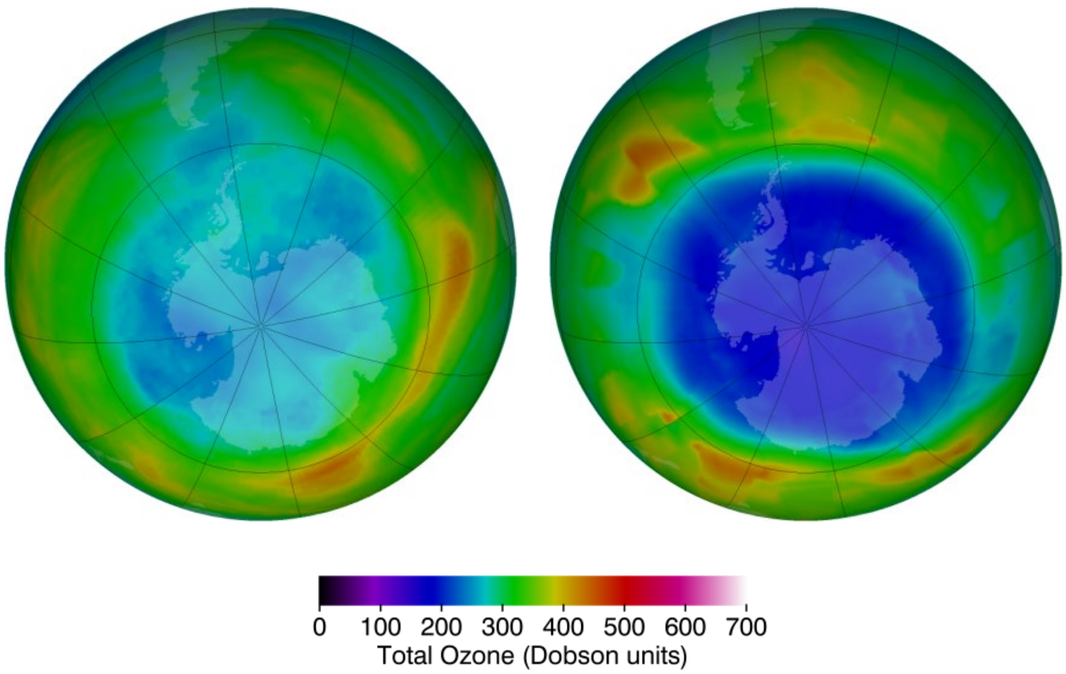

Figure 8: Massive ozone hole (blue region) seen over southern hemisphere August 31, 2011 (right), compared with earlier image of the same region August 31, 1982 (left) [11].

The lining of these lagoons often break causing E. coli bacteria from the feces to poison local water systems effecting downstream farms [13]. The media often report E. coli or giardia contamination of certain vegetables and the health risks of consuming them, but the factory lagoon that was the source of the problem is typically not mentioned or identified [13]. In N.Y. State alone, 3000 impaired river and stream miles are contaminated by factory farm animal feces. Lagoon spills are also a top contributor to the impairment of lakes and reservoirs, affecting over 300,000 lake acres in the state [13].

Figure 9: State of the art lagoon waste management system for a 900 head hog farm. The facility is completely automated and temperature controlled – United States 2002. © Photo courtesy of USDA NRCS/Jeff Vanuga [7].

Industrial buildings, including livestock factories, are responsible for more than half of the GHG emissions from buildings while the remainder is from residential buildings. Together, they account for 48% of global GHGs motivating the architectural community to work toward the development of very low energy buildings [15].

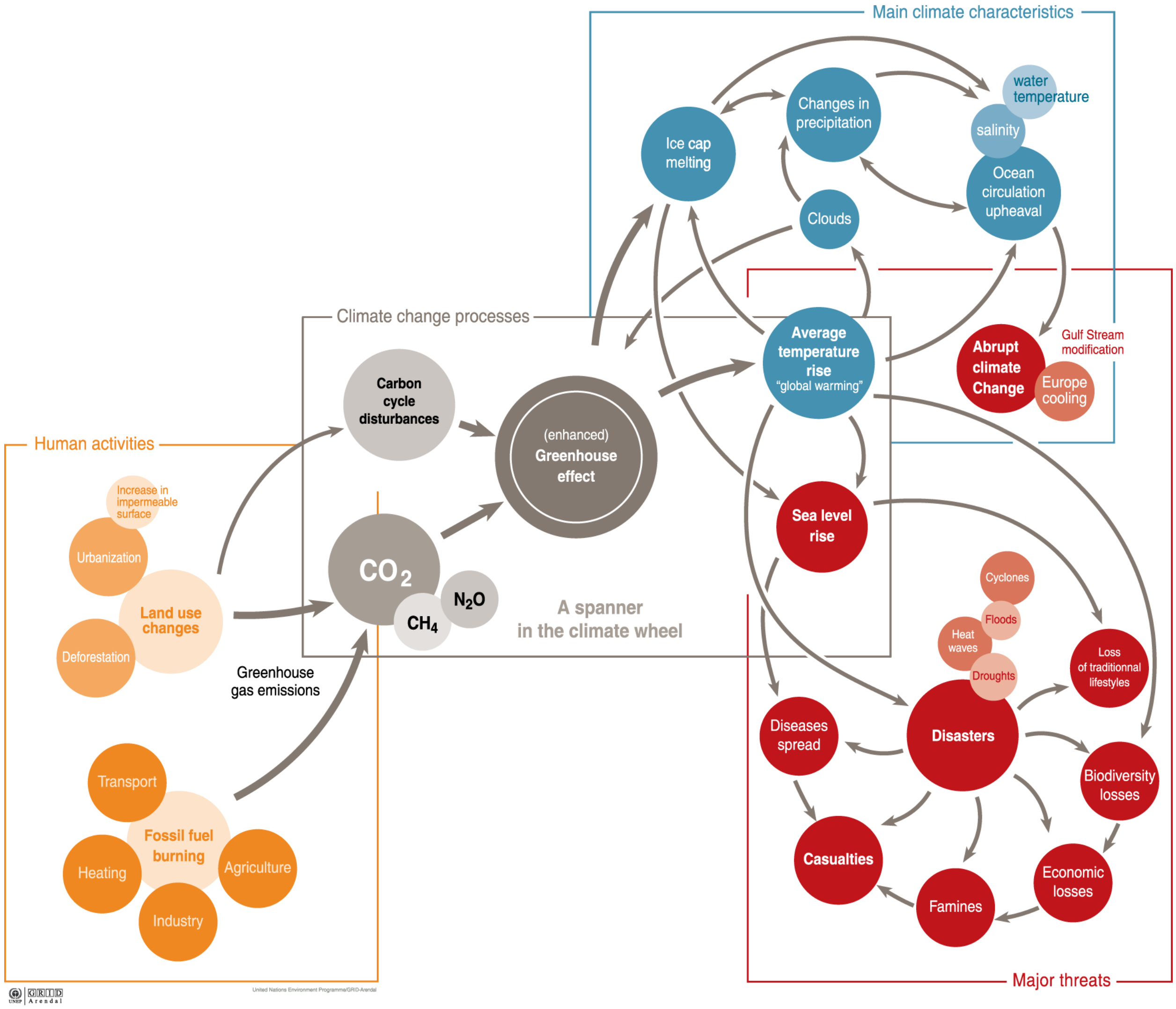

Figure 10: Climate Change: Processes, Characteristics and Threats. (2005). In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved December 31, 2011 from http://maps.grida.no/go/graphic/climate_change_processes_characteristics

In summary, unexpected sustainability problems can be found in systems from the nano-scale of chemical reactions, to the global scale of resource consumption and transformation. Furthermore, this complexity is affecting another highly complex system: the global climate (see Figure 10).

We have described the direct and indirect sources of ecological footprint contributors and have provided a taxonomy of resources to help define a sustainability trend. The taxonomy described virgin or recovered (replenishable or constant) renewable and non-renewable resources. We have shown how sustainability is a problem of both the scale and complexity, and have described the leading environmental issues with respect to land, water, and atmosphere pollution. However, solutions are possible, in terms of human diet change [14] and low-energy building design [15] that could have an enormous positive impact on minimizing the dangers of Global Warming Potential, Land Use Competition, and Human Toxicity.

Having discussed the major properties of our ecological footprint, we next contend that two key drivers of the growth of our ecological footprint are economics and infrastructure. These two areas both introduce a level of indirection in resource use that obfuscates causal relations. We propose that transparency in the lifecycle of a resource will improve sustainability.

Ecological Economics

The consumption of products and services results in pollution in the form of waste and emissions. While recycling programs have been running for decades to minimize waste, atmospheric emissions are inherently more difficult to capture and reuse in production processes. The current business approach to emission reduction is to introduce cap-and-trade schemes. While emission trading schemes have been established for CO_2e (equivalent amounts of GHGs to CO_2 with respect to global warming potential), some countries have found taxation to be more effective.

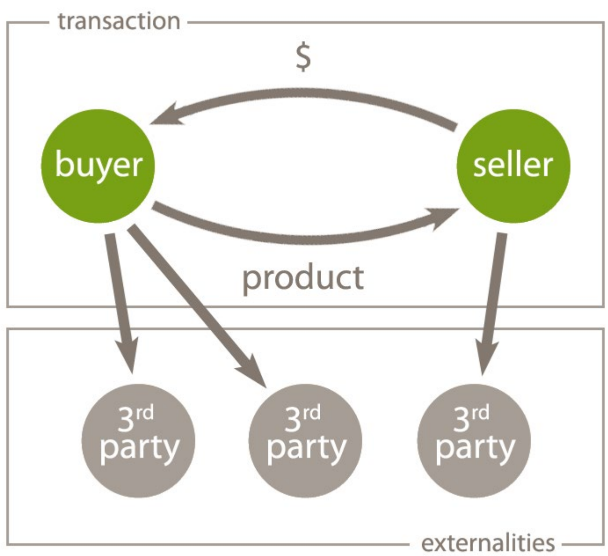

Figure 11: Transactions that are mutually beneficial to buyer and seller may have adverse effects on 3rd parties, such as people or the environment, that are not accounted for and are passed onto society at large.

Direct taxation supports cause-and-effect understanding while trades and subsides (funded by indirect taxation) obfuscate which behaviour creates which outcome. For natural resources, the complexities of different layers of subsidies, taxation, tariffs and pricing for different types of users in specific regions has resulted in a tangled web of causes and effects. These indirections render it impossible to properly calculate True Cost Pricing (TCP) of a product or service. Standard economic theory states that any voluntary transaction is mutually beneficial for the buyer and seller. However, an exchange of goods or services can cause additional effects on third parties, called *externalities* (see Figure 11) [16]. True Cost Economics is an economic model that includes the cost of negative externalities directly into the pricing of goods and services. The goal is for products and activities that directly or indirectly cause harmful consequences to living beings or to the environment to be accordingly taxed so that their price includes hidden cost. A leader in green tax reform, shifting taxation from labor to environment and energy, is Denmark:

> Denmark has become much greener during the last two or three decades. Most environmental indicators support this conclusion. The environmental improvements are of course the results of various kinds of regulations. During the last three decades the polluter-pays principle has been implemented widely in the Danish economy. In a Danish context this means that consumers or polluters pay not only the direct costs connected to supplying for instance water and energy, disposing of waste and waste water etc. They also pay the externalities connected to this consumption through a wide range of green taxes. Green taxes have thus played an important role in fully implementing the polluter-pays principle.
>
> Following the introduction of the tax on pesticides used by agriculture in 1996 the consumption has fallen by 40%. Likewise the introduction of the tax on drinking water has contributed to reduce the consumption of water by 25%. A reduction in the water consumption has the added effect of reducing the emissions of nutrients to the water environment from sewage treatment plants and industry. The tax levied directly on the waste water has had the same effect. And together with the direct regulation of sewage treatment the waste tax levied on phosphor, nitrogen and organic material has reduced the emissions of these substances by 75-85% from 1989 to 2008. [17]

While the implementation of green taxes must be carefully managed, as it is still a somewhat indirect system for the reduction of resource consumption, it can clearly have a significant impact. Eliminating externalities would allow products and services to be priced according to their true cost. This would greatly help individual and corporate consumers to make informed choices as they could compare options from vendors in a meaningful way. For example, a large supplier of industrial flooring and carpeting recycles old carpeting into new carpeting, and so, understands the costs and benefits compared to purchasing raw materials [18].

Unfortunately, for many products, especially electronics, the design process does not take into account the end-of-life recovery of materials making them practically impossible to recycle. Recently, however, product design software is integrating Life-cycle Assessment (LCA) features encouraging designers and engineers to consider both the manufacturing processes as well as the recycling processes necessitated by their design choices [19].

The Infrastructure Trap

Another indirection that obfuscates resource consumption is the use of infrastructure services such as electric power, natural gas and water. The term *infrastructure* can be defined in several ways. Infrastructure can be thought of as a spatial term. For example, common services for a number of buildings, such as water or energy, could be supplied by remote infrastructure instead of being locally generated. The term can also be considered as applying to large numbers of users, as opposed to services that only cater to a few individuals. Well-water is an example of a local water supply serving a single family while municipal water systems can serve millions of people. Finally, infrastructure could also be measured in terms of implementation cost or efforts, making these systems seem permanent once a large investment has been made. An example would be the deployment of telephone land-lines to every individual home and building in a city versus the installation of cellular phone transmission towers across the same area. Given these dimensions, we can see that great benefits can be had from the implementation of infrastructure. The development of reliable infrastructure services, notably in the first half of the 20th century, was an enabling technology propelling cities and some countries to economic dominance. Thus, the modern city assumes the existence of highly reliable common infrastructure services. The massive scale and cost of urban infrastructure projects, together with their ubiquitous nature, make them essentially invisible and, in a sense, this is the goal of infrastructure so that daily life is not burdened with finding clean water, food, and other basic necessities.

However, infrastructure is inherently an indirect method to supply services. When we turn on a computer, we do not see a truckload of coal being dumped into a distant furnace. Yet, coal-burning is the primary method for electricity generation in the United States [6]. These stations exhaust the resulting smoke (CO_2, SO_2, NO_x, and CO) into the atmosphere. As these GHG emissions are permitted at no cost to the power station, electricity can seem to be quite inexpensive but the cost of dealing with this pollution is indirectly passed on to society at large as an externality. Furthermore, the significant overhead in starting or stopping these stations means that they cannot dynamically respond to large changes in demand. For example, coal power stations can take 12 to 120 hours (0.5 to 5 days) to start, depending on their current temperature [20]. After the major power outage in the northeastern U.S. and Canada in 2003, nine nuclear power plants took 6 hours to 11 days to return to service [21]. This cycle-time overhead leads to a strategy of *oversupply* to ensure reliability in delivering electricity. To minimize the oversupply, a load balancing approach is being implemented in some regions. By varying the pricing depending on the demand at the time, the hope is to distribute the demand as evenly as possible. The concept of a *smart grid* was introduced that can vary pricing dynamically, as well as redirect a number of power sources to locations of power needs in an efficient manner. A smart grid system would also ideally be designed to accept more variable energy sources such as solar or wind power.

Urban infrastructure creates benefits and costs, especially as it relates to sustainability. Strategies, such as energy demand-response management, reflect scaling problems of infrastructure. But even if oversupply is minimized, this only minimizes *extra* waste. The amount of pollution created by generating the power required to meet the actual demand is unchanged. So, while smart grids should be developed to minimize extra waste and to enable alternate energy sources to participate more easily in the power grid, a smart grid is an enabling technology but is, itself, not a sustainability solution.

Alternatively, local supply of power and water removes the need and cost of infrastructure development, improvement, and oversupply strategies. A local supply strategy is also scalable and, as a direct method of supply, helps users to develop a sense of their usage as well as an inherent sense of scarcity rather than abundance. However, a local supply of resources does not provide the freedom to consume them at any rate as natural replenishment rates still apply.

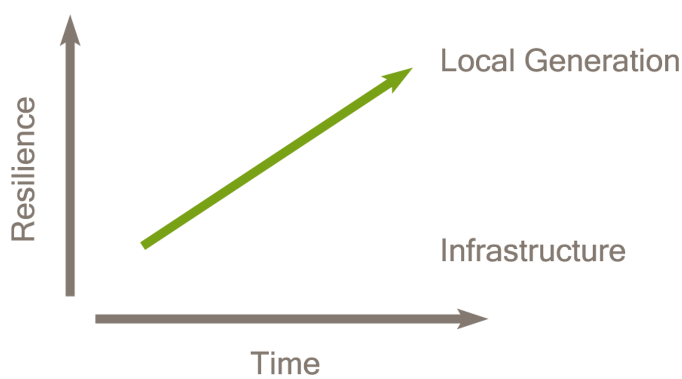

Figure 12: The resilience of individual buildings to withstand service disruptions increases when the need for infrastructure is reduced.

If individuals become more self-reliant, dependence on infrastructure is reduced, leading to an overall increase in resilience to large-scale disturbances (see Figure 12). However, off-grid structures typically require more land (for solar, rainwater, or wind collection as well as septic beds) making it difficult to achieve the population density of typical cities. In this sense, the development of high-density cities entraps citizens to be dependent on infrastructure that indirectly supplies services creating sustainability problems of both urban scale and human behaviour.

In some cases, the level of the community is an appropriate scale for the consideration of resource production and consumption. For example, an early experiment toward a 100% renewable energy community was the Danish island of Samsø in 1997. The Danish Ministry of Energy chose Samsø to "study how high a percentage of renewable energy a well-defined area could achieve using available technology." The island is 114 km² in area with a population of approximately 4200 people. By 2007, on-land and off-shore windmills and three new district heating systems were built, successfully generating all of their electricity and offsetting all carbon emissions. The Samsø community is now attempting to broaden their focus beyond energy to include the more comprehensive topic of sustainability [22].

Summary

Once we have a sense of our impact on the Earth in measured terms, together with an understanding that, to some degree, this is caused by our economic and infrastructure systems, we can develop sustainability strategies with measured results. In other words, if we can measure our environmental footprint, as well as measure the outcome of specific strategies to reduce our footprint, we will be able to learn which approaches work and which do not.

We propose that, as sustainability is a global problem, automated measurement will be required to make progress. These large data sets will require automated processing to support our understanding and decision-making processes. They will greatly improve the transparency of the resource lifecycle and, more specifically, these data sets can inform and calibrate our computational models to improve our cumulative knowledge about sustainability.

Computation

We have briefly touched on some key problems affecting environmental sustainability including animal consumption, energy consumption in buildings, economic models, and infrastructure scalability. Because of the overall problem scale, automation is necessary to measure materials and processes to help develop specific sustainability strategies, as well as to monitor results and progress. Humans monitor many systems to collect data but these efforts are limited by manual labor and often these values are not networked together to support aggregation. Automated monitoring, through digital sensors, be they real or virtual, satellites or thermometers, submeters or light switches, sales figures or odometers, can collect data in a more scalable manner that is also more amenable to aggregation. The process of aggregating the data will expose areas where additional sensors would help paint a more complete picture of human activity and environmental responses.

Automation, through computational instrumentation and computational modeling, can create the opportunity to perform multiscale analysis, develop and test hypotheses, and measure whether outcomes perform as expected when changes are implemented. We describe a method to combine instrumentation and modeling in support of decision making and then differentiate decisions that primarily effect the decision-maker from decisions that primarily affect others. For both types of decisions, we discuss examples of computational support.

Global Symbiotic Simulation

The combination of computational instrumentation and modeling is known as *symbiotic simulation* where the computational system interacts with the physical system in a mutually beneficial manner. Sensor-data serves as real-time input to the simulation that can execute a number of what-if experiments, trying different strategies, to generate alternatives. Selected scenarios that are put into practice can then be validated by monitoring the outcomes, using the same sensors, to help the system learn about the effectiveness of that decision. In turn, the physical system may benefit from the effects of decisions made by the simulation system [23].

The interaction could be direct or indirect. For certain real-time applications, the simulation could directly control the physical system, also called a symbiotic simulation control system (SSCS). For example, the HVAC (Heating Ventilation Air Conditioning) system in a building could be augmented with an SSCS by executing simulations of various expected occupancy and weather patterns. For a smart grid, a symbiotic simulation control system could be utilized to help direct energy flows in real-time from sensor data in a demand-response system, based on what-if simulations that attempt to predict various outcomes. However, for longer-term decision making applications, such as policy making, the interaction between the simulation and the physical system would be indirect, through visualizations and other decision-support mechanisms such as expert systems, supplied to human teams. Such “human-in-the-loop” systems are referred to as symbiotic simulation decision support systems (SSDSS) (see Figure 13).

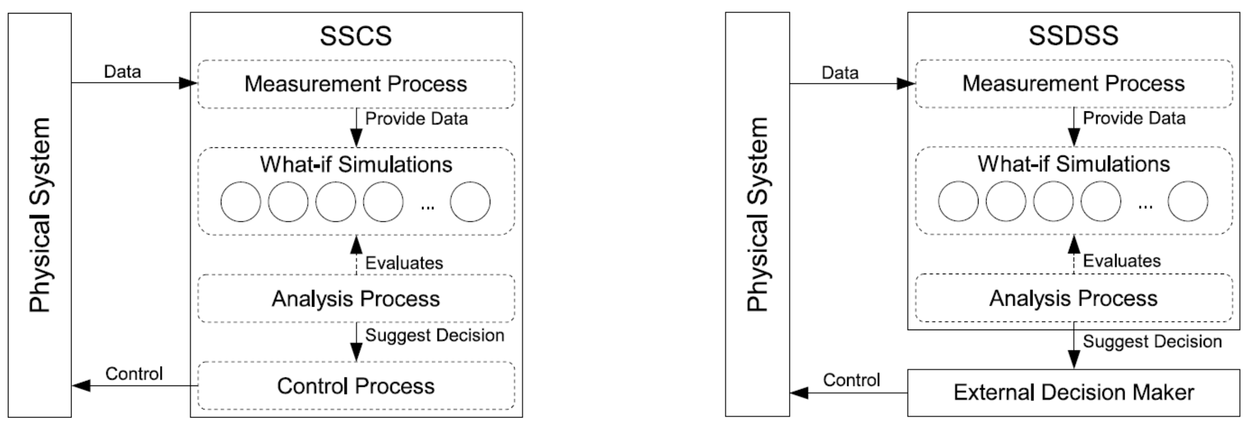

Figure 13: (Left) Overview of symbiotic simulation control system (SSCS). (Right) Overview of symbiotic simulation decision support system (SSDSS). [24].

In the context of sustainability, we propose that a Global Symbiotic Simulation (GSS) could provide a high level of automation for monitoring and analysis. Such a system would be continuously running, generating alternatives that would become increasingly more helpful as additional sensor data streams are supplied to the system. It would combine SSCS and SSDSS at low and high levels of abstraction, respectively. Decisions proposed and adopted would be tracked to study their actual impact and the difference from the predicted result.

A number of global simulation systems currently exist but are not symbiotic with the physical systems they examine. For example, global climate model (GCM) simulations are the primary systems that are global in nature [25] but they are solely for forecasting purposes. As an attempt to go further, the Group on Earth Observations is developing a Global Earth Observation System of Systems (GEOSS) specifically to “support decision making in an increasingly complex and environmentally stressed world” [26]. While not intended as a modeling and simulation platform, the GEOSS mission is to coordinate multidisciplinary scientific data in support of policy and decision making, and so, could function as the measurement process component of a GSS. The MIT Integrated Global System Model adds a Human Activity Model to improve estimates of economic drivers of resource consumption (http://globalchange.mit.edu).

A GSS, as described above, would require a multiscale multidisciplinary approach, including the modeling of environmental and economic activities. Known policies and adherence to them could be included as well to see if their impact can be detected. Undertaking the development of a GSS would necessitate a kaizen (continuous improvement) methodology so that the system can function despite knowing that the underlying model will always be incomplete.

The process flow for a GSS includes measurement, what-if simulation, analysis, and decision making (see Figure 13). The key value of creating such a system would come from the quality of the what-if simulations, which could be generated or manually created, in support of decision making.

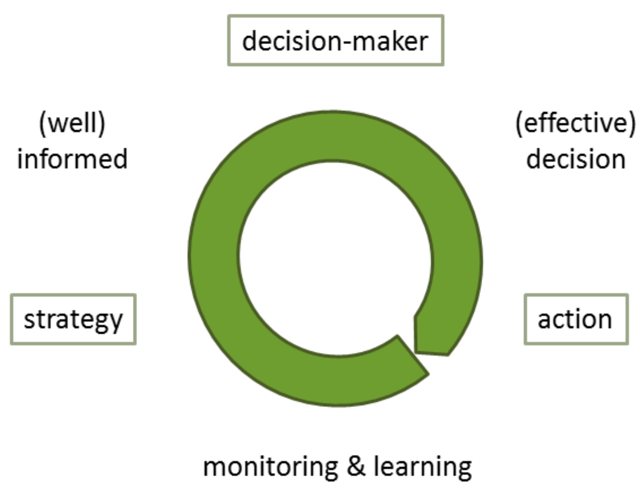

Figure 14: Decision making shown as a lifecycle in support of continuous improvement.

Decision making is often considered in isolation. However, in context, the decision making process can be viewed as a lifecycle (see Figure 14). Guided by a strategy, well-informed decision-makers can make effective decisions to take specific actions [27]. By monitoring the action and its outcomes, learning can guide new and improved strategies. Decisions have a fixed lifetime and only monitoring the outcomes will reveal when a new decision will be necessary [28]. For example, at a large scale, urban planners may decide to build a road connecting two regions that previously only had a railroad. By monitoring road traffic, planners can determine if the connection was successful and if additional lanes or additional trains would better support sustainable growth. At a smaller scale, by monitoring power usage and the availability of new technologies, consumers may decide whether a newer more efficient appliance would be better to purchase than continuing to operate an older machine.

Sustainability Strategies

Strategies help guide the decision making process. The types of strategies required will be determined by the types of causes of resource consumption. The primary causes can be classified as being either *elective* or *imposed*. For example, an animal-based diet versus a vegetable-based diet is an individual choice, while the amount of energy consumed to heat or cool a building is not an individual choice and is imposed by the design of the building and its systems (see Figure 15). Elective causes are chosen on an ongoing basis so opportunities to choose differently occur daily. However, imposed causes are inherently more difficult to change and these causes and their impact often remain in place for long periods of time.

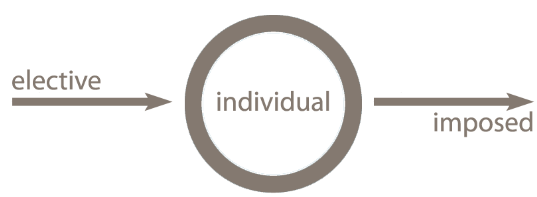

Figure 15: Elective causes of resource consumption are taken by individuals. However, individuals, such as architects and engineers, may also impose certain consumption rates on others through their design choices.

Imposed causes could also be called infrastructural to distinguish when and where changes would be necessary. This classification can help us to understand when human behaviour changes are necessary to solve a problem and when infrastructure improvements must be developed and applied. While not directly a cause, an implicit factor to consider is scale. That is, there are so many people and buildings involved that automation would be required to be an integral part of any solution if improvements are to outpace the normal growth of continued unsustainable practices. Unfortunately, sustainability is not the normal course of action. Worse still, process and economic complexity confounds efforts to be more sustainable. Complexity must therefore be addressed and plans must be laid, followed, monitored, measured, and managed, in order to achieve sustainability. Finally, lessons learned must be included in further planning.

Computation for Elective Consumption

Consumers elect which resources to use every day. By necessity, people make food choices daily that can greatly vary the amount of resources that are required. Beyond this, people may choose to purchase clothing, electronics, furniture, etc. Because these consumption patterns are routine, people may not reflect on the resource demands that their choices incur. While some people collect receipts to track their spending, it is considerably more difficult to monitor and track resource consumption. Ideally, resource consumption would be directly related to cost so that consumers would know that products that cost more clearly consumed more resources in their creation. However, as mentioned above, externalities are not normally accounted for in pricing so it would require in depth investigation into the specific goods and services and their histories and origins to determine the true costs to support meaningful comparative shopping and decision making.

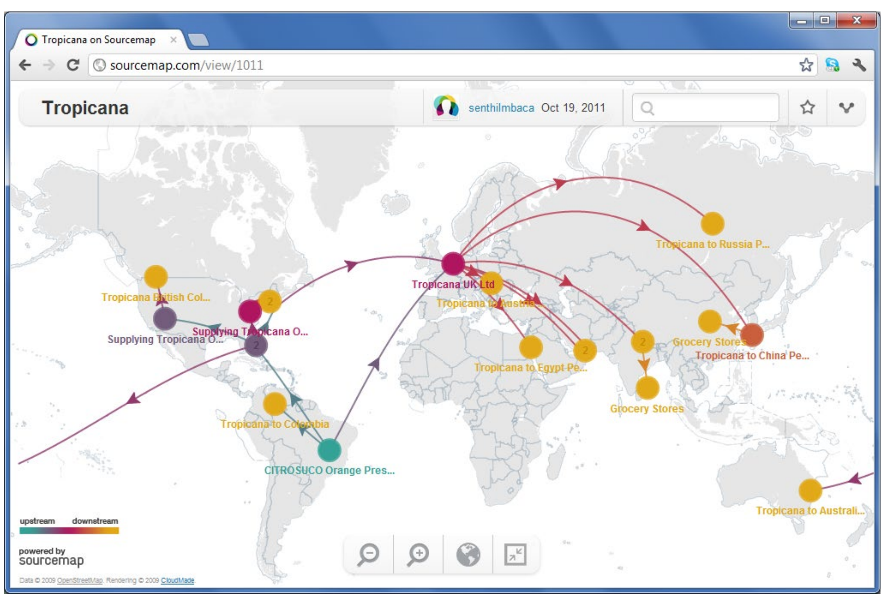

Figure 16: Supply chain mapping and visualization for a single product [29].

Even companies that provide goods and services would be challenged to provide resource consumption information and to accurately report such data. In fact, it would be necessary to include the entire supply chain in the reporting of any previous step in production. The importance of having detailed information about a supply chain was demonstrated during the mad cow disease crisis in the 1990s prompting farm-to-table traceability of all beef sold in Europe and Japan. To this end, www.sourcemap.com [29] supports the authoring of high-level supply chain maps (see Figure 16). Again, complexity calls for computerized automation to collect resource history and processes. Instrumenting supply chains with a number of sensor types would provide live data that could contribute to more automated, detailed and accurate cost and resource estimates. Simulations could also make use of this data to help optimize supply chains both in terms of cost and resource reduction.

Once aggregate resource consumption information can be delivered to consumers, computation can be utilized for resource tracking, goal setting, measurement, reporting, and persuasive encouragement for behaviour change. Some of these approaches have been explored in the areas of ubiquitous computing and human-computer interaction. In particular, the area of *persuasive technology* seeks to determine how best to influence users to transition and adhere to improved practices [30] in terms of health, resource consumption, and purchasing. Mobile computing has been used to enhance resource understanding for home energy consumption (see Figure 17) [31] and grocery purchasing (see Figure 18) [32,33].

Figure 17: Mobile computing to assist users in understanding home energy consumption. (Left) Total weekly household power usage (kWh) compared to similar household in the same geographic region showing a Low reading. (Middle) Graph of household consumption (kWh) over the last 24 hours. (Right) Chart of consumption per day for the last week compared to the week before.

Figure 18: Mobile computing to assist users in making healthy purchasing choices while grocery shopping [32]. First, place item in cart (left). The cart displays the item's classification as "eat most", "eat less", "eat least" (middle). Finally, (right), the summary for all items in the cart is updated for each of the three categories.

When efficiency efforts have been successful, a rebound effect has been observed where gains are lost because of new increased consumption. However, many treatments of this topic are oversimplified and changes in consumption must be considered together with co-benefits, negative side effects, and spillover effects [34].

The relationship between choices and consequences is difficult to determine without significant effort in measurement and tracking. However, computational support from the resource supply chain and during decision making can help users consume less or consume differently, adding more renewable resources and more efficient usage of all resources. Still, while consumers may intend to act more sustainably, many of their resource usage decisions have been made by others directly and indirectly. Next, we discuss consumption that is imposed upon consumers and citizens in general.

Computation for Imposed Consumption

To varying degrees, people have resource consumption imposed on them every day. Furthermore, people such as product designers, architects, and engineers make choices that impose consumption levels on others for the lifetime of their designs. These impositions can be beneficial or detrimental. Unfortunately, many critical design decisions are made early in the design process that implicitly dictate detrimental resource consumption during extraction, manufacturing, packaging, shipping, and usage. However, if the consequences of these choices were revealed to the designer before such decisions were made, significant improvements would be possible whose positive impact would exist throughout the artifacts lifetime.

Recently, design software has attempted to provide decision support through consequence visualization [19] indicating a number of related factors such as material attributes, CO_2 footprint, embedded energy and water, estimated raw cost of materials, Restriction on Hazardous Substances (RoHS) and Waste, Electrical and Electronic Equipment (WEEE) compliance, toxicity, and end-of-life regulations (see Figure 19). Given these estimates while still developing the computational model of the product, designers can reduce resources required during manufacture and usage, and improve the re-use and recycling of objects.

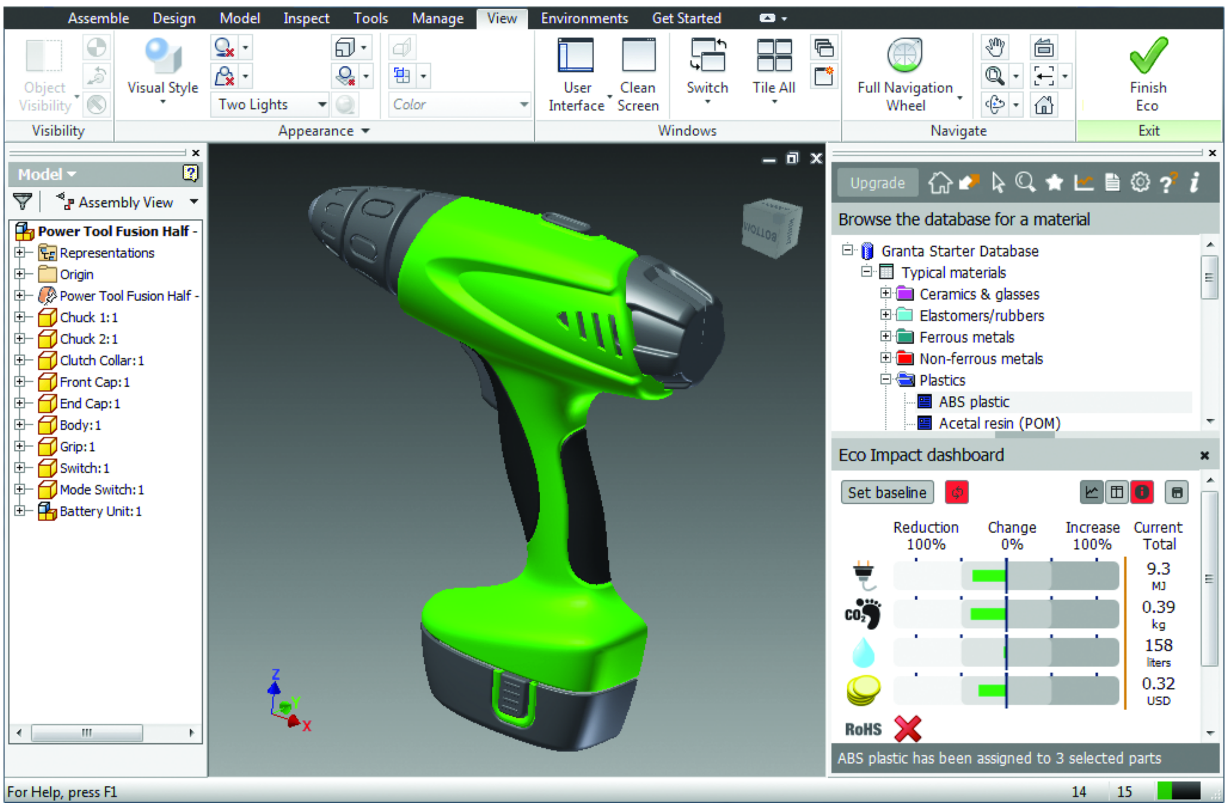

Figure 19: Computational modeling software for product design (Autodesk Inventor), with a sustainability panel (right-hand side) presenting material properties to support the decision making process.

While this is beneficial *before* usage, other systems are necessary *during* usage to help users understand what quantities of resources are used during the operation of a device or the consumption of the product. For consumer products and homes, mobile computing devices may be helpful in curbing resource consumption (see Figures 16, 17, 18), but for larger structures, complexity is greatly increased and specialized systems may be necessary. For example, buildings contain several types of mechanical equipment which include sensors as part of their normal function. Sensor types include thermostats for ambient temperature and humidity, motion detectors to control lighting, or meters and submeters for reporting and billing of power consumption (see Figure 20). However, despite this instrumentation of buildings in support of building automation, many buildings are manually controlled because of the complexity of appropriately programming the automation system for a specific building.

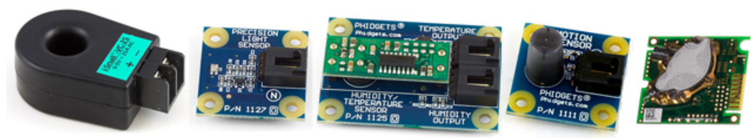

Figure 20: Sensors for measuring electricity, light, temperature and humidity, motion, and CO_2.

At COP15, the UN Climate Change Conference 2009 held in Copenhagen, a building on the campus of the University of Copenhagen, called the Green Lighthouse, was opened as the first public net-zero energy building in Denmark (see Figure 21). So-called net-zero energy buildings, that generate as much power as they themselves require, have been developed in the past few years indicating that there is enormous room for improvement to reduce, or even eliminate buildings as the primary cause of atmospheric CO_2.

> Generally, a net-zero building strategy starts with dramatic efficiency gains of 75% through design and technology, with the remaining 25% of power demand being generated locally with sources such as solar or wind power. Within the technological efficiency gains is the digitization of the building control system and its device and sensor network. This so-called "smart building" paradigm shift in building systems could form the basis of a reliable platform for ubiquitous computing for sustainability. [35]

As shown in Figure 21, buildings have many interacting subsystems that must be efficient individually but must also operate effectively together to achieve a net-zero energy footprint. The figure indicates both the complexity that causes so much energy use in buildings in the first place, and the complexity that will be inherent to any solutions that are designed, constructed, and occupied. Generally, this complexity is *designed* by the architects and engineers. In modern projects, Building Information Modeling (BIM) is often adopted in the design and construction phases of a building project to help capture and manage this complexity. BIM is essentially a computational model of a building using a database approach for managing the objects and relations between objects in an architectural model [36]. Standard data models have been proposed that also include mechanical, electrical, and piping (MEP) data, construction planning, and personnel information. In following the principles of an SSCS outlined above, combining the BIM with the buildings sensor network [37] to create an improved Building Automation System (BAS) will enable a significant portion of a GSS. In a fully instrumented building, effects and properties shown simply as static artist interpretations in Figure 21 can be shown in the context of a detailed computational model as dynamic values updating in real-time, as in Figure 22.

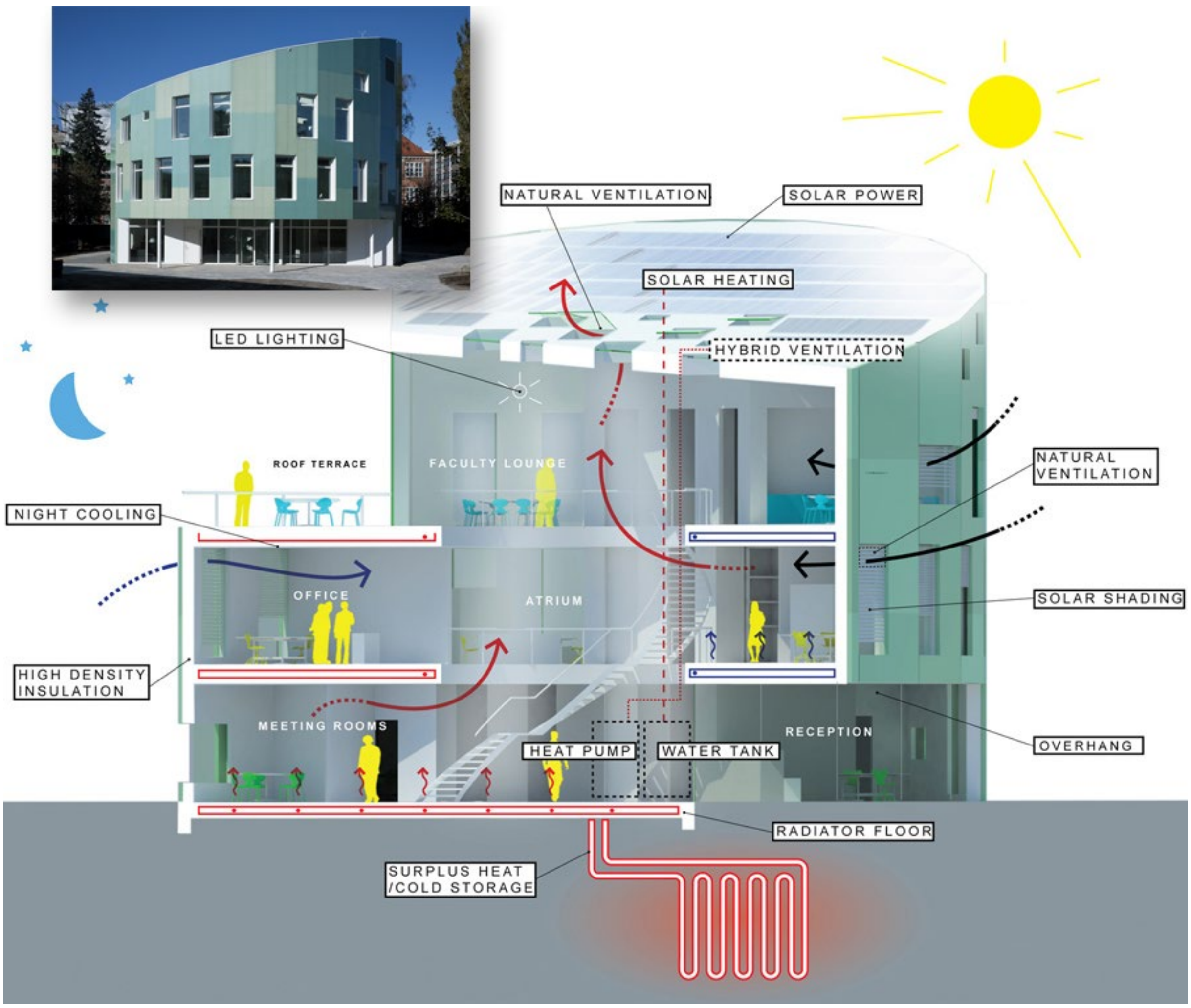

Figure 21: Green Lighthouse diagram of low-energy techniques, such as natural ventilation, heating, and cooling, together with depiction of occupants and environmental conditions. (Christensen og Co. Arkitekter A/S, Green Lighthouse, University of Copenhagen, 2009)

Many opportunities exist to greatly reduce imposed consumption in both product design and creation as well as in the design and operation of architecture. Decision support software in design and operations tools with lifecycle monitoring, together with advancements in simulation for architecture and urban design, could enable many aspects of a GSS.

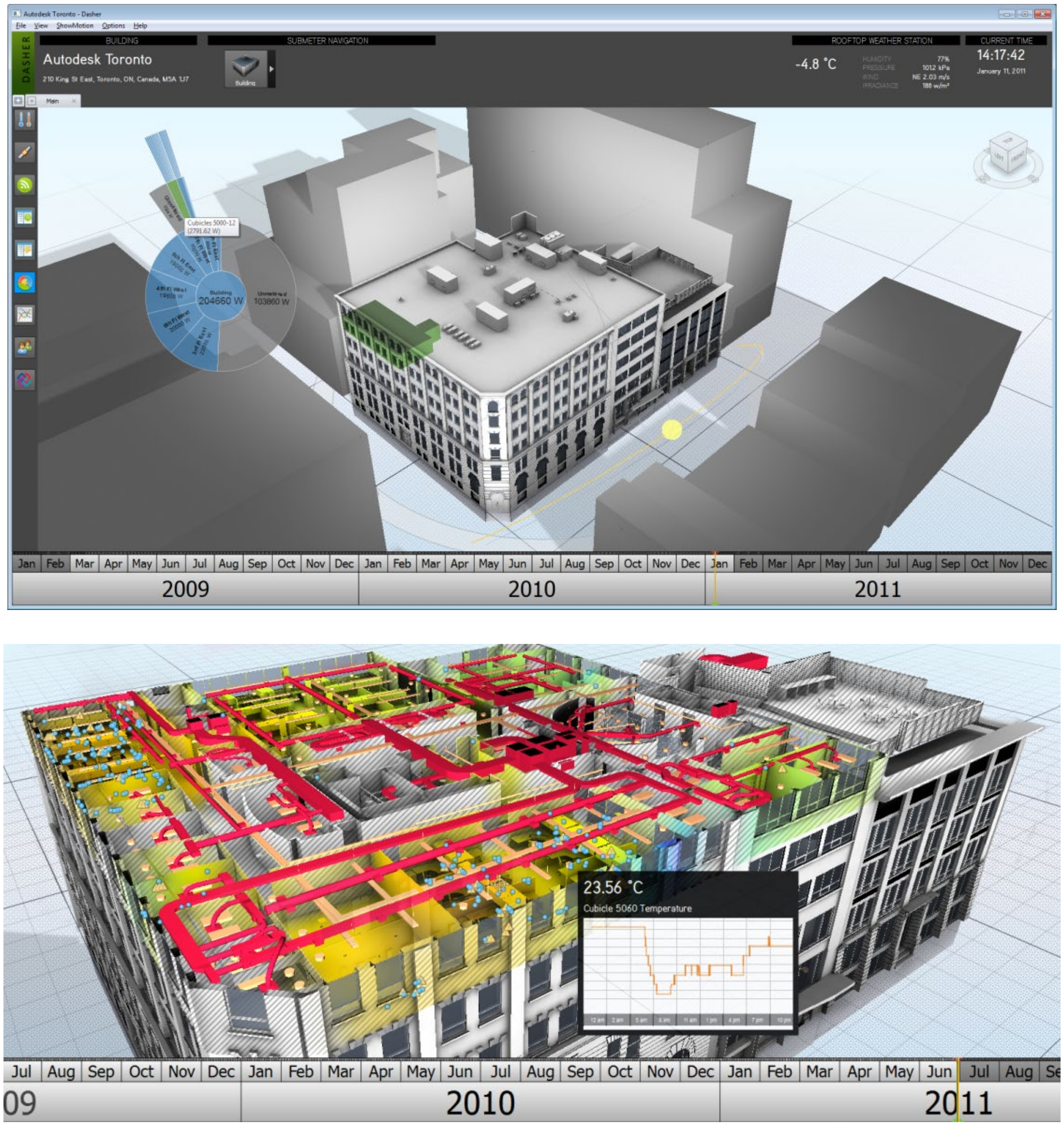

Figure 22: Visualization software for data aggregation and animation over time of building usage and responses based on collected sensor, meter and submeter data streams [37]. The software superimposes the visualizations of the physical sensor data over top of the computational building model.

Ways Forward

We propose that each aspect of the GSS problem be encoded into a large collaborative cyberphysical simulation framework that can support multiple disciplines and that can be continuously refined and improved. While such a system calls for both theoretical and pragmatic advancements in dynamic distributed simulation, knowledge representation, human-computer interaction, and software engineering, work is progressing in all of these areas as part of the general advancement of the scientific method to include collaborative computational modeling and simulation. In particular, the Symposium on Simulation for Architecture and Urban Design (SimAUD) has begun to take this on as its mission. The core approach is the Discrete Event System Specification (DEVS) formalism, first proposed by Ziegler [38]. Strict adherence to a simulation formalism such as DEVS will likely be necessary to ensure scalability of the system with automated model checking. The SimAUD research community is currently developing a DEVS-specific IDE (Integrated Development Environment), called DesignDEVS, as a customized interface to a large distributed collaborative simulation framework (see Figure 23). The intent is to leverage the modular and hierarchical nature of DEVS computational modeling to support contributions from industry, academia and government. Interacting with such a large complex system is also a fundamental challenge, for both authors and users, with respect to elective and imposed consumption. In the field of human-computer interaction research, a sustainability community has been formed to examine these issues at the SIGCHI conference [39]. Ultimately, research communities in most areas of computer science will be necessary to participate in this global challenge.

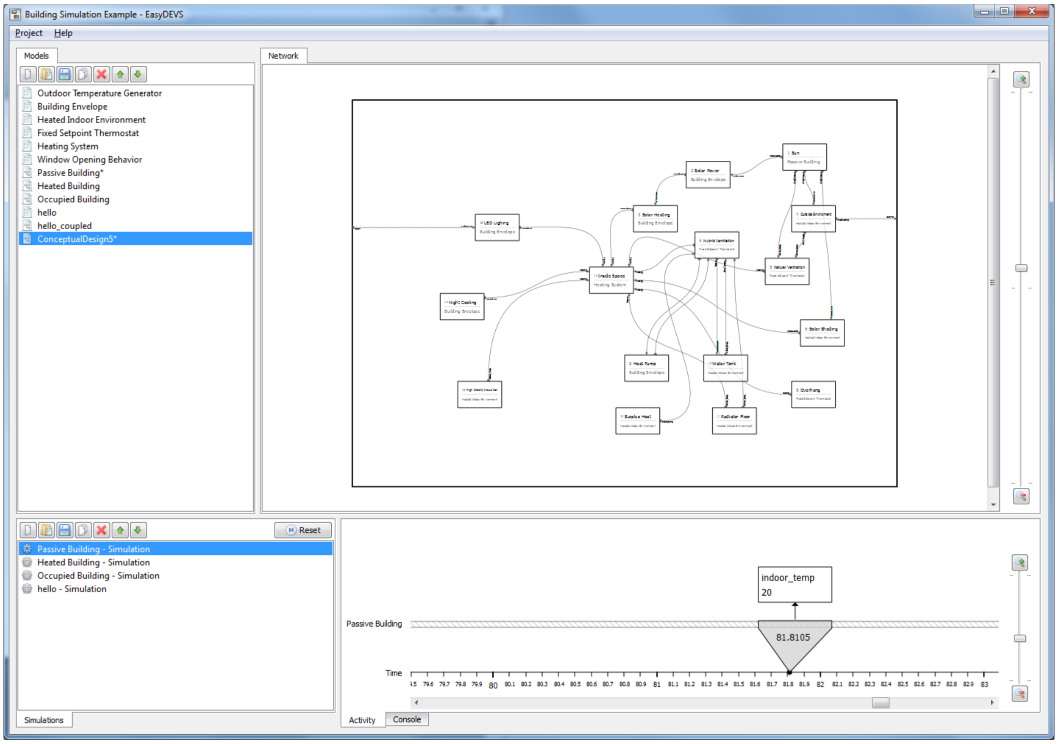

Figure 23: DesignDEVS IDE under development to explore the design of a large collaborative computational simulation framework (Rhys Goldstein and Simon Breslav).

Conclusion

We have presented environmental and economic processes, characteristics and threats as they relate to sustainability. These issues are further burdened by scale and complexity. To both understand and address sustainability, we have proposed computational approaches to measurement and modeling to improve the simulation of sustainability.

The multidisciplinary nature of a global symbiotic simulation of sustainability calls for a collaborative solution. A challenge in the development of such a system is the coordination of disparate types of measurements and models required to represent actual systems at several levels of detail. Moreover, the ability for a system to support continuous improvement during continuous operation will be critical. Decision making and policy making supported by simulation are further areas of research that will be necessary, involving human-computer interaction and visualization research.

Although measuring and modeling sustainability is a grand challenge for the computing community, we are optimistic that progress can quickly be made to better inform and support individuals, groups, and societies in living sustainably.

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