Journal of Computational Science 10 (2015) 108–125

Contents lists available at ScienceDirect

Journal of Computational Science

journal homepage: www.elsevier.com/locate/jocs

Sustainability analysis of complex dynamic systems using embodied energy flows: The eco-bond graphs modeling and simulation framework

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ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
17 September 2014
Accepted 14 October 2014
Available online 1 November 2014

Keywords:
Energy
Sustainability
Emergy
Bond graphs
Modelica

ABSTRACT

This article presents a general methodology for modeling complex dynamic systems focusing on sustainability properties that emerge from tracking energy flows.

We adopt the embodied energy (*emergy*) concept that traces all energy transformations required for running a process. Thus, energy at any process within a system is studied in terms of all the energy previously invested to support it (up to the primary sources) and therefore sustainability can be analyzed structurally.

These ideas were implemented in the bond graph framework, a modeling paradigm where physical variables are explicitly checked for adherence to energy conservation principles.

The results are a novel Ecological Bond Graphs (EcoBG) modeling paradigm and the new EcoBondLib library, a set of practical ready-to-use graphical models based on EcoBG principles and developed under the Modelica model encoding standard.

EcoBG represents general systems in a three-faceted fashion, describing dynamics at their mass, energy, and emergy facets. EcoBG offers a scalable graphical formalism for the description of emergy dynamic equations, resolving some mathematical difficulties inherited from the original formulation of the equations.

The core elements of EcoBG offer a soundly organized mathematical *skeleton* upon which new custom variables and indexes can be built to extend the modeling power. This can be done safely, without compromising the correctness of the core energy balance calculations. As an example we show how to implement a custom sustainability index at local submodels, for detecting unsustainable phases that are not automatically discovered when using the emergy technique alone.

The fact that we implemented EcoBondLib relying on the Modelica technology opens up powerful possibilities for studying sustainability of systems with interactions between natural and industrial processes. Modelica counts on a vast and reusable knowledge base of industrial-strength models and tools in engineering applications, developed by the Modelica community throughout decades.

1. Introduction

Modern societies rely on complex interactions with natural systems at many spatio-temporal scales. Such interactions often operate at rates exceeding the natural systems capacity to renew [30], leading to unsustainable structures.

As all human-driven processes depend ultimately on natural resources, their depletion, or overexploitation in case of naturally renewable ones, will necessarily shape the intensity, or even feasibility, of these processes in the future.

In order to study feasible future scenarios for human-driven processes, different approaches are required depending on the sustainability of the humans utilization of non-renewable and renewable services and goods, notably those from ecosystems.

For this kind of analysis it may be key to take into account the whole pathway of energy transformations that human-driven processes require (e.g. notably the combustion of fossil fuels).

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http://dx.doi.org/10.1016/j.jocs.2014.10.001
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Means are needed to model systems and analyze the sustainability of such energy transformation paths.

A sustainable socio-natural system can be thought of as a "healthy ecosystem" [8]. Quantitative views of ecology [5] help defining, measuring, and interpreting ecosystems' health. In the seminal textbook [23] H.T. Odum (the book author's brother) proposed to quantify also the relations among components of an ecosystem in a systems theoretical manner to enable ecosystem management. He then extended this idea [24,27] to represent related elements of ecological systems in energy equivalents, e.g. as contained in biomass (the energetic content of biomass was used as a unifying measure for universal descriptions across differing ecosystem types).

It was recognized that ecosystems have structures and functions that operate across a broad range of spatial and temporal dimensions [2,29] and the overall integrity of a system, when adding human dimensions, may differ depending on the hierarchical scale at which the ecosystem is being utilized (e.g. an ecosystem supporting an industrial society may be "healthy"; however, an ecosystem receiving extensive waste from industrial processes may become "unhealthy").

A modeling approach known as Energy Systems Language (ESL) [23,26] was proposed to represent and analyze such systems across many spatial and temporal scales and hierarchies of organization (e.g. [1]).

Modeled processes should observe the laws of thermodynamics just like their physical counterparts [27]. H.T. Odum proposed that the emergence of hierarchical organization results from dissipation of the available energy [24]) and that feedback loops are created if energy is available in sufficient amounts [25]. The transfer of energy throughout a hierarchy served Odum as the basis for defining "embodied energy", or emergy.

ESL proposes a modeling approach that represents all conceivable resources in terms of a common accounting unit. As a simple illustration, consider a hypothetical supply chain for a biofuel, where 1000 J of sunlight are needed to produce 10 J of biomass, which in turn are used to produce 1 J worth of fuel [3]. Note all those energy amounts correspond to each other and are equated by introducing some common unit. Say 1 J of biofuel is equal to 1000 solar equivalent Joules (sej). Such an approach allows for adding various further resources in terms of their solar equivalents, and the assumption of substitutability is satisfied. This approach retains information on resource quality, thereby diminishing criticism about the loss of information due to energy path aggregation [17].

An energy quality indicator referred to as "Transformity" (Tr) converts all resources into solar-equivalent joules. It has been proposed that resources with higher transformity values are of higher quality and may be scarcer [27].

Emergy analysis is therefore of great importance as it features the unique capability of quantifying the contribution of diverse ecosystem goods and services under a common and meaningful measure, enabling a comprehensive, yet rigorous sustainability analysis.

Nevertheless, the emergy approach relies on detailed knowledge about complex socio-natural systems, which is likely to be inaccurate and incomplete. As a consequence, the method is considered controversial by some authors [18].

Emergy analysis is predominantly applied to systems at equilibrium, where averaged input/output flows into/from storages match, and even the dynamics for studying small departures from steady state are linearized for the sake of simplicity.

But emergy analysis also permits the modeling of flows of energy by means of highly non-linear dynamic functions, the system being at any type of operating point (stabe/unstable) or phase (steady state/transient). Therefore, very complex behavior can arise even with very simple equations [20].

It becomes then difficult to guarantee that the resulting model is consistent with physics, i.e. that the laws of thermodynamics are not violated. However up to the present, correctness in terms of the adherence of models to physical first principles relies to a large extent on the experience of the modeler, and little assistance is provided by current modeling and simulation technologies.

The usual practice is to perform iterative improvements or other refinements in such models by including the latest insights or by increasing resolution, often implemented over the course of several years. We claim that this approach, when not supported by adequate tools, adds particular risks for the thermodynamic feasibility of the upgraded model. It may well be that a model is not only improved by reducing inaccuracies or removing incompleteness, but also exacerbated by becoming thermodynamically inconsistent.

Therefore, there arises a need for a modeling methodology that supports all of the good features of ESL while guaranteeing thermodynamic feasibility.

1.1. Solutions proposed

Here we propose a new methodology that offers not only means to extend and enhance models incrementally, modularly, and hierarchically, but also provides techniques for tracking flows of matter and/or energy through the system in a systematic and rigorous way.

We present a formal system-theoretic Modeling and Simulation (M&S) framework, named Ecological Bond Graphs (EcoBG), along with a software tool that supports this novel methodology. This methodology is expected to be applicable in a flexible and efficient, yet rigorous and sound manner in M&S of complex natural and socio-economic systems, in particular when studying sustainability.

The framework consists of two pivotal cornerstones: an abstract graphical specification layer to work with system elements and structures (served by bond graph technology) at the top, and a specific equation encoding level (served by Modelica technology) at the bottom. Such an approach offers separation of the model specifications from implementation details while still aiding hierarchical modeling of target systems at all levels in an integrated manner.

2. Background

2.1. Bond graphs

Bond graphs (BG) [4,10] are a multi-physics modeling paradigm intimately concerned with the conservation of energy flows. The interdisciplinary concept of energy flow creates a semantic level that allows BGs to be independent of the modeling domain. Basic concepts of physics, such as the laws of thermodynamics, can be verified in a bond graph independently of their application domain.

Three different Modelica libraries have been created for dealing with different modeling goals embracing the bond graph approach: BondLib, MultiBondLib, and ThermoBondLib.

BondLib [13] makes use of the regular (black) bonds shown below.

$$\xrightharpoonup[f]{e}$$

Regular bonds carry two variables, the effort, e, and the flow, f. They do not carry units in order to make them usable for all application areas. If a bond gets connected, e.g. to an electrical system, the bond inherits units of Volts for the effort variable and units of Amperes for the flow variable and propagates those units across junctions throughout the model topology.