Sustainable Construction Modelling: A Systems Engineering Approach

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Abstract

Modelling in the architecture, engineering, and construction (AEC) industry is a fundamental step for product and project delivery, and serves multiple purposes from visualization, communication, simulation, analysis, decision making, to performance assessment. For long, the AEC industry has used different types of modelling schemes. Typical examples include 2D and 3D models that capture geometric and spatial information, project schedules that capture sequence and durations, and process models that capture methodologies and work flows. With the advent of sustainable construction, it was realized that modelling in the AEC industry has to capture a new array of information and correlate such information to both the construction product and process. Examples of these information include embodied energy content, emission of pollutants, resource consumption, and noise and acoustics, just to name a few.

Modelling for sustainable construction requires representing parameters pertaining to the environment and sustainability as well as different information related to the building geometry and its production method and execution plan. As part of a research undertaken by the authors, this paper proposes a systems-based model where: (1) the environmental system, (2) the building system (the product), and (3) the construction system (the production/management system) are represented as three interacting systems of systems that fundamentally exchange (1) energy, (2) matter, and in some cases (3) information, according to systems theory. While other modelling approaches are based on proceeding individually and sequentially in the process of evaluating environmental impacts caused by different multidisciplinary practices in the AEC industry, this systems-based model shall facilitate simultaneous evaluation of sustainability by the system as a whole. The focus on system flows of energy and materials shall highlight focus areas for impact mitigation and performance optimization as outlined in the paper. The Systems Modelling Language (SysML) is utilized to build the model.

Keywords: sustainable construction, systems engineering, SysML, construction modelling, sustainability parameters

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1. Introduction

A model is an abstraction, simplification or idealization of reality that can be used for realization, simulation or as a prototype (Turk, 2001). Modelling in the architecture, engineering and construction (AEC) industry has always revolved around products and processes. Typical models used included geometric models (2D and 3D models), process models, project schedules, etc. Such models served well for long, as much as the governing industry paradigm has been that well-known triad of *time, cost,* and *quality.* For more than three decades, the time, cost, and quality triad has been continuously challenged by new factors and parameters such as safety, efficiency, and recently sustainability. These new parameters continuously stress the need for altering or extending the current techniques of modelling used in the AEC industry, or the introduction of new ones.

For sustainable construction modelling in particular, models have to capture and create links between multiple types of information pertaining to sustainability and the environment including embodied energy content, emission of pollutants, resource consumption, noise and acoustics, etc. while simultaneously linking these to different project executing entities and across different phases of a project lifecycle. Current industry models and techniques, however, inefficiently address the multidisciplinary requirements of sustainable construction by focusing – each, individually – on one sole aspect of the industry: the products, the processes, the geometry, the sequence, the durations, etc. Moreover, whenever sustainable construction is considered, it is usually addressed by different industry entities both in sequence and individually. This typically results in fragmented and inefficient evaluation of only parts of the system, not the system as a whole.

This paper proposes a systems-based modelling approach using the principles of systems engineering and analysis to facilitate proper realization of sustainable construction.

2. Modelling in the AEC Industry

Models are fundamentally related to identifying, specifying, and communicating data and information related to a specific product. For long years, the AEC industry has used different models to capture and utilize information related to its products. The following sections briefly refer to the most common modelling approaches used by the AEC industry and point to their utility and possible shortcomings addressing sustainable construction.

2.1 Common Modelling Techniques

The most common modelling techniques used in the AEC industry typically served the purposes of detailing and communicating (1) building product design; e.g. dimensions, geometry, spatial orientation, material specifications, (2) process; including workflow, inputs and outputs, (3) schedule; including durations and work breakdown, and (4) financials; e.g. costs and cash flows. The following table has been compiled based on Aouad et al (2012), Azhar et al (2011), El-Gohary (2008) and Chen and Li (2006) to provide a brief overview of common modelling techniques used in the AEC industry.

Table 1 Common modeling techniques used in the AEC Industry

Modelling Technique	**Modelled Information**	**Key Uses**	**Typical Examples**
Product Models	Mainly geometry and spatial information	- Product Design - Product Specification - Multidisciplinary technical communication	- 2D drawings - 3D drawings - Building Information Models (BIM)
Process Models	- Workflow and sequence - Inputs, outputs, and conversion	- Process optimization and reengineering - Productivity Assessment	- IDEF0 - Generic Construction Process Modelling Method (GEPM) - Information/Integration for Construction (ICON)
Schedule Models	- Project activities and durations - Sequence and logic	- Project Planning - Project Management	- Gantt Charts - CPM and PERT networks - Line of Balance (LOB) technique
Economic & Financial Models	Financial information related to costs and revenues	- Cost Estimation - Financial feasibility analysis - Calculation of investment ratios	- Activity Based Costing (ABC) - Financial feasibility models - Cash flow models

Each set of these techniques focuses on the modelling, estimation and assessment of information related to one or more aspect(s) of an AEC industry product/project. Each of these techniques could contribute *indirectly* to the evaluation and assessment of sustainability parameters, for example by allowing the quantification of materials used as a prerequisite for assessing consumption of resources or embodied energy content, or by identifying inputs and outputs of construction processes as a prerequisite for measuring efficiency and identifying waste. However, considering the multidisciplinary nature of sustainable construction and its key parameters, none of these modelling techniques provides neither direct nor thorough means for environmental computations and assessment. For example, none of these models directly considers the emission of pollutants to the atmosphere or the noise produced during construction activities. The ultimate capacity of such techniques, from a sustainable construction perspective is to provide information for further compilation in other more sustainability oriented models, such as life cycle assessment (LCA).

2.2 Modelling Techniques that Directly Consider Sustainability

There still is a set of other modelling techniques and tools that are used in the AEC industry, and even address sustainable construction. Amongst these is Life Cycle Assessment (LCA). Crawford (2011) adopts a definition of LCA as a tool “to determine and evaluate the environmental loadings and impacts of a particular product or process, including those effects associated with processes upstream in the supply chain." LCA is one of the most powerful tools for evaluating environmental loadings and assessment of sustainability. To date, however, it cannot be easily utilized by typical industry practitioners due to its complexity. Moreover, it requires case by case truncations and adaptations to identify where to stop and how to set boundaries when addressing AEC projects (Crawford, 2011).

3. A Systems Approach to Sustainable Construction

In spite of its recognized importance and the development of knowledge through over 20 years, sustainable construction is not yet a standard practice of the industry. Recent statistics list a total number of some 110,000 BREEAM certified buildings and some 35,000 LEED participating green building projects worldwide. These figures represent much less than 1% of buildings worldwide (The Zofnass team, 2012). Matar et al (2008 and 2010) list a number of barriers that hinder the widespread implementation of sustainable construction as a standard practice of the industry. One of the most important barriers is the *inefficiencies* of current tools and approaches to sustainable construction.

The Zofnass team (2012) identified approximately 120 rating systems and sustainable construction evaluation tools either in use or under development up to early 2012. Although much of these tools agree on many criteria for sustainability evaluation, they still leave many other criteria in argument, pointing to an absence of a solid consensus on what issues are key and important, and hence their relative weights upon consideration. Furthermore, most of the current tools were developed and have shown adequacy principally addressing the design phase of a building project, leaving a strong need for addressing the construction, operation and maintenance phases of a built facility (Shen 2005, and Chen et al, 2005).

Moreover, the top two ranking tools by use are BREEAM and LEED. Alarmingly, a detailed evaluation of LEED by the US National Institute of Standards and Technology (NIST) has identified discrepancies in the calculation method leading to disparities and inconsistencies of calculated outcomes (Scheuer and Keoleian, 2002). The Zofnass team (2012) also identified that LEED tends to favour "credit popularity" over science in order to facilitate marketing LEED to stakeholders. While encouraging widespread use of the tool and promoting sustainable construction is desirable, relaxing scientific rules raises questions and concerns (Scheuer and Keoleian, 2002).

This paper proposes a systems-based modelling approach that can lay a robust foundation for realizing sustainable construction. The following sections list some fundamental principles and definitions then proceed to build the model according to the needs and requirements of sustainable construction.

3.1 Basic Definitions

3.1.1 Systems and Systems Engineering

The "Guide to the Systems Engineering Body of Knowledge" defines a system as "an interacting combination of elements viewed in relation to function" (INCOSE, 2004). Wasson

(2006) defines a system as “an integrated set of interoperable elements, each with explicitly specified and bounded capabilities, working synergistically to perform value-added processing to enable a User to satisfy mission-oriented operational needs in a prescribed operating environment with a specified outcome and probability of success.”

Systems engineering also has a large number of definitions, but in the most general form is defined as “an interdisciplinary approach and means to enable the realization of successful systems” (INCOSE, 2004).

3.1.2 Systems of Systems

Recently, with the rapid technological advancement and intricacies in the 21st century, there has been a growing interest in shifting the paradigm from addressing particular systems individually to considering *classes of systems* whose constituents are themselves complex (Jamshidi, 2009). These have gradually become to be described as “System(s) of Systems.” Typical examples of such systems of systems have been proven to exist in aerospace, manufacturing, security, and disaster management disciplines and industries, just to name a few.

A practical definition for a System of Systems (SoS) is that “it is a super-system comprised of other elements that themselves are independent complex operational systems and interact among themselves to achieve a common goal” (Jamshidi, 2009). There is an increasing interest in achieving synergy between these independent systems to achieve desired overall system performance or performance objectives.

3.1.3 The Systems Modelling Language (SysML)

The Systems Modelling Language (SysML) was developed under the leadership of the Object Management Group (OMG) as a general-purpose graphical modelling language that supports the analysis, specification, design, verification, and validation of complex systems. These systems may include hardware, software, data, personnel, procedures, facilities, and other elements of manmade and natural systems. The language is intended to help specify and architect systems and specify their components and interactions principally through identifying, specifying, or developing a system (1) structure, (2) requirements, (3) parametrics, and (4) behaviour. SysML utilizes nine types of diagrams to serve its purposes and objectives (Friedenthal et al, 2008).

3.2 A System of Systems Model for Sustainable Construction

The previous sections of the paper compared modelling techniques, highlighted some key definitions, and concluded a strong need for some well-defined approach that adequately addresses critical areas of sustainability in line with the current framework of the AEC industry, as a multidisciplinary industry with extremely diversified products and a large number of executing entities and stakeholders.

The following sections outline a systems-based model where: (1) the environmental system, (2) the building system (the product), and (3) the construction system (the production/management system) are represented as three interacting systems of systems that fundamentally exchange (1) energy, (2) matter, and in some cases (3) information, according to systems theory. Each of these systems is described using SysML notation and a System of Systems model is described afterwards. A system of systems model is crucial for the case of sustainable construction, because the ultimate objective is to consume resources at a rate that neither overloads the environmental system nor depletes its resources at an unsustainable rate, meaning simultaneous optimization for all of: the environment, the built facility, and the construction system. The multidisciplinary nature of the AEC industry, with products that comprise architectural, structural, and electromechanical components designed and executed by a large number of entities, requires a holistic model that can simultaneously evaluate the environmental loadings and sustainability impacts generated by a myriad of entities at different stages and project lifecycle phases.

3.2.1 The Environmental System of Systems

The Environmental System of Systems, refers to the natural systems that primarily support the existence, development and evolution of all other systems of systems on planet Earth (Hipel et al. 2009). The Environmental SoS principally comprises five main component systems. According to Wasson (2006), Jorgensen (2007) and Hipel et al. (2009), these are:

- The *atmosphere* system component, representing the gaseous layer that extends from the surface of a planetary body outward to some pre-defined altitude.

- The *lithosphere* system component, comprising the rigid or outer crust layer of Earth, including continents, mountains, islands, etc; containing most of material resources.

- The *hydrosphere* system component, consisting of all liquid and solid water systems such as lakes, rivers, rain, underground aquifers, oceans, etc.

- The *biosphere* system component, defined as the environment comprising all living organisms on Earth, including all environments that are capable of supporting life above, on, and beneath the Earth's surface as well as the oceans. Thus, the biosphere overlaps portions of the atmosphere, hydrosphere, and lithosphere.

- The *energy* system component, which is most fundamental for all systems; natural or manmade, to operate and perform their roles and missions. There are essentially seven forms of energy, most of which are commonly encountered in everyday life, such as heat, electromagnetic (e.g., light), kinetic (or mechanical) forms.

Figure 1 represents a *block definition diagram (bdd)* for the Environmental system and its subsystems using SysML notation.

Many of the currently available building rating systems and sustainability evaluation tools show no clear basis for classifying and categorizing environmental impacts considered. The systems-model, however, visualizes the environment as a system of components and subsystems, providing a logical way to classify and categorize environmental impacts and sustainability parameters according to the exact subsystem they affect and are related to.

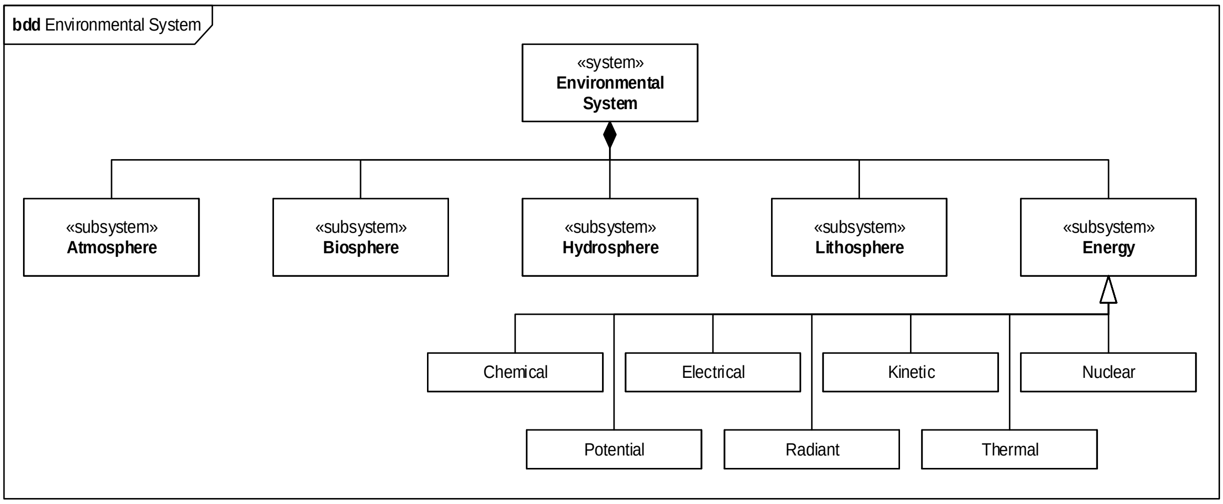

Figure 1: The Environmental System and its subsystems

Figure 2 illustrates sustainability impacts considered in the SoS model according to this logic. Most impacts recognized fall under the principles of generating undesirable particulate materials and emissions, consuming resources at unsustainable rates, and generating waste through inefficient conversion processes. All of these categories are efficiently recognized by the systems-model.

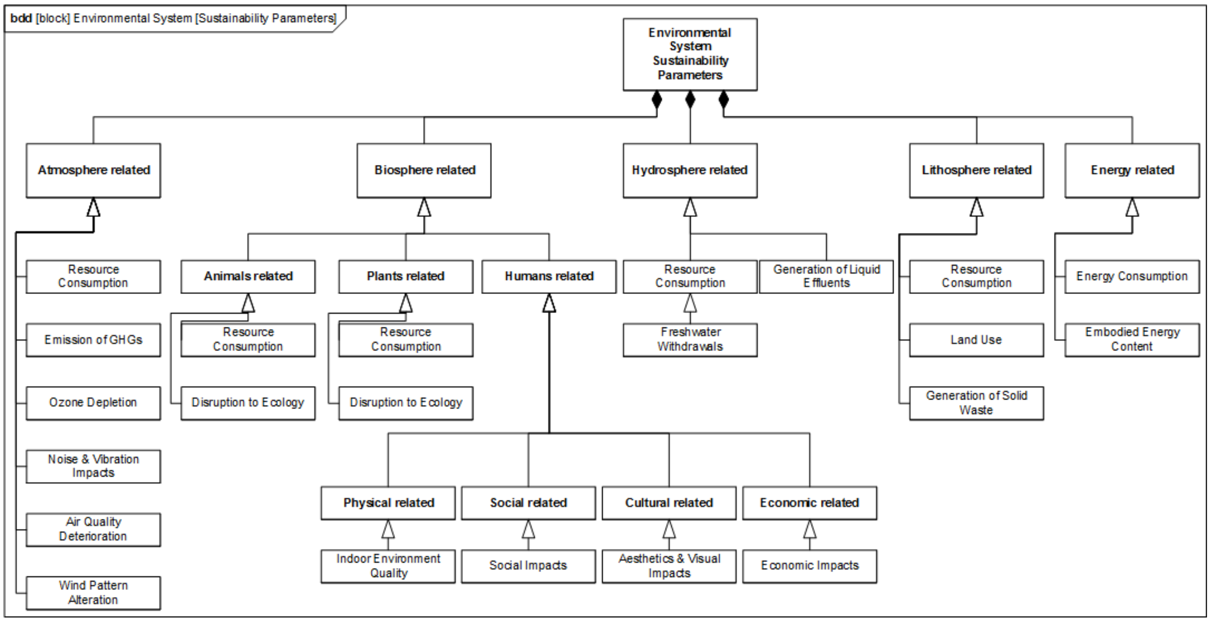

Figure 2: Sustainability Parameters

3.2.2 The Construction Product System

Construction products generally comprise buildings and infrastructures. Either of them could be visualized as a group of independent but interacting systems. Typically, these systems are the architectural, structural, mechanical, and electrical systems. The minimum for any construction product is at least to have a structural system to support its components. Figure 3 illustrates the general case for a construction product and its subsystems.

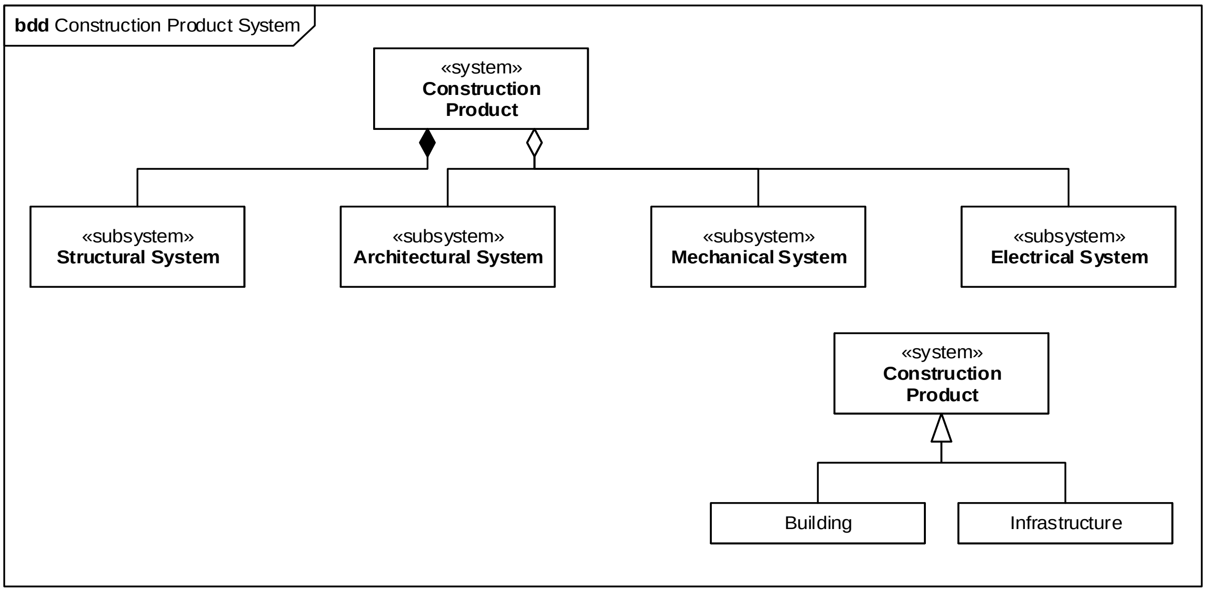

Figure 3: Construction Product System

By SysML notation, the structural system is represented as an elemental, compositional element, while the other three systems might or might not exist according to case. Buildings typically have all of the four subsystems, while an underground pipeline might have only a structure (with some electromechanical sensors in case of sophisticated pipelines). The subsystems of a construction product together define its function, shape, utility, comfort, and environmental performance.

- The *architectural* system defines the volumes, functions, and aesthetics of a building. It is usually the lead system: designed at the very beginning according to specific brief and requirements, and sets course and boundaries for other building systems.

- The *structural* system is fundamentally concerned with the support and transfer of all building loads to the ground. The structural system primarily uses different techniques and materials in specific skeletal arrangements to achieve the primary functions of load bearing and load transfer, in addition to helping in providing building shape, and functional objectives of other systems within the building.

- The *mechanical* systems in a building are designed to perform a variety of functions. They are responsible for heating, ventilating, and cooling the indoor environment as well as supplying freshwater and disposing of wastewater. In addition to these, mechanical systems extend to include fire protection systems.

- The *electrical* systems in buildings are primarily the electrical power supply systems, and data/communications and signal systems. Electrical systems include lighting, alarm systems, distribution systems, acoustic and auxiliary systems.

To produce these systems at the construction/production phase of a built facility life cycle, resources are consumed and co-products are released to the environmental system of systems. During the life span of the built facility, these systems continue to consume resources and produce products and co-products (wastes, emissions, etc.) The efficiency of their operation determines their performance with regard to environmental sustainability.

3.2.3 The Production and Management System

The third system of systems involved is the construction production/management system, as exemplified in Figure 4. The term "production" is intentionally used in analogy to other industries, as any construction project is, in fact, a series of conversion and flow, value-adding and non-value-adding activities that start from project inception and end by operation through the operational life of a facility, and finally by possible deconstruction.

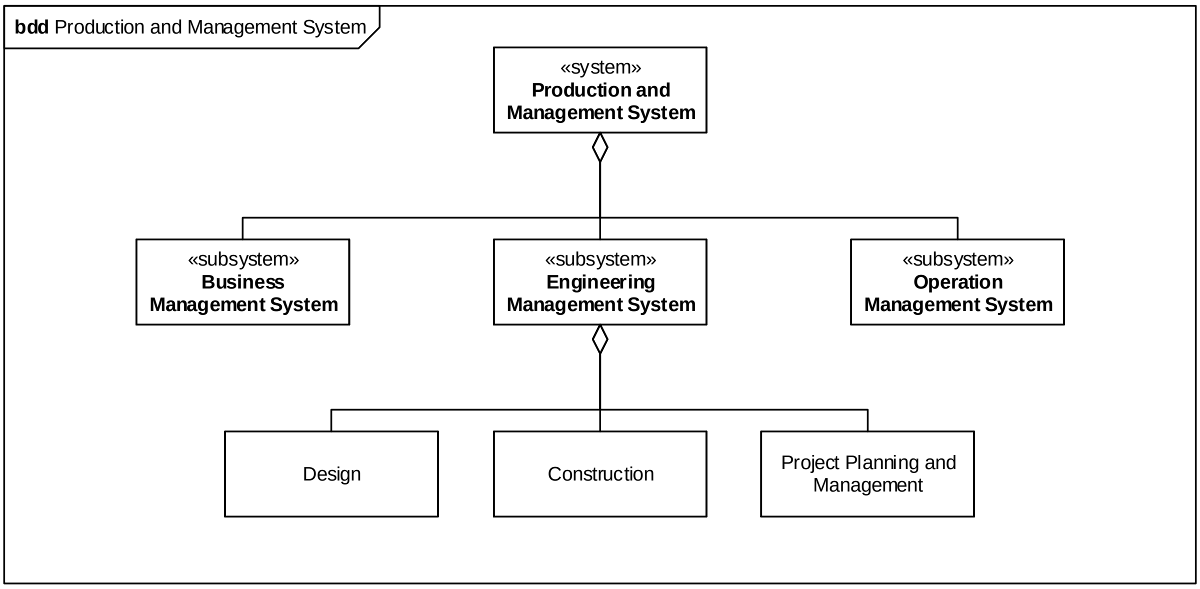

Figure 4: Essential Components of the Production and Management System

This production system involves a number of interacting subsystems that include, for instance:

- The *business* system necessary for the management and operation of any construction industry organization and its project endeavours.

- The *design* management system responsible for the production of the whole package of design drawings and specifications for the built facility system of systems, including architectural, structural, mechanical, and electrical systems.

- The *project planning and management* system principally responsible for realizing project goals of scope, time, cost, and quality.

- The *construction* system responsible for field production of a built facility system of systems.

- The *facilities management* system responsible for operating and maintaining a built facility with all of its subsystems at maximum efficiency.

Each of these systems operates to deliver its products and goals, consuming resources and producing loadings at different levels of hierarchy, ranging from the organizational, project, and activity levels all the way to the operation, process, and work task levels (Halpin 2006).

3.3 Using the System of Systems Model for Sustainability Evaluation

There are some basic principles that govern the behaviour of the proposed systems model, derived from standard rules that govern systems behaviour in general, and the environmental system in particular as described by Wasson (2006) and Jorgensen (2007). Amongst these rules, the following two principles are fundamental for the utility of the proposed System of Systems model for assessing and evaluating sustainability and environmental impacts/loadings:

1. All natural ecosystems are open systems embedded in an environment from which they receive energy-matter input and discharge energy-matter output.

2. Mass and energy are conserved. This principle permits writing balance equations to track material and energy flows and conversions, where:

$$accumulation = input - output$$

Environmental loadings could be defined as the increase or decrease of specific materials and constituents that alters the system state to a new state other than the “best” condition. For example, a construction process that results in emissions and pollutants to the atmosphere in a specific area does not harm the atmosphere itself; it just changes the concentration of particles in that specific area. However, this change in concentration could render air harmful for breathing, for example, or at least decrease its quality.

Another dimension of sustainability includes the rate of consumption of resources and the generation of waste. Resource consumption in itself should not represent a problem; it is the rate of consumption of resources that is. If the rate of consumption exceeds the rate of the environmental system capacity to generate or substitute consumed resources, then such resources will simply be depleted. Moreover, if the consuming system conversion processes were inefficient, then the conversion processes will result in waste. Minimizing waste is one key pillar of construction sustainability. The systems model proposed is designed to capture material and energy flows between the three interacting systems of systems. Figure 5 illustrates the essential high level system flows during typical construction, using SysML notation for *internal block diagrams (ibd)* and *flow ports.*

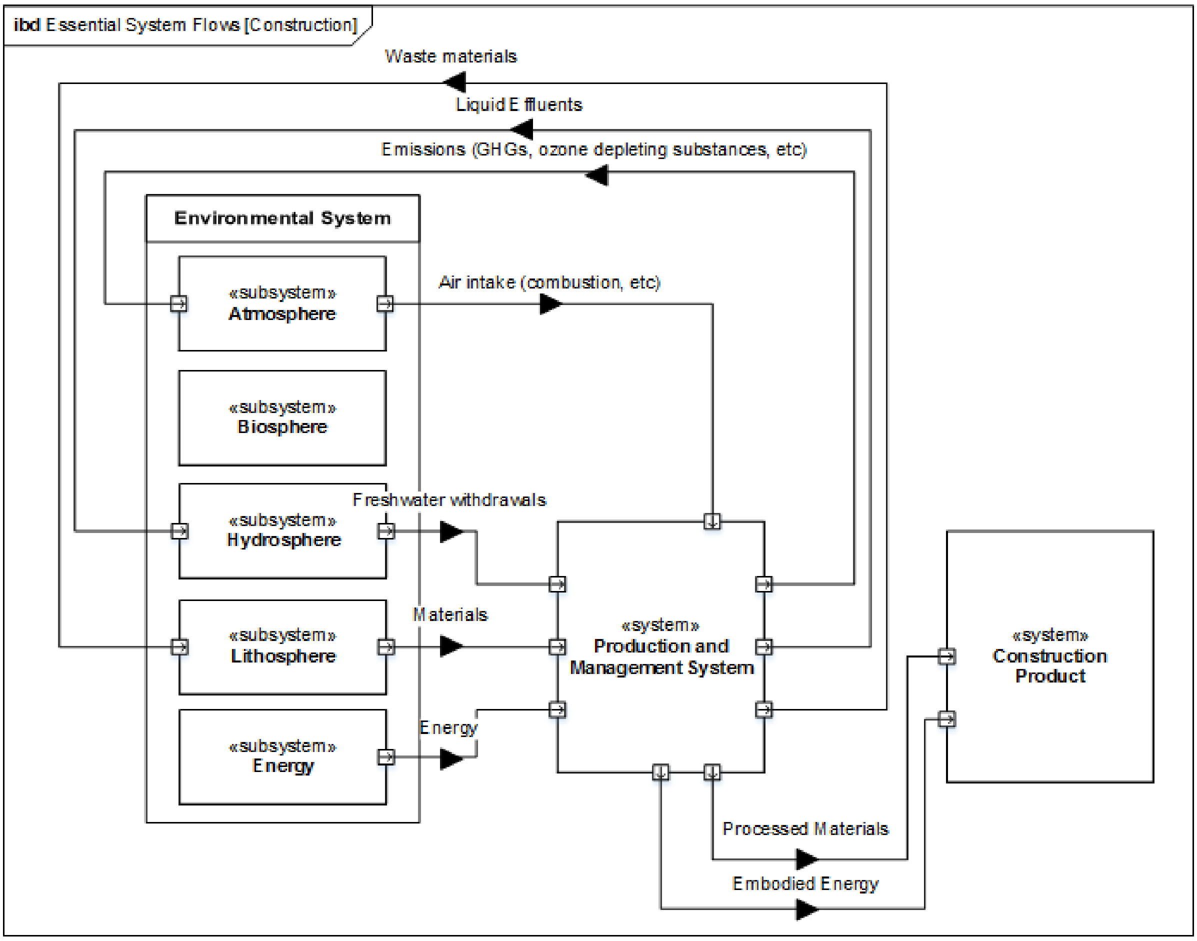

Figure 5: Essential System Flows during Construction

Tracking the flow of undesirable materials will identify what emits pollutants, their quantities as accurate as possible, and hence means for minimization. Tracking the flow of energy and materials in general and using balance equations will facilitate recognizing systems efficiencies and where wastes are generated. The multidisciplinary nature of the systems model allows recognizing all subsystems of a construction product system together and hence help visualizing a complete picture of sustainability performance of the construction product as a whole and its production/management system. In contrast to all other geometry based modelling techniques, where material, energy and environmental performance data in particular are captured as static values (at best, and hence are evaluated on a case-by-case basis), a systems model can accommodate geometry-based values – especially if linked to a BIM database – and multidisciplinary information simultaneously to allow dynamic, systems level evaluation. The versatility of systems engineering allows addressing sustainability performance at different levels as desired. Systems engineering and SysML can model systems at the top, system level, all the way down to the activity and process levels. For example, the model can address the consumption of energy to construct the building foundations in total, or can address a specific part of the process, such as excavation. Figures 6 and 7 illustrate an example for the definition of constraints and then the utilization of a *parametric diagram* to capture the consumption energy for a typical excavation activity. Equations governing the calculation of excavation area and excavation energy are defined within the system package through *constraint blocks* as shown in Figure 6.

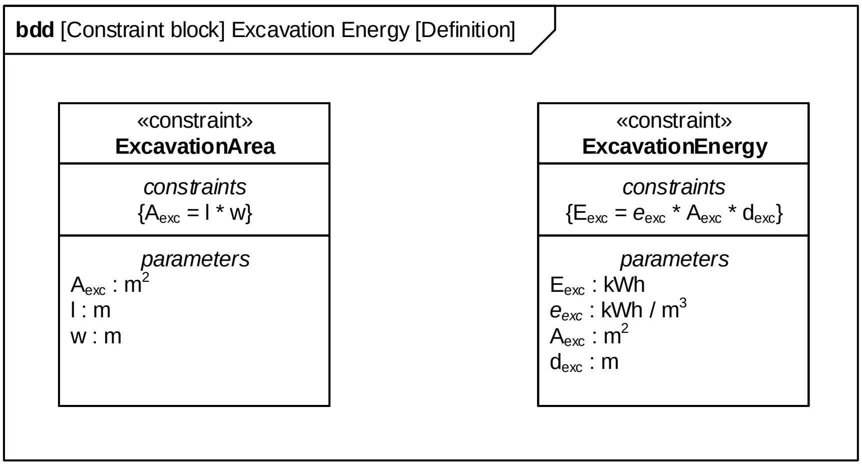

Figure 7: Constraint Blocks Capturing Equations for Excavation Energy Calculation

As illustrated in Figure 7, the system calculates energy consumed during excavation utilizing equations defined in the constraint blocks within the *bdd* for excavation energy calculation, augmented by case-by-case inputs such as the "*ExcavationEnergy.Unit*" representing the kWh consumption by excavating machine according to the type of soil, and the "*ExcavationDepth*" variable that differs according to the building and foundation design.

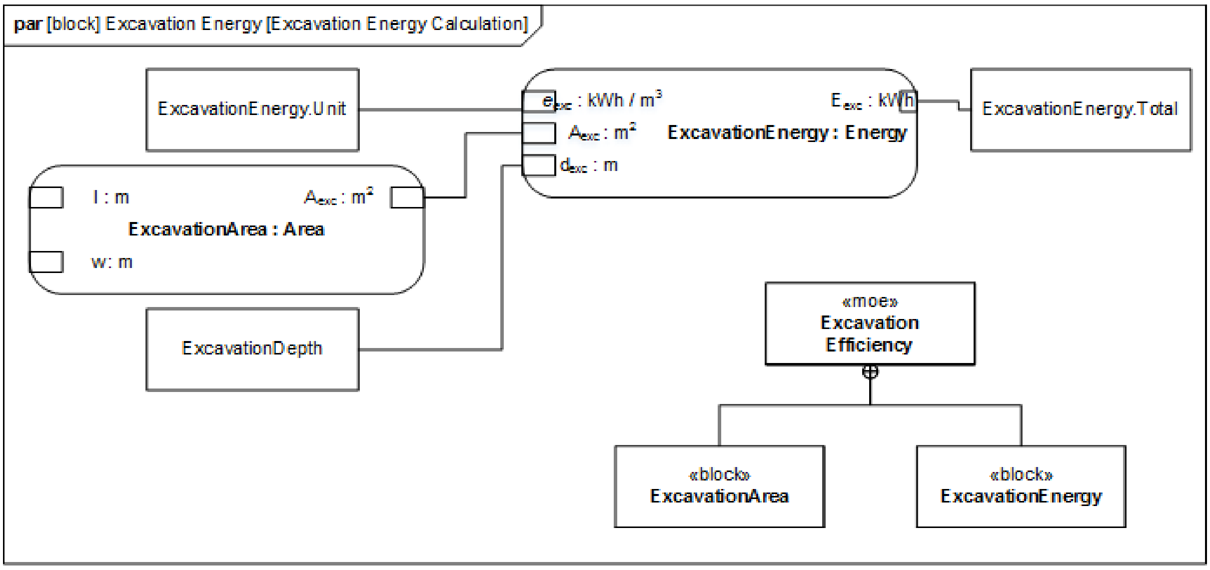

Figure 6: Calculation and Performance Evaluation for Excavation Activity

Evaluation is done through defining *measures of effectiveness (moe);* in this case evaluation is based on minimizing the excavated area (that is, not to excavate large areas unnecessarily), and minimizing the overall excavation energy consumed, as illustrated in the lower section of Figure 7.

4. Conclusions and Future Work

A systems model has been developed to enable and facilitate the realization of sustainable construction across the multiple disciplines involved in delivering any AEC project and across different lifecycle phases. The environment, the construction product, and the production/management systems have been modelled as three interacting systems of systems and were described using SysML notation. This setup has been useful in the development of a logical classification of sustainability parameters according to which environmental subsystems they are related to, and identifying what exact production activities generate which environmental impacts.

The systems model developed addressed a number of key issues faced by traditional models that usually hindered their capacity to directly model, evaluate and hence contribute to the realization of sustainability in the AEC industry. While traditional models were typically developed by different disciplines to capture specific phases and instances of a project in its lifecycle, the holistic approach used addresses the product, the processes, and the environment altogether. This facilitates the tracking of energy, item flows, environmental loadings, etc. in terms of where they are consumed/ generated, when, and by which project entities. The versatility of the model allows addressing sustainability performance at the top, system-level, all the way down to the activity and process levels. Moreover, the adoption of SysML opens a clear path to system automation, especially upon linking to a BIM model.

Future work should investigate automation through linking the systems model to BIM environments in order to directly read construction product data from different design disciplines. This should facilitate dynamic optimization and accelerate the sustainability evaluation process.

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