Evaluation of Design Performance through Regional Environmental Simulation

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Abstract: Computational building simulation tools have historically viewed buildings as artefacts isolated and disconnected from their contexts. At most, the external environmental conditions have been viewed as outside influences or stressors encapsulated in, for example, weather files for energy simulation or sky models for lighting simulation. In the field of environmental assessment, life cycle analysis (LCA) has followed a similar path of isolating the artefact under analysis from its context. Modeling the building artefact as a participant in multiple contexts over time so that the interactions and dependencies between the regions and the building can be adequately explored in the design process requires support for the modeling of regional areas, as well as the artefact and the related life cycle processes. Using computational design and evaluation tools can provide the computing capability required for effective design decision support. This paper presents the implementation of the affordance impact assessment method and the regional environmental simulation in Ecologue. Ecologue is the computational tool for life cycle environmental impact assessment in the SEMPER integrated building design and simulation system. Ecologue contains a building model and an environmental model. The building model is automatically derived from the shared building model of the SEMPER system. The environmental model is a combination of a representation of the processes and emissions occurring in the life cycle of buildings and an impact assessment model. The impact assessment model is a combination of a context model of the physical characteristics of a region and a sub-regional fate and transport model based on the fugacity concept.

1. INTRODUCTION

1.1 Buildings interaction with the environment

Buildings exchange mass and energy flows with their surroundings and the wider environment in multiple ways throughout their service life. A life cycle framework is essential to understanding and evaluating these interactions. A life cycle assessment is typically broken down into six stages: raw materials acquisition, manufacturing, processing, transportation, use/reuse/maintenance, and recycling/waste management. An equivalent set of stages for a building or building component would be raw material mining or harvesting (i.e., mining clay, stone, ore, gravel, or harvesting wood), building material production (i.e., milling and fabrication, metal smelting, rolling, and shaping, and assembling), building construction (site work, structural frame, enclosure, and finish work), building operation (heating and cooling, lighting), and building decommissioning (reuse, recycle, disposal).

The principal raw material acquisitions for buildings fall into three categories: abundant materials, such as sand, clay, and gravel; potentially renewable resources, such as wood and fibre; limited and non-renewable but possibly recyclable resources such as metal ores (bauxite, iron and copper ores), and plastics from fossil feed stocks. Impacts from raw material acquisition can include land degradation, hazardous waste generation from extraction and refining, and resource depletion.

The building component production phase includes the manufacturing of constituent materials, such as metals and rough lumber through the fabrication of products such as studs, cement, windows, and doors. Materials and components can be highly finished in a factory or minimally processed with additional work required on site. Typical impacts from this stage are releases related to the manufacturing processes and energy use in material production and fabrication.

The principal impacts in the building construction stage are waste generation and energy and equipment use for assembly. The construction waste generated by the construction of an average home in North America was found to be approximately 20 kg • m^{-2} of floor area 4,000 kg for an average 185 m^2 (2,000 ft^2) house (NAHB 1996 see *Figure 1*).

The principal impacts in the building operation phase are energy-related (heating, cooling, lighting and equipment), maintenance-related (repair and replacement of building components) and related to indoor environmental quality. Despite the introduction of energy efficiency measures, residential and commercial energy related greenhouse gas emissions have outpaced the rate of population increase (*Figure 2*). Operational loads can comprise a significant proportion of the total life cycle environmental loading (*Figure*

3). Additionally, indoor environmental quality is an important occupant health issue. Concentrations of pollutants can be significantly higher indoors when compared to ambient air (Ott and Roberts 1998).

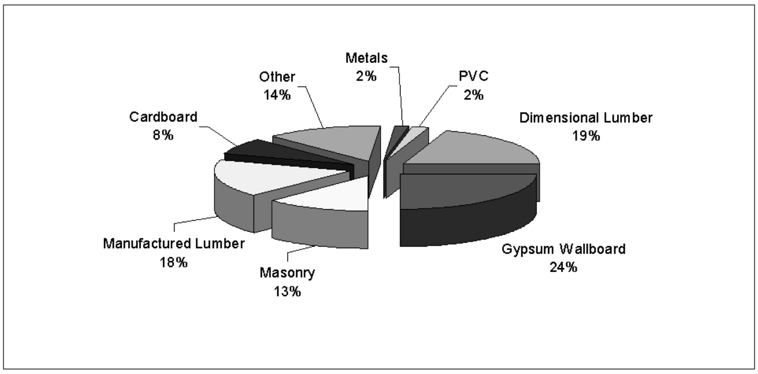

Figure 1. Characterization of the construction waste generated by the average home construction in the United States (NAHB, 1996)

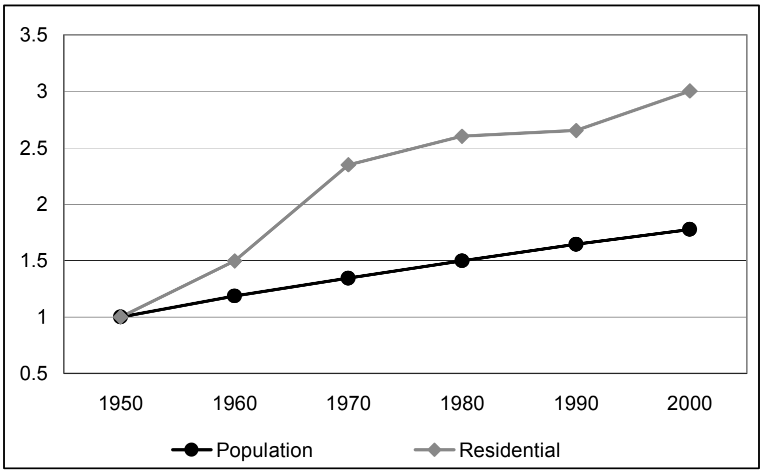

Figure 2. Increase in energy-related greenhouse gas production in the US 1950-1998 relative to population in the residential building sector (1950 = 1)

Building decommissioning and demolition generates primarily inert materials that have historically been landfilled. Principal components of demolition waste are wood and concrete, which together comprise two-thirds of the demolition waste of an average house. The most common materials recycled are concrete and asphalt, wood, asphalt shingles, metals, and drywall. Five states report an average of 48% recycling rate for construction and demolition debris (USEPA, 1998).

Considering the implications of the life cycle of buildings to the understanding of its environmental impact, a life cycle assessment framework should be considered an essential part of the design of the built environment.

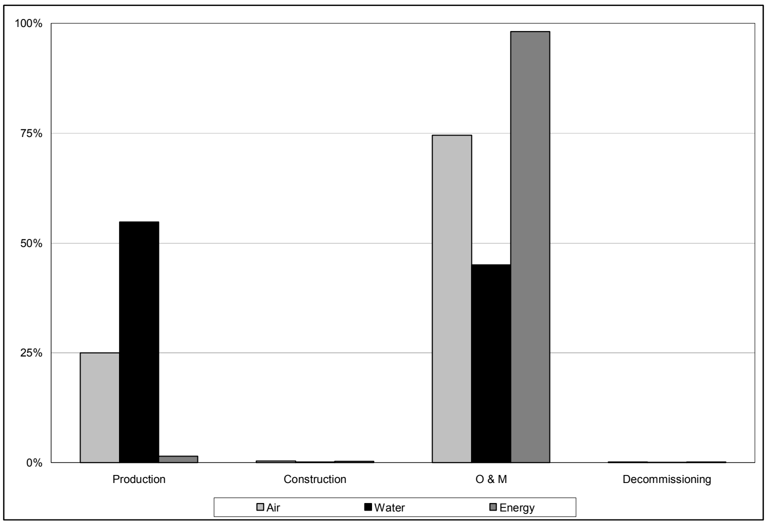

Figure 3. Distribution of life cycle air, water, and energy use impacts among four life cycle stages (Ries, 2000)

1.2 Life cycle assessment

LCA is defined as a four phase process (Fava et al., 1991) consisting of goal definition and scoping, which defines the objectives of the study and determines the analysis boundary; inventory analysis; impact analysis; and improvement analysis, which is an evaluation of the environmental loads identified in the previous stages in order to determine modifications to the product or process that will reduce environmental impact. Within the LCA framework, environmental assessment methods differ primarily in how the inventory analysis is performed and in how the impacts are evaluated.

Life cycle inventories are most commonly calculated as the sum of pollutant releases and/or energy use for the processes related to the material or component in question. Life cycle impact analysis evaluates the effects of the constituents of the life cycle inventory. Estimating the effects of the life cycle inventory is perhaps the most difficult stage of the LCA. The methods developed have used a number of different strategies. The most straightforward and simple methods use factors such as energy use or the mass of pollutant emissions from the life cycle inventory as indicators of environmental performance. Other methods use categorization and weighting strategies. These gauge the effects of the emissions and use a weighting or effect formulation to normalize, compare, and group emissions so that a single indicator value or multiple values can be calculated.

Impact analysis methods have evolved from the energy- and pollutant mass-only methods. However, a number of limitations remain. In current LCA practice, impact analysis is based on the life cycle inventory stage, which is a mass- or intensity-only accounting of pollutant emissions and material and energy use. The aggregation of the life cycle releases into a single dimension has the following constraints. This type of aggregation does not take into consideration the varying intensities (e.g., emission or use per unit time) that occur in actuality. A short-term high intensity emission release may aggregate to the same mass as a long-term low intensity release, although the environmental impact may not be equivalent. Aggregation also does not take into account the spatial distribution of an emission release. Emission releases equivalent in mass terms could be distributed over different volumes of media, result in different concentrations and therefore potentially different environmental impact. Emission inventories also do not consider the characteristics of the context or region where releases occur. As a result, the sensitivity of the context to an emission release cannot be included in the analysis. Additionally, most LCA impact assessment methods require a comparison of alternatives, but do not necessarily determine whether any of them are within the ability of the ecosystem to sustain the environmental loading over a period.

Analysis of the results of a life cycle analysis of a prototype residential home using the Critical Volume method of environmental impact assessment illustrates some of these points (Ries, 2000, Etterlin et al., 1992). *Figure 3* shows that relatively, the building material production and operation and maintenance phases are the principle life cycle phases for environmental impact. In addition, when aggregated over the life of the building, estimated at fifty years in this case, the majority of the impacts from emissions to the air and energy use occur in the operation phase. *Figure 4* shows the relative emission and energy use rates for the same prototype residential building. The emission impact and energy use rate is defined here as the unit impact or use over unit time. When comparing the two figures, one can see that the rate of environmental impact from emissions and energy use are greatest in the building material production phase, and the relative importance of the operation phase has been reduced.

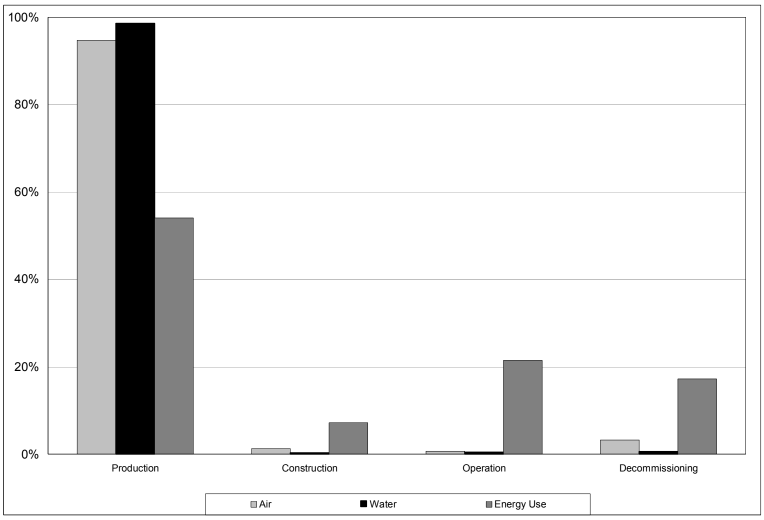

Figure 4. Distribution of air, water, and energy use impact rates among four life cycle stages

These limitations have motivated the work toward the impact assessment method called affordance. Affordance is an indicator that calculates a spatial allocation for emissions and resource usage and has units expressed in kg $\cdot$ m^{-2} $\cdot$ yr^{-1}. The implementation of affordance described here uses a model evaluative environment, which allows for the consideration of the emission rate and the spatial distribution of an emission release in the indicator calculation. The evaluative environment models the characteristics of the context or region where releases occur. As a result, the sensitivity of the context to an emission release can be included in the indicator calculation. In addition, the affordance concept is similar to carrying capacity in that it evaluates the ability of the ecosystem to sustain the emission rates over a period. Lastly, the allocation of an emission rate per unit area makes the indicator useful for land use and resource planning. The context-based representation of a life cycle inventory with a model that includes spatial and temporal distributions of environmental emissions will improve environmental evaluation of the design, construction and operation of the built environment and lead to improved design decision-making.

2. IMPLEMENTATION

The majority of current LCA software tools are general purpose and stand-alone, i.e., outside of a CAD environment. A number of software tools have been developed specifically for the building industry. Examples are

ATHENA (Trusty et al., 1998), LEGOE (Hermann et al. 1998), and BEES (Lippiatt, 2000). ATHENA and BEES are stand-alone, and LEGOE is an example of an integrated software tool that includes energy analysis and LCA.

In the stand-alone systems, the user specifies the construction system and building components through an interface that describes the constituent elements of the building, such as walls, floors, foundations, beams, or columns. The user specifies the area or quantity of each building element. Once the building description is complete, the tool applies the environmental factors for the specified components and finishes. The environmental factors are based on detailed LCA data, but this is not accessible to the user. Therefore, the capability to construct custom assemblies out of materials or components in the tools is limited. In-depth analysis of the causes of the resulting environmental impacts is limited because the underlying LCA data is not available. These systems also require at least two materials, components, or building descriptions for comparison.

The affordance impact assessment method has been implemented in Ecologue (Ries 1999). Ecologue is the computational tool for life cycle environmental impact assessment in the SEMPER integrated building design and simulation system (Mahdavi, 1999). Ecologue contains a building model and an environmental model. The building model is automatically derived from the shared building model of the SEMPER system. As a result, the environmental assessment tool does not require separate user input of the building description. A portion of the building description includes references to, for example, technical elements and construction types. These additional elements are fully described from domain viewpoints in database representations that are accessed by Ecologue. The combination of the building model and the database elements are used by Ecologue to generate the building representation from the environmental domain viewpoint. An interface is provided to create new and edit existing domain-specific database representations. The environmental portion of the Ecologue model is a combination of a representation of the processes and emissions occurring in the life cycle of buildings and an impact assessment model. The impact assessment model for affordance is a combination of a context model of the physical characteristics of a region and a sub-regional fate and transport model based on the fugacity concept (Mackay, 1991).

2.1 Affordance Impact Assessment Model

Determining the environmental impact value of a process in a context using the affordance method requires the modeling of the fate and transport of the process-related emissions, and the estimation of the resulting concentrations in the context. The regional or context model in Ecologue is a multi-compartment model (see *Figure 5*). A compartment is defined by its physical characteristics, such as the size (area and volume) and the rates of advective flow of the media. A fugacity-based model is used within each compartment. Fugacity is a property of a substance that is used for predicting mass and concentration distributions, reaction characteristics, and persistence of a chemical released into an environment.

The fate and transport processes modeled are emissions to air, soil, and water (E_i), transmissions between media (D_{ij} representing diffusion, deposition, and runoff), reactions (R_i), and advection (A_i). Mass balance equations are used to determine the distribution tendency and concentration. The evaluative environment is not intended to simulate the real environment, but is intended to provide the behavioral characteristics of the substance in terms of partitioning among the media (air, water, soil, and sediment).

The context is modeled as a bounded system, and therefore no transfers of mass occur across the boundary. Conceptually, the scale of the context model can range from a world model, a geographical region, or rooms in a building interior. A regional context model can correspond to a naturally defined area, such as a watershed.

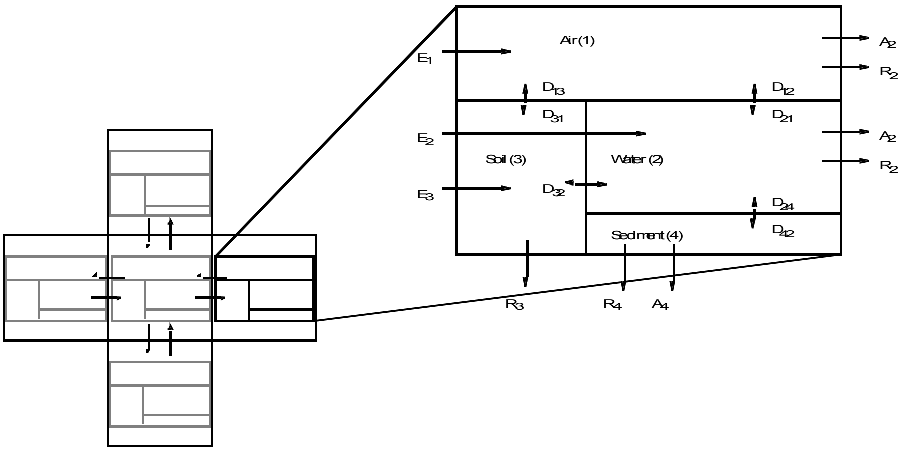

Figure 5. A five-compartment system with mass transfer between compartments and an expanded view of a compartment showing the transfer phenomenon modeled in the evaluative environment

Process and Emission Model

Processes and the related components (see *Figure 6*) are the principal elements used in the calculation procedure. Processes model activities in the environment, and are related to an element of the Ecologue building model. Each process can be composed of multiple processes, each with a set of related emissions and one related context (see *Figure 7*). Emissions are modeled as a set of chemical and physical attributes. The interrelationship of the characteristics of the emission and the context together determine the distribution and concentrations of the emission in that context.

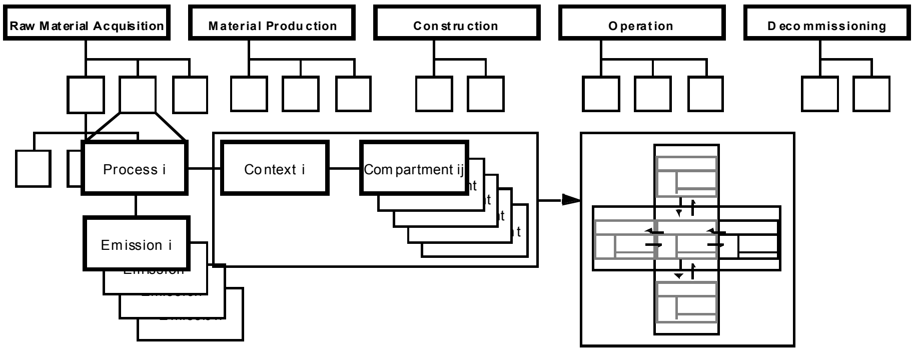

Figure 6. Relationship of the process model to the building life cycle

2.2 Calculation Procedure

In the affordance method, the allowable emission rate for each emission in each process in the context is calculated using the model described in the previous section. The calculation procedure evaluates each emission-context pair. The combination of the context characteristics, including the transfer between compartments, the emission properties, and the emission rates determines the allowable concentrations. The model is calculated iteratively and the allowable emission rate is found when the concentration in one of the media in a compartment reaches the target concentration range (Sittig, 1994), within a tolerance factor. The allowable emission rate is then divided by the developable area in the process compartment, resulting in the allocation of the emission rate per unit area.

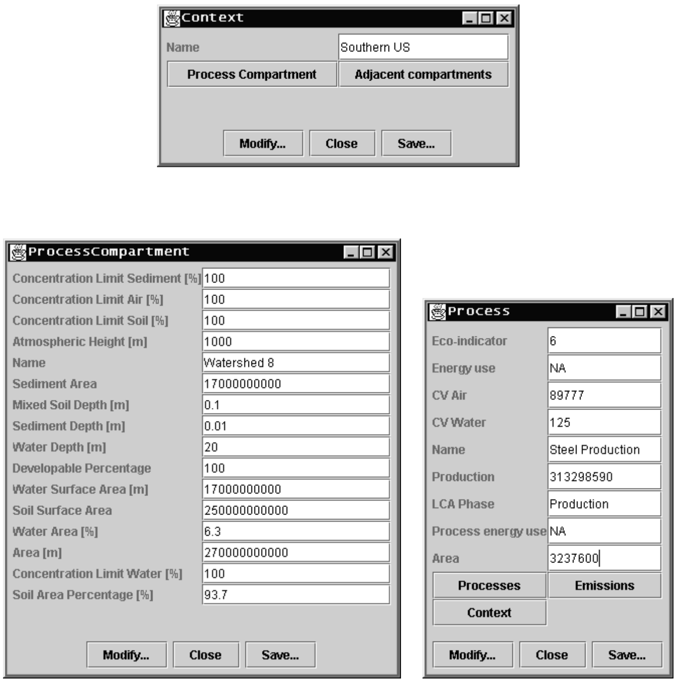

Figure 7. User interface windows for the specification of a context, compartment, and process

3. ILLUSTRATIVE EXAMPLE

3.1 Emission and Context Characteristics

This scenario presents the affordance calculations for a process in the material production portion of the building life cycle. The process is a typical manufacturing process with four emission types: formaldehyde, methanol, phenol, and methyl ethyl ketone. All emissions are released to the air. The process occurs in a facility with a 4,000,000 m^2 land area.

For calculating the allowable emission rates, the process is modeled in a five-compartment context of the type described in the previous sections and shown in *Figure 5*. Each context has the same land and water areas. The concentration limits for each emission and each media are set at 100% of the legal threshold limit for all compartments. The assumption is that one half of the context area will be developed, with the remainder undeveloped.

3.2 Results

The results of the affordance calculation are presented in *Table 1*. The calculations show that the spatial emission rate is exceeded largely for two of the emissions - formaldehyde and phenol, and to a lesser extent by methyl ethyl ketone. Methanol is below the allowable rate, resulting in an impact less than 1.

Table 1. Results of the illustrative affordance calculation

Emission	Actual spatial emission rate e [$kg \cdot m^{-2} \cdot yr^{-1}$]	Calculated affordance emission rate e_{max} [$kg \cdot m^{-2} \cdot yr^{-1}$]	Impact ($e \cdot e_{max}^{-1}$)
Formaldehyde	$4.30 \cdot 10^{-4}$	$4.91 \cdot 10^{-8}$	8790
Methanol	$8.80 \cdot 10^{-5}$	$8.62 \cdot 10^{-4}$	0.10
Phenol	$2.80 \cdot 10^{-4}$	$4.02 \cdot 10^{-8}$	7070
Methyl ethyl ketone	$1.69 \cdot 10^{-5}$	$1.17 \cdot 10^{-6}$	14
		Total impact:	5640

The results indicate that if all developable areas of the evaluative context were to release substances at the rate that this process does, it would cause a concentration in excess of the legal threshold limit for four of the five substances. Therefore, the emission rates of this process are above the capacity of the ecosystem, and should be reduced. The other alternative would be to reduce or eliminate the rate of emission of these substances on additional areas of the region. Similar to emission credits, this could conceivably be achieved through negotiation.

4. CONCLUSIONS AND FUTURE WORK

A first step to enhancing the fugacity-based context model would be to expand the scale of the model. Coupling multiple context models by linking the input and output mass flows of adjacent multi- compartment context models would allow a larger-scale regions to be modeled iteratively (see *Figure 8*).

Linking the input and output mass flows of context models would allow the development of a spatial hierarchy of nested context models. The models within a hierarchy multiple scales would be used to assess impacts that occur at dissimilar spatial scales. Each of the multi-compartment context models could be scaled to the appropriate size for each assessment desired.

The affordance method could be realized with alternative or additional environmental and geophysical models that would utilize a model to calculate affordance values for contexts depending on the type of the mass or resource flow. A limitation of the current fugacity-based fate and transport model is that it was developed for organic compounds, and is not universally applicable for all types of emissions. Incorporating multiple models would improve the scope of the current application.

Assessing the environmental impact of a large-scale artefact with a long service life, which is the product of a heterogeneous system of processes, such as a building, is a complex problem requiring a large amount of information. Additionally, there is a significant amount of uncertainty in the analysis. Uncertainty is introduced into the analysis in three principal areas: in the estimation of the quantity of emissions from processes in a life cycle inventory; in the estimation of the environmental impact of those processes and activities in a life cycle impact assessment; and in the prediction of future building activities and functions. A life cycle analysis with multiple stages can propagate uncertainty throughout the model, leading to a result with a wide range of variability. Incorporating the calculation of uncertainty into the data model and assessment calculation would improve the current implementation.

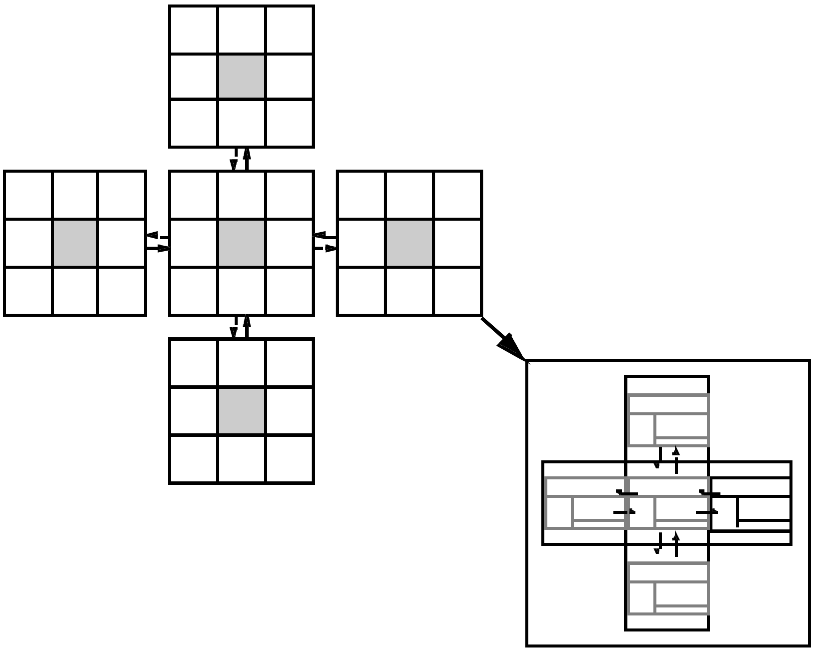

Figure 8. Expansion of the multi-compartment context model into multiple coupled contexts

LCA has provided a framework for the investigation of the environmental impacts of products and processes, and has led to the development of various methods and software tools developed for or applied to the building industry. Impact analysis methods have been consistently improved since the initial energy and pollutant mass methods. The affordance impact assessment method presented here has the potential to address some of the limitations of the mass- or intensity-only accounting of pollutant emissions and resource use used in most methods with a spatial allocation formulation for environmental impact. The affordance method allows for the consideration of the emission rate and the spatial distribution of an emission release in the indicator calculation. The modeling of the characteristics of the context or region where impacts occur allows the carrying capacity and sensitivity of the ecosystem to be included in the indicator and makes the indicator useful for land use and resource planning.

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