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Life Cycle Assessment modeling of an institutional building: Evaluation of the BEES 2.0b software

An internal report

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LIFE-CYCLE-ASSESSMENT MODELING OF AN INSTITUTIONAL BUILDING: EVALUATION OF THE BEES 2.0b SOFTWARE, AN INTERNAL REPORT
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Project Objectives

- Test the use of BEES 2.0 b on a state-of-the-art commercial building, and combine BEES' per-unit outputs with the building materials inventory in order to generate an overall environmental profile of the building's materials.
- Develop a total Life Cycle Assessment (LCA) of Sam Wyly Hall (SWH) using BEES 2.0 b in combination with thermal modeling software, while also incorporating the end-of-life phase.
- Identify materials and environmental impacts not included in BEES 2.0 b, both, through a detailed material inventory, and the use of other LCA resources.
- Recommend improvements of the current BEES version based on these results.

Methods

Sam Wyly Hall is a 7306m^2, 6-story mixed-use building on the University of Michigan Campus. Construction was completed in 1997. A material takeoff list for SWH was developed based on contractor documents and examination of architect's plans. This list calculated the total installed mass of each building component, based on actual mass information or computations of mass from installed area. Components in the material takeoff list were researched to determine their actual composition and create a total inventory of individual materials. Manufacturing losses, construction losses and replacement rates over the lifespan of the building were also factored into the material requirements. Operational energy requirements were based on thermal modeling of an approximately equivalent system as is used in SWH. This was due to the fact that actual data for SWH operations is unavailable from the University of Michigan. Separate LCAs of the Ann Arbor Water Treatment Plant and the Ann Arbor Wastewater Treatment Plant were utilized to determine impacts from water consumption. Additional data on transportation, construction and decommissioning requirements was also researched using contractor information as well as published research. For each material and each energy demand determined through this inventory an environmental flow dataset was used. All of these datasets were aligned so that the total environmental burdens could be calculated. These environmental burdens were divided among the various life cycle stages, pre-use, use phase, decommissioning. Additionally transportation and construction were subsets of the pre-use phase burdens. The results of this modeling provide the basis for the LCA of SWH (enclosed as a draft paper for publication).

Additional research looked at the use and application of the BEES 2.0b database. From the material takeoff list it was determined which components were available in the BEES database. Early on it became clear that the BEES database would be limited for conducting a full LCA (see below) and so the SWH LCA was developed separately, but a comparative study of BEES was developed. For this study we looked at the overall applicability of BEES to SWH in terms of material coverage and environmental impact. This process consisted of first assessing how much of the building mass could be accounted for using BEES modules and second, comparing all the BEES modules that could be matched to SWH building components in terms of environmental impacts. The results of this study are included in this report.

Definitions

The following terms are used within this report. This does not include definitions of more common life cycle analysis terminology.

CSS: Center for Sustainable Systems.

SWH LCI: The total material and energy flows for construction, operation and decommissioning of SWH

SWH LCA: The comprehensive Sam Wyly Hall Life Cycle Assessment is an environmental impact assessment based on the environmental flows from the SWH, which uses various non-BEES sources for LCI data on the production and manufacturing of building materials[1].

SWH MCI: The Sam Wyly Hall Material Construction Inventory. This is the total material and energy requirement for SWH for initial construction, as well as lifetime replacement of materials. Included in this inventory are transportation and construction energy requirements. This does not include operational or decommissioning energy or material requirements.

BEES Modules: Individual product datasets used in the BEES 2.0 b software database. For example, B2011A: Brick and Mortar

Generic products: General product categories. Specifically those referenced in BEES 2.0 b. For example Paint, Concrete, Insulation.

Specific products: These are the individual products (BEES modules) available within a Generic product category. For example, Virgin Latex Paint, 15% Flyash Concrete, R30 Fiberglass Batts.

Components: A part of the building, which fulfills a particular function and consists of one or more materials (e.g., paint, door, pre-cast concrete wall element)

Materials: Individual substance(s) that either make up a component, or fulfill a function on its own (e.g., cement, steel, polyamide). Individual datasets for LCA modeling are typically organized by single material production (e.g., cement production, EAF Steel).

Environmental Flows: Natural resource use, emissions to air, water, etc., energy demand and waste resulting from a process.

BEES Model: The complete list of specific products present in the SWH MCI which had a comparative BEES module were inventoried by mass. The mass of each specific product was converted to the units of measurement for its BEES module and computed into that module. All of the environmental flows from the BEES modules for those specific products were combined and summed. Primary energy demand and environmental impacts were calculated based on the output from this combined flow.

BCOM Model: The BEES Comparison Model. The BEES model inventory of specific products was broken down into masses of individual materials according to the product's specifications in the SWH MCI. Using DEAM datasets the environmental flows for these materials were combined into one model (transportation was also included based on information collected in the SWH MCI). Primary energy demand and environmental impacts were calculated based on the output from this combined flow.

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[1] e.g., DEAM 3.0 (Ecobilan), Franklin Database (Franklin Assoc.), "Handbook of Industrial Energy Analysis" (Boustead & Hancock), "Eco-Profile of Lumber Produced in the Western United States, Life Cycle Inventory of WWPA Western Lumber" (WWPA/SCS)

BEES testing and analysis

While developing the SWH MCI, we identified a subset of materials that had relevant BEES modules. Through this approach we discovered a set of significant issues regarding the use of BEES for whole-building LCAs.

1. Generic products available in BEES cover only about half of the SWH MCI mass. Specific products available in BEES only cover 17% of the SWH MCI mass. Please refer to appendix 1 for a diagram of these categories. BEES modules which matched closely to SWH specific products in this inventory are listed in appendix 2.

2. Some of the BEES modules, while matching a generic product category in the SWH MCI, did not match well the specific product inventoried. For example, oil based paints were used in SWH, but there is not an oil based BEES module.

3. BEES modules are aggregated for entire components. Particular components in the SWH MCI were found to have two variances from BEES modules when examined on the level of constituent materials. First, there were often different aggregate material compositions than the BEES modules. For example, much of the paint used in SWH had a polyvinyl acetate resin base, but included a large amount of titanium dioxide. Second, in the SWH MCI we sometimes found a range of material compositions for a single specific product. For example, concrete came in several varieties, with different balances of density and flyash content, the majority of which were not available in a BEES module.

4. However, for BEES modules which could be compared to SWH MCI materials, we discovered a high agreement between the environmental burdens calculated with the BEES model and those from the BCOM model. For instance, the BEES model generated 96% of the nutrification potential, 94% of the acidification and 92%the global warming potentials of the BCOM Model. Only the ozone depletion category had unusual results with the BEES model producing 46%% of the ODP found in the BCOM Model. These differences in ODP are described in Appendix 3.

Partially as a result of the factors mentioned above, the full SWH LCA, separate from the BEES assessment, was conducted using data sets from various LCA sources, including the DEAM software (developed by Ecobilan, who developed the BEES modules data) but not the BEES modules themselves. The use-phase consumption of energy was computed using thermal modeling software, because actual building consumption data were not available from the University of Michigan. Hot and cold water use was determined based on occupancy schedules and an inventory of the installed bathroom fixtures. For a more detailed description of the inventory procedure of all life cycle phases and the final results please refer to the enclosed SWH LCA paper, currently being submitted to the journal *Energy and Buildings*.

After completing the SWH MCI and establishing LCA metrics for environmental impacts, the BEES modules were further analyzed based on the following two comparisons[2].

1. Material mass coverage:

   a. Initial and life cycle mass for the SWH MCI vs. initial and life cycle BEES generic and specific product mass coverage. The results are presented in Appendix 4[3].

   b. Distribution of BEES specific product mass coverage among equivalent SWH MCI generic material categories. The results are presented in Appendix 5.

2. Life cycle impacts:

   a. The environmental flows from BEES modules were compared to a similar set of environmental flows from CSS sources. This comparison was accomplished by developing the two models described in the definition section above (see appendix 6 for BEES model to BCOM Model conversion). The purpose of this comparison was to explore the results in order to assess the effects of differences in data sources and material constituents used. Since the BEES modules which were similar to SWH MCI products often did not match exactly the material constituents of SWH we wanted to assess their general applicability, as well as their use in place of a more specific inventory method such as the SWH MCI. The following comparisons were made between the BEES model results and the BCOM Model results:

      i Primary energy demand for material production (including transportation). Each model's results were further compared to the following (for results see appendix 7);

      - Primary energy for SWH LCA excluding primary energy for operations and decommissioning.
      - Primary energy for SWH LCA including primary energy for operations and decommissioning.

      ii Greenhouse gas emissions (expressed as GWP in kg CO_2 eq.) for material production (including transportation). Each model's results were further compared to the following (for results see appendix 8);

      - GWP for SWH LCA excluding GWP from operations and decommissioning.
      - GWP for SWH LCA including GWP from operations and decommissioning.

   b. A comparison of impact potentials used by the BEES model and the BCOM Model was undertaken for Global Warming, Acidification, Nutrification and Ozone Depletion. See Appendix 9 for results.

   c. In both, the BEES model and the BCOM Model, the ratio of material production primary energy demand and material production GWP to total life cycle primary energy demand and total life cycle GWP respectively are similar. This result reflects the findings of the majority of other LCA studies.

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[2] Note that in all cases the BEES data sets were used in their raw form. The BEES interface does not allow for comparison of unrelated components or a cumulative impact assessment for multiple materials.

[3] While BEES modules already include life cycle replacement mass, this comparison was based on simple mass requirements to look at the difference between initial mass and replacement mass.

d. Several data quality issues appeared in the form of gross discrepancies between the BEES model data and the BCOM Model data in regards to particular air or water emission categories. Please refer to appendix 10 for a listing of emissions with a greater than 400% discrepancy. While different modeling procedures were used, possibly accounting for some discrepancies, the sheer size and number of these discrepancies warrants further investigation. In some cases the discrepancy could be traced to a single BEES module.

Recommendations for BEES development

BEES is one of the few life cycle databases in existence specifically for building materials. It is the only database designed for simple user comparison of different materials. As such it offers a valuable tool for anyone involved in the building process to analyze material choices. This study found that, in general, life cycle environmental impacts from BEES modules, when compared to a building component in SWH were similar to the results from a comprehensive and materially specific LCA. As such BEES modules could be generally applicable in situations where a similar product to one in a BEES module is being examined. However, limited current availability of modules reduces the options for comparison in a whole building. The following recommendations are intended to offer suggestions to enhance BEES' capabilities.

1. *Expanded specific product modules:*
   The specificity of material choices in BEES modules restricted the application of BEES modules to the full SWH LCA. For example, there is a wide range of solvent-based paints and stains present in SWH, which cannot be represented by the virgin latex paint module. Since concrete is such an omnipresent material in construction and comes in many different densities and constituent material mixes, the limited selection in the BEES modules was a significant factor in our decision not to use it. Further, the limitation of the concrete module to stop at the gate eliminates all the end-product-manufacturing variations (e.g., hollow core, precast) which could have a significant impact. In some cases the choices do not reflect a range wide enough for existing industry choices, both in terms of traditional materials as well as for more "green" choices. Manufacturer-specific modules, might be beyond the scope of BEES but could facilitate more specific comparisons especially in cases where individual manufactured components are much different in material production or material composition, though interchangeable in terms of function[4]. Options for the development of a broader variety of specific products could include the following[5]:

   a. Conventional products: polyisocyanurate insulation, solvent-based paints & stains, EPDM roofing, treated concrete (exterior finish), standing-seam steel roofing, virgin-material ceramic tile, sealed or painted concrete flooring, virgin wood flooring, wider range of types as well as assemblies of concrete.

   b. "Greener" and/or traditional products: rice-hull ash and blast-furnace slag concrete, adobe, rammed-earth, logs, cement/wood-fiber siding, recycled cotton insulation, airkrete™ insulation, recycled rubber/wood roofing shingles (e.g., eco-shakes™), slate tiles, plant- or milk-based paints, newspaper/soybean protein resin panels, certified wood[6], cork (as flooring and wall covering), paper and sisal wall covering, recycled-rubber and –PVC flooring, flooring tiles with recycled porcelain/stone/marble, bamboo, wood-flour floor

[4] The "BEES Please" program was announced as this report was being finalized. The authors felt it was still valuable to include this comment, though it is apparent that NIST is addressing this issue already.
[5] This list was determined based on products present in SWH, as well as general familiarity with building products.
[6] Certified to be sourced from "sustainably managed forests" e.g., FSC certification

tile, reclaimed-wood flooring, recycled-PET carpet, pervious parking lot surface products, recycled-content HDPE toilet compartments

2. *Expanded generic products:*
   The range of products available in BEES modules does not sufficiently reflect (in this study) the products in this building. In the BEES database there are no structural steel modules. Products such as drywall, sand for backfill, and copper wiring which were found to be major contributors to mass or energy burdens are not available in the BEES database. Some additional product categories (including their alternatives) are:

   - structural steel vs. concrete structure vs. masonry structure vs. wood
   - copper wiring for electrical and telecom
   - piping (copper vs. steel, PVC vs. cast iron vs. vitrified clay)
   - steel reinforcement in concrete
   - wall board and cabinetry options (gyp board, straw board, bamboo, recycled wood MDF, newspaper/soybean protein resin)
   - ceiling tiles (virgin vs. recycled-content and/or industrial/agricultural byproducts)
   - window frame options
   - door material options (many shell and core material options)
   - fireproofing options (for steel structures)
   - carpet cushion options (many recycled and virgin materials)
   - stone (as structural, flooring, or wall finish)
   - countertops options (conventional vs. "greener" options).

3. *User specification for re-used products, and user modification of recycled-content percentage:*
   For some products these two aspects can be highly variable with potentially large environmental differences. It is important that different types of recycled content be considered carefully. For example there are differences between using flyash, an industrial by-product and denim cuttings, which are still basically new manufactured material. There are different environmental implications for a material which is the result of manufacturing inefficiency such as the denim cuttings, than for a product which is an unavoidable by-product of another system such as the flyash. While both displace raw material resources, their source is of varying value. Consideration should also be given to post consumer versus post industrial recycled content. Post consumer content is generally preferable, since the material will then serve a double life. For example, cellulose from newspapers being turned into insulation. On the contrary, post-industrial recycled content only becomes a useful product after being processed twice, without any use between the two cycles of manufacturing. This commentary oversimplifies the complex assessment of recycling benefits which inclusion of this feature would require.

4. *Unrestricted user-defined input of transportation distances:*
   In the SWH LCA transportation primary energy only accounted for 4% of material embodied energy and .18% of total life cycle energy. A sensitivity analysis revealed increases in primary energy to 25% for material embodied energy, and to 5.7% for total life cycle energy, when the SWH MCI average transportation distance of 64 miles was increased to 500 miles. While not a significant burden in the SWH LCA, transportation (and material production) will become increasingly important as operational efficiencies of buildings improve in the future. At the same time, BEES' options for choosing from among three different distances rarely corresponded to the actual distances found on this particular project and the limited range of options could under- or over-estimate impacts. We feel that it would be helpful to be as specific as possible with this issue by giving the user the option to type in the distance in

miles. At the same time, a default option should be offered which might use values of average transportation distances for various products.

5. *Eliminate toxicity and resource depletion categories:*
   CSS feels that the currently available factors for human and ecosystem toxicity highly uncertain, mainly because of the incoherence of emissions covered in different studies, fate modeling parameter issues and/or due to the range of toxicity factors for a particular emission reported in those studies. The methods currently used for computing the resource depletion impact of a product system are highly debatable as well. A crucial factor for calculating the resource depletion impact is the globally available resource base for a particular material, which typically is based on highly variable economic parameters. This, in turn, skews both the contribution of the product system studied, as well as that of other, competing material consumers. Please refer to the associated LCA paper for a more detailed discussion of this issue.

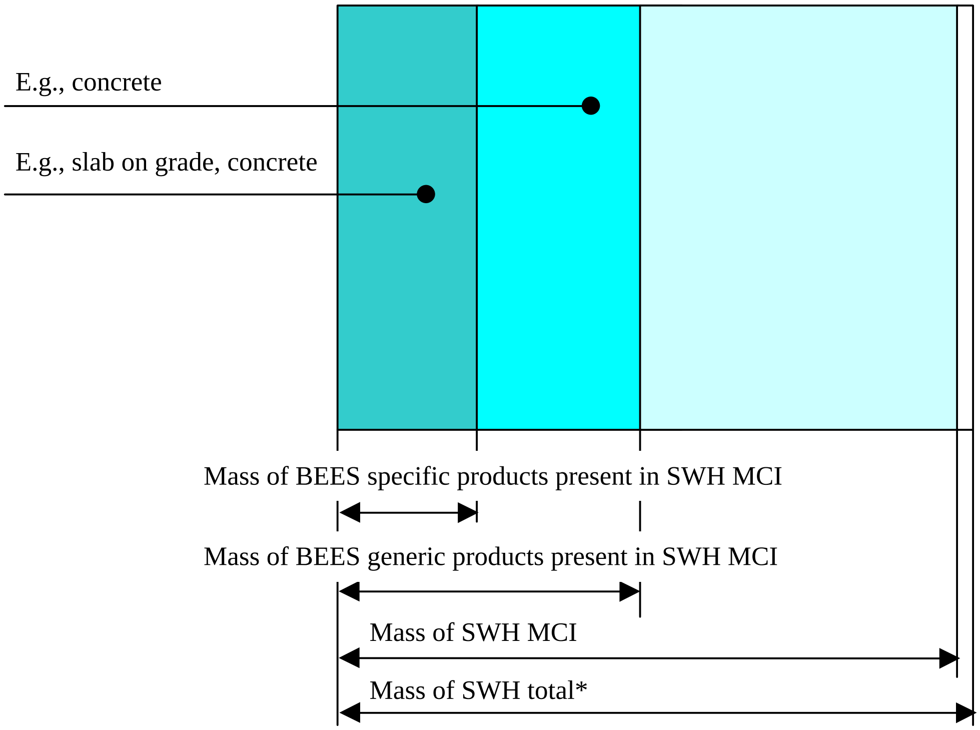
6. *Consider relative impacts within Life Cycle of Building:*
   Overall the findings of the SWH LCA indicate that material burdens are slight compared to operational burdens. For instance, the absolute environmental savings from reducing the ozone depletion potential of paint by 50% could be much lower than those from reducing concrete's ozone depletion potential by only 20%, as the total mass of concrete is significantly higher. Further, reductions in material environmental impact which have negative impacts on operational performance could actually create more environmental damage than other, less "green", alternatives. Architects might greatly benefit from seeing comparisons between embodied energy of envelope materials and the impacts on operational energy for those materials that influence a building's thermal performance (e.g., insulation, sheathing and roofing materials, glazing, window frames) [Pierquet, 1998 #200] (based on "typical" office buildings).

7. *Provide for simple total building modeling:*
   To better capture the relative impacts of various building materials and components to one another, allow for a simple input procedure to facilitate the mass calculation of the actual building (e.g., based on sqft numbers), or provide import option for CAD files and/or other software with a mass-inventory option (such as 3D-Home Architect®).

8. *Clarification of roofing operational energy feature:*
   When comparing various roofing products, the user is alerted to the fact that for buildings in the Sunbelt region "BEES will account for the 50 year heating and cooling energy, based on the roofing material". It is not transparent how this is done (e.g., addition to the embodied energy of the product), and what the basis for such calculation would be (e.g., building size and use). We suggest removing this feature, as it is not only inconsistent with the approach taken with other modules, but also presents a simplified approach to accounting for a building's operational energy consumption.

9. *Account for regional power grid effects:*
   It might be worthwhile to account for the regional differences in the fuel mix of the electricity grid, dependent on the location of the material manufacturing facility. With at least 7.5% of the primary energy demands for SWH's material production energy demand being met by electricity, the impact on many air-emissions-dominated environmental impact categories are potentially significant. For example, coal is 89% of the Mid West power grid, while the Pacific Northwest's grid features mainly hydropower, which generates practically no air emissions.

Appendix 1 –Illustration of material coverage definitions



*building mass requirements includes installed mass as well as manufacturing and construction waste losses

This diagram is a graphic representation of the various measurements of building material mass coverage used in this report. The specific products are the individual modules from BEES, which matched closely an actual building product from SWH. The generic products are broader categories of materials which BEES modules represent, but for which there may not be a specific module that matched something in SWH. The SWH MCI mass is the total mass of the building for which there were environmental flow datasets. The SWH mass total is the total calculated mass of the building.

Appendix 2 – BEES modules used for all SWH MCI comparisons

A1030B: 15% Flyash Concrete
B2011A: Brick and Mortar
B2012E: R13 Fiberglass Batts
B3012B: R30 Fiberglass Batts
B2013A: Steel Framing
C3012A: Virgin Latex Interior Paint
C3020C: Vinyl Composition Tile
C3020L: Nylon Broadloom w/Trad. Glue

This list of BEES modules represents the modules, which were found to be similar in composition to a product in SWH. For example there are several types of concrete in SWH, only some of which are approximately 15% flyash content, and only some of which are used in similar applications as the BEES module description from the BEES 2.0 Technical Manual.

Appendix 3 – Ozone Depletion Examination

BEES model	**total**	**ODP factor**	**ODP**
Broadloom Carpet			
methyl bromide	0.67 g	0.37	0.25
latex paint			
halon 1301	0.13 g	12.00	1.53
		ODP of these items	**1.77**
		total ODP of BEES model	**1.85**
		ratio	**0.96**
BCOM Model	**total**	**ODP factor**	**ODP**
cement			
methyl bromide	2.89 g	0.37	1.07
Latex paint (polyvinyl acetate)			
halon 1301	0.22 g	12.00	2.59
		ODP of these items	**3.66**
		total ODP of BCOM Model	**4.05**
		ratio	**0.91**
		BCOM Model / BEES model	***2.06***

This table identifies the products or materials in the BEES and BCOM Models which contribute most significantly to the calculation of Ozone depletion potential. Ozone depletion factors used in this comparison were the BEES sources. The total ODP for the BEES model is 1.85 g CFC11 equivalent. Air emissions from methyl bromide in broadloom carpet manufacture and halon 1301 in latex paint manufacture accounted for 96% of the total ODP for the BEES model. The total ODP for the BCOM Model is 4.05g CFC11 equivalent. Air emissions from methyl bromide in cement (from concrete primarily) production and halon 1301 from polyvinyl acetate (from paint) accounted for 91% of the total ODP. Interestingly the ODP for the BCOM Model is over two times the ODP for the BEES model, and the primary source for this is the high amounts of Halon in polyvinyl acetate. Also worth noting is that for the BCOM Model the dominant amounts of methyl bromide are from cement manufacture, while there was virtually none present in the BEES module for concrete.

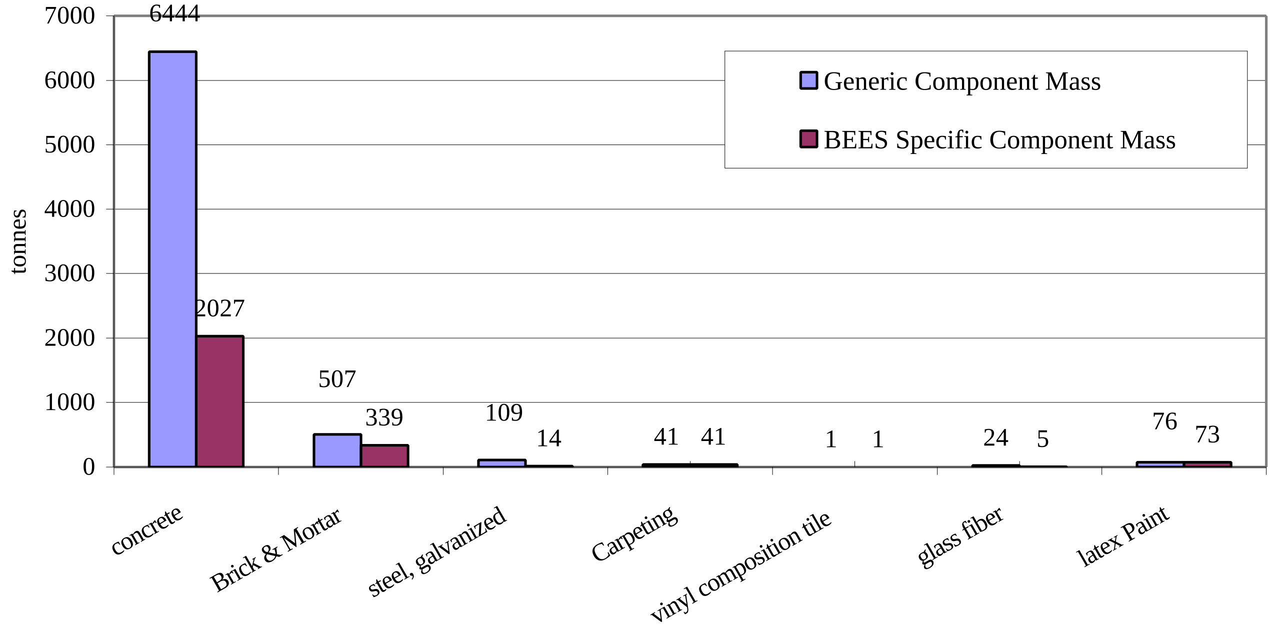
Appendix 4 – Material coverage SWH MCI, BEES generic and BEES specific products

Accounting scope	Mass (metric tonnes)	Percentage of total mass
SWH MCI Initial building material requirements	14,347	99.8 %*
BEES generic products initial building material requirements	6,637	46 %
BEES specific products initial building material requirements	2,394	17 %
SWH MCI Life cycle material requirements	14,497	99.8 %
BEES generic products Life cycle material requirements	7,202	50 %
BEES specific products Life cycle material requirements	2,500	17 %

* this represents "total mass of required building materials with emission data sets available" / "total mass inventoried" (14,375 tons)

The SWH MCI initial mass represents the material mass for initial construction as well as manufacturing and construction losses. This is less than 100% of the total initial mass because it does not include materials for which there were no environmental data. The initial mass is the installed mass before adding any replacement mass. The initial mass of BEES generic products is based on using BEES modules for entire initial generic products mass regardless of whether or not it is a match to the actual product in SWH. For example, using the virgin latex module for all latex paint. Please see Appendix 5 for a graphic representation of this difference. The initial mass of BEES-specific products is a calculation of the total mass of products in the SWH MCI which could be accounted for with a specific BEES module. The SWH MCI, BEES generic and specific product life cycle masses are the same as their initial mass but includes their replacement material mass, according to the schedule of material replacements developed in the SWH LCA. While the BEES modules already include replacement mass in their calculation of total requirements this comparison uses the SWH LCA replacement rates to calculate replacement mass.

Appendix 5 –Generic vs. specific coverage



This graph compares the SWH MCI material requirements in generic categories present in BEES to the specific mass accounted for by specific BEES modules. For example, brick and mortar present in SWH includes paving bricks while the BEES module is specific to face brick. Two approaches were used in this comparison

1. A whole product category was compared to the BEES module used. For example, the mass of all concrete products used in SWH were compared to the mass of concrete in SWH which was 15% flyash content and also matched the applications specified in the BEES manual. The materials that were treated this way are:

Generic category	**BEES module**
Concrete	15% flyash concrete
Galvanized steel	steel studs
Vinyl composition tile	Vinyl composition tile
Glass fiber	fiberglass batts R30 & R15
Bricks and mortar,	Bricks and mortar

2. In others cases the comparison was restricted to products more explicitly similar to the module. For example, the generic category of latex paint was compared to the BEES virgin latex paint module because oil based paints are a completely different process and material composition. The materials that were treated this way are:

Generic category	**BEES module**
Nylon carpeting	Nylon broadloom carpeting
Latex paint	Virgin latex paint

Appendix 6 – BEES model to BCOM Model materials conversion

BEES model			BCOM Model			
units		BEES products	Material consituents		Tonnes	transport
1,431.2	cuyds	15% Flyash Concrete	concrete		2,026.7	30
				sand	784.2	
				gravel	592.1	
				cement	396.6	
				flyash	51.9	
				water	201.9	
22,509.0	ft2	brick/mortar	brick		271.0	30
			mortar/grout		67.8	5
119,849.6	ft2	Virgin Latex Paint	Paint		76.4	
				Water	42.0	100
				Resin(polyvinyl acetate)	19.1	
				silicon hydroxide	0.1	
				nepheline syenite	0.2	
				ethylene glycol	0.4	
				diatomaceous earth	0.3	
				hydrous alum silicates	1.5	
				titanium dioxide	5.9	
				calcium carbonate	6.3	
				carbon black	0.1	
				silica, chrystalline	0.5	
54,226.0	ft2	Broadloom Carpeting	carpet		40.8	100
				SBR latex	21.0	
				primary nylon	12.4	
				recycled nylon	1.4	
				Polypropylene	6.0	
69,296.0	ft2	steel framing	steel, galvanized		14.5	100
				virgin content steel	10.1	
				recycled content	4.3	
28,804.7	ft2	R13 Fiberglass	glass fiber		4.9	100
7,432.0	ft2	R30 Fiberglass		primary glass fiber	3.7	
				recycled glass fiber	1.2	
				Kraft paper	0.4	
381.4	kg	vinyl composition tile	vinyl composition tile		0.6	100

This table is the conversion template for the BEES model to the BCOM Model. Individual BEES modules were compared to equivalent SWH MCI products. The BCOM Model uses the actual material constituents found to be present in SWH for calculations. Items in red in the BCOM Model did not have an associated material emissions dataset available, so they are not accounted for. The square footages used as functional units in each BEES module for the BEES model are based on the actual area for each product found in the SWH LCI. The total masses used in the BCOM Model were also based on the same areas converted to mass based on calculations done for the SWH LCI. Since BEES modules already include manufacturing losses and replacement, only the initial area for the BEES model is input, so the BEES modules schedules of replacement determine total life cycle mass for the BEES model. The schedules of replacements, manufacturing and construction losses from the SWH LCA were used to calculate total life cycle mass for the BCOM model.

Appendix 7 – Primary energy comparison, BEES model vs. BCOM Model

	Prim. Energy MJ
BEES Model Building Material Requirements*	8,600,000
BCOM Model Building Material Requirements*	7,600,000
SWH LCA**, *excl.* operation & decommissioning	58,000,000
ratio BEES model to "life cycle, excl. op & decomm"	14.8%
ratio BCOM model to "life cycle, excl. op & decomm"	13.2%
SWH LCA***, *incl.* operation & decommissioning	1,243,000,000
ratio of BEES model to "life cycle, incl. op & decomm"	0.7%
ratio of BCOM model to "life cycle, incl. op & decomm"	0.6%
* includes energy for all model building materials, replacement materials, transportation but not construction	
** includes energy for all SWH building materials, replacement materials, transportation and construction	
*** includes energy for all SWH Life cycle stages	

Appendix 8 – Global warming potential comparison, BEES model vs. BCOM Model

	GWP kg CO_2 eq.
BEES model*	730,000
BCOM Model*	800,000
SWH LCA**, *excl.* operation & decommissioning	4,900,000
ratio BEES model to "life cycle, excl. op & decomm"	14.9%
ratio BCOM model to "life cycle, excl. op & decomm"	16.2%
SWH LCA***, *incl.* operation & decommissioning	81,800,000
ratio of BEES model to "life cycle, incl. op & decomm"	0.9%
ratio of BCOM model to "life cycle, incl. op & decomm"	1.0%
* includes GWP for all model building materials, replacement materials, transportation but not construction. Impact potentials are from CSS sources (See SWH LCA paper appendix for specific references)	
** includes GWP for all SWH building materials, replacement materials, transportation and construction	
*** includes GWP for all SWH Life cycle stages	

Note: While primary energy for the BCOM Model is lower than the BEES model, total GWP is higher. This was determined to be a result of the impact of higher emissions factor for concrete in the CSS data (251.3g CO2/kg concrete vs. 106g CO2/kg concrete for BEES)

Appendix 9 – Environmental impact potentials comparison, BEES model vs. BCOM Model

	Global Warming	**Ozone depletion**	**Acidification**	**Nutrification**
CSS Impact Potentials[1]	kg CO_2	kg CFC11	kg SO_2	kgPO_4
BEES Model	730,000	0.002	3,700	370
BCOM Model	800,000	0.004	4,000	380
ratio	0.92	0.44	0.94	0.96
BEES Impact Potentials[1]	kg CO_2	g CFC11	g H	gPO_4
BEES Model	750,000	1.8	117,000	380,000
BCOM Model	800,000	4.0	130,000	389,000
ratio	0.94	0.46	0.90	0.98
[1] CSS impact potentials taken from current impact literature (see appendix of the enclosed SWH LCA paper), BEES impact potentials from BEES 2.0b database				

The BEES model and the BCOM Model had strong correlations with either BEES impact potentials or CSS impact potentials. The only unusual result is the ODP which has been discussed above. The strong correlations indicate that both modeling approaches are in relative agreement for environmental impact. The consistent 10-15% reduction in three of the four environmental impact categories in the BEES model over the BCOM Model could be a factor of different replacement rate data used in the BEES database, or different energy calculations. Appendix 7, primary energy demand, also shows a 9% reduction in the BEES model over the BCOM Model.

Appendix 10.1 – Environmental flows with large discrepancies between BEES and BCOM Models

Environmental Flow	BCOM	BEES	BEES / BCOM	Source
(a) Halogenated Matter (unspecified)	8.5E-12	8.8E-01	103015472976	latex paint
(a) Metals (unspecified)	1.6E+02	1.2E+12	7444312704	bricks & Mortar
(a) Halogenated Hydrocarbons (unspecified)	2.1E-08	1.4E+01	673018396	broadloom carpeting
(r) Zinc (Zn, ore)	2.2E-05	9.4E+02	42115876	
(r) Manganese (Mn, ore)	3.5E-04	7.8E+02	2230505	
(a) Phenol (C6H5OH)	3.8E-01	3.3E+04	88444	fiberglass
Iron Scrap	9.6E-01	9.0E+03	9302	
(ar) Radioactive Substance (unspecified)	6.5E+01	4.3E+05	6552	galvanized steel
(wr) Radioactive Substance (unspecified)	6.0E-01	3.9E+03	6503	broadloom carpeting
(a) Chlorine (Cl2)	2.5E-03	1.5E+01	5990	broadloom carpeting
(w) Organic Matter (unspecified)	1.2E-01	5.6E+02	4863	broadloom carpeting
(w) Mercury (Hg+, Hg++)	3.1E-03	1.5E+01	4766	broadloom carpeting
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	3.0E-01	7.8E+02	2631	
(a) Hydrogen (H2)	7.0E+00	1.1E+04	1520	broadloom carpeting
(r) Sulfur (S, in ground)	3.7E-01	5.3E+02	1416	
(w) Copper (Cu+, Cu++)	5.1E-01	2.2E+02	441	broadloom carpeting
(w) Nickel (Ni++, Ni3+)	9.0E-01	2.2E+02	249	broadloom carpeting
(r) Lignite (in ground)	1.4E+01	3.4E+03	235	
(a) Chlorinated Matter (unspecified, as Cl)	2.3E-01	3.6E+01	154	vinyl comp tile
(w) Sulfate (SO4--)	2.1E+04	2.7E+06	130	latex paint
(r) Lead (Pb, ore)	9.5E-04	8.8E-02	92	
(w) Nitrate (NO3-)	8.1E+03	6.6E+05	81	broadloom carpeting
(w) Organic Dissolved Matter (unspecified)	7.6E+02	5.1E+04	67	
(a) Formaldehyde (CH2O)	1.7E+02	6.1E+03	36	
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3	1.2E+02	3.6E+03	30	
(a) Nitrous Oxide (N2O)	1.9E+04	3.4E+05	17	broadloom carpeting
(w) Ammonia (NH4+, NH3, as N)	2.6E+03	3.7E+04	14	
(a) Aromatic Hydrocarbons (unspecified)	1.0E+02	1.1E+03	11	
(a) Ammonia (NH3)	1.8E+03	1.6E+04	9	
(w) Aluminum (Al3+)	4.1E+01	3.0E+02	7	
(r) Barium Sulfate (BaSO4, in gro	2.6E-01	1.9E+00	7	
(r) Dolomite (CaCO3.MgCO3, in ground)	4.3E+02	3.0E+03	7	
(w) Dissolved Matter (unspecified)	4.2E+04	2.8E+05	7	
(s) Sulfur (S)	2.0E+00	1.3E+01	6	
(s) Zinc (Zn)	4.9E-02	3.2E-01	6	
(r) Bauxite (Al2O3, ore)	1.5E+01	9.2E+01	6	
(w) Chromium (Cr III, Cr VI)	5.7E-01	3.0E+00	5	
(w) Salts (unspecified)	2.1E+02	1.1E+03	5	
(r) Uranium (U, ore)	4.6E-01	2.1E+00	4	
(r) Iron (Fe, ore)	1.3E+04	5.3E+04	4	

For this table raw environmental flows across several materials or products in the BEES and BCOM Models were compared in total output. In cases where the BEES model total or the BCOM Model total exceeded the other by a factor of four or greater it was considered significant. Appendix 10.1 is sorted in descending order of BEES model results over BCOM Model results. Appendix 10.2 is the opposite. In some cases backtracking through the BEES modules revealed a single module which contained the majority of this output. In those cases they were indicated. This is not a definitive statement on either the BEES or BCOM Model datasets since their modeling techniques and material constituents were different. However given the size of some of these ratios and the fact that Ecobilan generated the datasets used in both models, it seems like a worthwhile starting place for investigation.

Appendix 10.2– Environmental flows with large discrepancies between BEES and BCOM Models

Environmental Flow	BCOM	BEES	BCOM / BEES
(r) Sand (in ground)	4.3E+09	1.8E+04	242258
(r) Calcium Sulfate (CaSO4, ore)	2.0E+04	4.4E-01	44762
Waste (Mfg.)	3.4E+08	9.4E+04	3679
(a) Carbon Dioxide (CO2, biomass)	1.7E+05	4.8E+01	3437
Gasoline	7.4E+03	1.1E+01	705
(w) Inorganic Dissolved Matter (unspecified)	7.8E+03	1.4E+01	563
(a) Particulates (unspecified)	3.5E+09	9.4E+06	372
(s) Oils (unspecified)	2.5E+01	1.3E-01	195
(w) Metals (unspecified)	3.3E+05	8.0E+03	41
Sand	2.2E+07	9.1E+05	24
(a) Zinc (Zn)	2.9E+02	1.3E+01	22
(w) Halogenated Matter (organic)	8.3E-06	4.0E-07	21
Waste (total)	1.9E+05	9.8E+03	20
Raw Materials (unspecified)	1.2E+04	7.4E+02	16
(a) Aldehydes	1.9E+04	1.7E+03	11
(a) Particulates (PM 10)	1.5E+01	1.6E+00	10
(a) Chromium (Cr III, Cr VI)	1.2E+02	1.6E+01	7
(a) Dioxins (unspecified)	5.1E-04	7.8E-05	7
(a) Furan (C4H4O)	2.1E-03	3.6E-04	6
(w) AOX (Adsorbable Organic Halogens)	2.1E+00	4.0E-01	5
(a) Arsenic (As)	4.9E+01	9.8E+00	5
(w) Acetic Acid (CH3COOH)	3.2E+00	6.5E-01	5
(a) Ethylene Dichloride (C2H4Cl2)	9.4E-01	1.9E-01	5
(a) Vinyl Acetate (C4H6O2)	1.8E-01	3.6E-02	5
(a) Isophorone	1.4E+01	2.8E+00	5
(a) Di(2-ethylhexyl)phthalate (DEHP, C24H38(	1.7E+00	3.5E-01	5
(a) Ethyl Chloride (C2H5Cl)	9.9E-01	2.0E-01	5
(a) Methyl Bromide (CH3Br)	3.8E+00	7.6E-01	5
(a) Chloroacetophenone (2-C8H7ClO)	1.6E-01	3.3E-02	5
(a) Benzyl Chloride (C7H7Cl)	1.6E+01	3.3E+00	5
(a) Methyl Chrysene (5-C19H15)	5.2E-04	1.0E-04	5
(a) Chlorobenzene (C6H5Cl)	5.2E-01	1.0E-01	5
(a) Methyl Hydrazine (CH6N2)	4.0E+00	8.1E-01	5
(a) Diphenyl ((C6H5)2)	4.0E-02	8.1E-03	5
(a) Methyl Methacrylate (CH2C(CH3)COOCH3	4.7E-01	9.5E-02	5
(a) Methyl Chloride (CH3Cl)	1.2E+01	2.5E+00	5
(a) Ethylene Dibromide (C2H4Br2)	2.8E-02	5.7E-03	5
(a) Bromoform (CHBr3)	9.2E-01	1.9E-01	5
(a) Dimethyl Sulfate (C2H6O4S)	1.1E+00	2.3E-01	5
(a) Chloroform (CHCl3, HC-20)	1.4E+00	2.8E-01	5
(a) Dinitrotoluene (2,4-C7H6N2O4)	6.6E-03	1.3E-03	5
(a) Acrolein (CH2CHCHO)	6.8E+00	1.4E+00	5
(a) Propionaldehyde (CH3CH2CHO)	8.9E+00	1.8E+00	5
(a) Methylene Chloride (CH2Cl2, HC-130)	6.8E+00	1.4E+00	5
(a) Acetophenone (C8H8O)	3.5E-01	7.1E-02	5
(a) Carbon Disulfide (CS2)	3.1E+00	6.2E-01	5
(a) Trichloroethane (1,1,1-CH3CCl3)	4.7E-01	9.5E-02	5
(a) Tetrachloroethylene (C2Cl4)	1.0E+00	2.0E-01	5
(a) Methyl Ethyl Ketone (MEK, C4H8O)	9.2E+00	1.9E+00	5
(a) Benzo(bjk)fluoranthene	2.6E-03	5.2E-04	5
(a) Cumene (C9H12)	1.2E-01	2.5E-02	5
(a) Methyl tert Butyl Ether (MTBE, C5H12O)	8.2E-01	1.7E-01	5
(a) Cyanide (CN-)	5.9E+01	1.2E+01	5
(a) Styrene (C6H5CHCH2)	5.9E-01	1.2E-01	5
(w) Fluorides (F-)	2.4E+02	5.1E+01	5
(a) Manganese (Mn)	8.8E+01	1.9E+01	5
(a) Beryllium (Be)	5.0E+00	1.1E+00	5
(a) Cadmium (Cd)	5.9E+00	1.3E+00	4
(a) Fluorene (C13H10)	2.2E-02	5.1E-03	4
(a) Selenium (Se)	3.3E+01	7.4E+00	4
(a) Hydrocarbons (unspecified)	8.6E+05	2.0E+05	4
(a) Fluoranthene	1.8E-02	4.2E-03	4
(a) Phenanthrene (C14H10)	6.6E-02	1.6E-02	4
(a) Acenaphthylene (C12H8)	6.0E-03	1.4E-03	4
(a) Nickel (Ni)	1.8E+02	4.4E+01	4