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LCA OF WASTE MANAGEMENT SYSTEMS

Teaching life cycle assessment in environmental engineering: a disinfection case study for students

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Abstract

Purpose To help educators increase the extent and effectiveness of integrating sustainability into undergraduate education, a case study in life cycle assessment (LCA) is developed and presented using the context of disinfection of wastewater.

Methods Design and operating parameters are presented for three alternatives: chlorine/sulfur dioxide, ultraviolet (UV) light, and sodium hypochlorite/sodium sulfite. The case study includes student learning objectives, design assumptions, system boundaries, supporting calculation files, descriptions of LCA simulation scenarios, expected simulation results, and interpretation. LCA simulations, using the ISO methodology approach, are performed with varying assumptions about design flows, study duration, electricity fuel mixes, an alternative LCIA methodology, and weighting scenarios. Results are presented primarily at the midpoint level, and the effects of weighting are illustrated using a ternary plot. Life cycle costing is performed by calculating net present worth cost of construction materials and selected ongoing operation and maintenance costs.

Results and discussion After interpreting simulation results, students should be able understand and apply several LCA skills including identifying significant impact categories, describing tradeoffs between different life stages, identifying "hot-spots" in the life cycles, illustrating the impacts and limitations of weighting, and observing differences across LCIA methodologies. Using the assumptions herein, chlorine disinfection results in larger initial impacts due to the larger basin required for hydraulic retention time (HRT), but operating impacts associated with electricity consumption cause the UV impacts to overtake those of the chlorine alternative. The results are sensitive to the LCIA method, the electricity grid's fuel mix, and the electricity consumed per unit of wastewater disinfected. Finally, consideration of non-environmental and non-cost factors (risk, safety) provide students with an opportunity to reflect on broader societal impacts.

Conclusions Adaptable for various audiences and to provide differing levels of technical rigor, the case study should aid students in understanding and becoming proficient in performing LCA to facilitate life cycle thinking. It is the author's hope that by providing a transparent, comprehensive LCA case study comparing engineering alternatives, educators can better integrate life cycle thinking and systems thinking into engineering curricula.

Keywords Life cycle assessment · Teaching LCA · Undergraduate education · Engineering · Wastewater disinfection · Chlorine · UV · Hypochlorite

1 Introduction

1.1 Background, aims, and scope

Integrating sustainability into undergraduate education and engineering programs is a current trend and a necessary step to train professionals who can envision, design, create, and maintain more sustainable societies (Boyle 2004). It also transcends several of the US National Academy of Engineering's

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Grand Challenges (NAE 2008). Unfortunately, "integrating" sustainability into a curriculum may begin by only requiring one course in environmental science or environmental engineering, or it may only take the form of training or certification in sustainability metric systems such as LEED and Envision^{TM}. Such approaches will likely fail to capture the full needs of sustainability, broadly defined by Mihelcic et al. (2003) as "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment." In contrast to the approach of requiring a single course, more rich experiences involving life cycle thinking and systems thinking must be codified into the broader perspectives of today's students. Curricular transformations to achieve these integrated experiences are in progress at many institutions in the USA (Murphy et al. 2009) and around the world. As these transformations are refined and reach maturity, then, as described by Wood (2012), "If systems literacy translates into a worldview and way of life, then sustainability is possible."

To develop this systems literacy and life cycle thinking, undertaking a life cycle assessment (LCA) of an engineering project or projects is a particularly useful experience for university students. While current LCA tools are largely limited to environmental impacts, benefits of using LCA to introduce life cycle thinking are numerous. Students learn to give consideration not just to current and future design criteria (drinking water demand, source water quality, wastewater flows and loads, population projections) but also to operation and maintenance, inputs of material and energy (electricity, chemicals, transportation), end-of-life scenarios (project decommissioning, recycling of materials), geographic specificity (local materials, regional fuel mixes, etc.), and other factors. Teaching LCA opens the door for expanded thinking to include life cycle costing (LCC) and social LCA (SLCA), which can be incorporated to connect their learning to economic and social pillars of sustainability, as well. Students begin to understand the open-ended nature of problems in contrast to the engineering problem solving (EPS) mindset that is limited to "givens, assumptions, and calculations," which can be a misleading representation of actual challenges facing society. For instance, a transportation engineering project may seem to be driven by the need to build a road, where instead, the need could more accurately be described as the need to transport people and goods in a certain manner and pattern. The latter mindset opens up many alternatives besides the business-as-usual commuter roadway. In this manner, engineering transitions from "problem solving" to "problem definition and solution," as described by Downey (2005).

Options for teaching life cycle assessment range from conceptual discussions of the process all the way through advanced computational tools processing tens of thousands of energy and material flows. In teaching life cycle thinking and LCA, consideration should be given to the following questions: Is the goal to teach students a software tool for performing LCA? Or, is the goal to teach students the structure and process of LCA, which can be applied broadly across multiple LCA tools? The answer may be somewhat dependent upon the audience, the time available to spend in the endeavor, and students' previous understanding of LCA. The topic of this article assumes the ability and desire to achieve both goals, but priority is always given to the second. Being able to understand and apply the process of LCA, including the nature of LCI databases and the methods of LCIA classification, characterization, and normalization, are more important as learning outcomes than mere proficiency in one or more software tools. The process of learning LCA can occur largely in the absence of any software tools other than those publicly available for free, as discussed later. However, due to the size of many LCI databases combined with the complexity of engineering projects, a comprehensive LCA experience is greatly benefitted by the use of a computational tool.

One previously identified barrier to furthering the incorporation of LCA into curricula is the lack of well-developed examples (Smith Cooper and Fava 2000). This article describes one example case study that can be used for teaching LCA: the disinfection of secondary effluent wastewater prior to discharge into a surface water receiving stream. The author has used this example for 3 years in a class entitled Sustainability Principles for Engineers. Students learn the ISO methodology for LCA and gain experience applying three LCA-related tools. Alternative LCA methodologies, such as economic input–output (Hendrickson et al. 1998) and hybrid LCA (Suh et al. 2004), are introduced but only briefly due to time limitations, and no active exercises are assigned using those frameworks. Enrolled students have come from multiple class levels ranging from sophomores to second-year M.S. graduate students. To date, all participants have been engineering students, the majority within civil and environmental engineering but also some from mechanical and chemical engineering programs. The case study illustrates many aspects of the process of LCA and is well suited to capitalize on the power of advanced software tools, if available, to create opportunities for advanced interpretation, parameterization, and sensitivity analysis. The paper presents the case study itself, its associated LCA learning objectives, information that is given to the students, possible assignments/tasks, and expected results that illustrate answers to different life cycle questions. The case study is framed as a narrative with all supporting assumptions and calculations included (most in the Electronic Supplementary Material, "ESM") in the hope that it can be tailored or modified to fit specific audiences with unique backgrounds with or without software tools.

1.2 Learning objectives

Table 1 provides a list of learning objectives from which the instructor/adviser can draw in teaching LCA through the use of this example. In the course described here, the author and colleagues spend approximately 4 weeks on LCA, meeting 4 h per week. Early LCA sessions are spent on conceptual topics followed by progressively more advanced tools for performing LCA: examining the US Life Cycle Inventory (LCI) database (National Renewable Energy Laboratory, NREL) and the European Life Cycle Database (ELCD), working with the Building for Environmental and Economic Sustainability (BEES) tool from the National Institute of Standards and Technology (NIST), EcoCalculator (Athena Sustainable Materials Institute, Ottawa, Ontario), and ultimately working in SimaPro (Pré Consultants, Amersfoort, Netherlands; Earthshift, Huntington, VT, USA). The remainder of the article is organized loosely around this structure of learning objectives.

1.3 Target audience and level of complexity

With regard to the audience for the case study, the level of complexity and the tasks assigned can be easily adjusted based on the level of the students, as described in Table 2. For example, if students are new to both LCA and to the content of the example (wastewater treatment and/or disinfection), a small amount of time can be spent orienting them to the topic(s), followed solely by a demonstration of the LCA simulations with emphasis placed on the tradeoff between initial impacts associated with larger capital facilities and ongoing impacts of operation. In this manner, the author has presented LCA examples during one-class sessions in other fields (courses of 12–24 students in management and environmental studies), with positive feedback from both students and other instructors. It is recommended that defining a functional unit be taught even at this most introductory level, due to its importance in LCA. Moving beyond introductory audiences, for intermediate-level students with a working knowledge of wastewater treatment but limited design skills, a working LCA model can be provided to them for experimentation and for varying parameters to illustrate changes in LCA results at both midpoint and endpoint levels. Finally, for graduate students or undergraduates with advanced design experience, the raw design criteria can be presented for them to use in designing the capital facilities and building the LCA model, followed by advanced simulations with parameterization of variables and life cycle costing. At Bucknell University, in a combined course with sophomores in the environmental engineering major and juniors and seniors in the civil engineering major, a combination of levels 3 and 4 is targeted in a 1-week assignment, following several (3–4) prior weeks of reading, instruction, and activities in LCA concepts. The class size has ranged from 13 to 23 students and typically meets twice per week for 2 h each meeting. Sessions devoted to LCA work are held in computer laboratories either with each student having their own workstation or at most two to a computer.

Table 1 Example learning objectives for teaching LCA, organized by the steps outlined in ISO methodology plus systems-level objectives

Goal and scope definition

1. Define and describe the concept of an LCA[a]
2. List the four components of an LCA as specified by ISO[a]
3. Define an appropriate functional unit and system boundary for a product or service[a, b]

Life cycle inventory (LCI)

4. Describe what information constitutes a life cycle inventory (LCI)[a]

Life cycle impact assessment (LCIA)

5. Learn to classify LCI flows into appropriate impact categories (midpoints) and damage categories/areas of protection (endpoints)[a, b]
6. Apply characterization factors to LCI flows to convert impacts into one unit per category[a]
7. Describe the normalization process of an LCA, in which midpoint or endpoint measures are aggregated into comparable units[a, b]

Interpretation

8. Given a graph or figure showing LCA results, interpret an LCA in order to:[a, b]
    a. Achieve the specified goal of the LCA, possibly including making recommendations
    b. Identify the life stage(s) that contribute most to impacts
    c. Identify the process and material flows that contribute the most to impacts
9. Understand the power and limitations associated with weighting impacts in an LCA[b]
10. Interpret the effects of weighting using graphical methods such as a ternary plot[b]
11. Describe differences between egalitarian, hierarchist, and individualist perspectives in some LCIA methodologies[b]
12. Apply parameterization for rapid sensitivity analysis[b]

Systems thinking

13. Apply engineering economics to achieve life cycle costing[c]
14. Discuss social/societal implications of different alternatives in an LCA[c]

[a] Learning objectives that the author typically teaches prior to introducing the example described in this article

[b] Learning objectives addressed through the use of the example described in this article

[c] Recommended additional learning objectives to incorporate economic (LCC) and social (SLCA) perspectives

Based on those intended student audiences, the audiences for this manuscript are intended to be those engaged in courses similar to those described above. The case study could be

Table 2 Level of detail appropriate for varying audiences

Student background	Information to provide	Tasks to assign
1.Non-technical students	Demonstration only—summary of the case study and its alternatives	Define functional unit in groups Demonstrate simulation and results Perform interpretation as group activity
2.Introductory technical students: little to no background in engineering design	Completed design parameters Working LCA model Fixed parameters (flow, electricity demand, design life)	Define functional unit Perform LCA simulations for scenarios 1 and 2 Interpret LCA results at midpoint level
3.Intermediate technical students: some engineering background but limited design	Completed design parameters Working LCA model Ability to vary parameters (flow, electricity demand, design life)	Same as above, plus: Perform LCA simulations for scenarios 1–6 Interpret LCA results at midpoint and endpoint levels
4.Advanced technical students: senior undergraduates or graduate students with design background	Basis of design No working LCA model Ranges of parameter values Parameter distributions (advanced)	Design disinfection facilities (tank sizes and chemical/ electricity requirements) Create LCA models in software Perform LCA simulations for all scenarios Interpret LCA results at midpoint and endpoint levels Evaluation of uncertainty impacts Switch to “consequentialist” LCA Conduct LCC and qualitative SLCA

adapted by the adviser of a senior design project team, delivered in community college and engineering technology programs, and, as mentioned previously, condensed into a one-lecture demonstration for students in any field of study. An attempt has not yet been made to adapt the case study for high-level K-12 education, but the possibility remains. Beyond the case study, it is hoped that this manuscript can provide value to any instructor considering teaching LCA and life cycle thinking, by encouraging thoughtful development of learning objectives, a flexible context in which multiple scenarios can be explored, and consideration of economic and social factors, as well.

2 Methods

2.1 Description of case study

The case study is framed around the need to disinfect nitrified secondary effluent wastewater prior to discharge in order to limit the occurrence of pathogens in receiving waters; this is the defined “function” of multiple alternatives within the case study. A developed/industrialized society is assumed with centralized wastewater treatment, access to electricity and chemicals, and a regulatory structure such as that in the USA (secondary treatment standards). Designing an engineered system to achieve this function with narrow system boundaries would involve identifying design average and peak flows, reviewing applicable regulatory standards, and performing calculations for sizing basins, addition of chemicals, and electricity requirements.

Three alternative systems are offered to students for consideration: chlorine disinfection followed by sulfur dioxide dechlorination, ultraviolet light, or sodium hypochlorite disinfection followed by sodium bisulfite or sodium sulfite dechlorination. These three alternatives exhibit unique characteristics at different life stages, as illustrated in Table 3. Hence, they are ideally suited for illustrating life cycle impacts throughout their design lifetimes.

2.2 Base calculations and assumptions

Pertinent design assumptions and parameters are displayed in Table 4. For the reader’s use in implementing this case study, additional calculation materials are provided in the electronic supplementary material in both spreadsheet format (MS Excel, Microsoft, Redmond, WA) and in the form of portable document format (pdf, Adobe Systems, San Jose, CA) created from Mathcad (PTC, Needham, MA). Some of the parameters are later varied in LCA scenarios, and the user can adjust any of them as desired to tailor the case study to specific needs. For chlorine basin sizing, redundancy is not included in the chlorine system (only one process train is assumed), whereas the UV system includes two channels. Again, these calculations can be modified as needed depending on the level of the students’ design abilities.

2.3 Goal and scope definition: defining functional unit and system boundaries

In the author’s experience, defining LCA functional units proves to be challenging for undergraduate students new to LCA. For instance, in comparing a re-usable ceramic mug against a disposable Styrofoam cup as options for daily morning coffee, the temptation to compare one mug versus one cup is difficult to overcome (despite the longevity of a ceramic mug measured in years). Students are guided to a more

Table 3 Disinfection alternatives and relative life stage input requirements

Disinfection alternative	Initial construction materials	Operational chemical requirements	Operational energy requirements
Cl_2/SO_2	High	High	Low
UV	Low	Low	High
$NaOCl/NaHSO_3$ or Na_2SO_3	High	High	Low

appropriate functional unit of "the ability to contain 8 ounces of a hot beverage, used once per day over a period of five years" (adapted from Ligthart and Ansems 2007). As a second example, in asking students to define a functional unit in an LCA comparing incandescent, compact fluorescent, and LED light bulbs, students often include in their answers "the number of kWh" or "g of CO_2 emitted," both of which are LCI flows. For that example, students are guided towards "the

Table 4 Design parameters and assumptions for disinfection alternatives

Parameter	Value
Design average flow, mgd	8
Flow peaking factor, unitless	3
HRT at peak flow, min (for chemical disinfection)	15[a]
Chlorine dose, mg/L	6[a]
Chlorine residual requiring dechlorination, mg/L	2
SO_2 dose/chlorine residual ratio, mg/L per mg/L	0.9
Na_2SO_3 dose/chlorine residual ratio, mg/L per mg/L	1.6[b]
Chlorine tank aspect ratio (length/width)	Approx. 10:1
Specific gravity of concrete	2.4
Reinforcing steel type/spacing on center	No. 4 bars at 12-in (30.5 cm)
Unit weight of reinforcing steel, lb/ft (kg/m)	0.668 (1.0)
Slab, wall thickness, in. (cm)	18, 12 (45.7, 30.5)
Chemicals required per unit volume treated, kg/(d-mgd)[c]	
Cl_2	22.7
SO_2	6.81
NaOCl	22.7
Na_2SO_3	12.1
Electricity required per unit volume treated, kWh/(d-mgd)	
Cl_2/SO_2	0
UV	94.6 (0.025 Wh/L)[d]
$NaOCl/NaHSO_3$	8.95
Design life	25 years
Power grid	US NERC region RFC (2008)
UV system materials[e], kg	
304 (18/8) stainless steel[f]	144.5
Glass	99.9
Steel, low-alloyed, hot rolled	60.6
Aluminum, primary molten	9.1

[a] GLUMRB (2014), Ch. 100 Disinfection

[b] Metcalf and Eddy (2003)

[c] Mass of active chemical required, as opposed to mass of solution including dilution water (e.g., for NaOCl)

[d] Estimated from multiple sources (Lee et al. 2012; Young 2008; Dabkowski 2012)

[e] Lee et al. (2012). Scaled down linearly from 100,000 m^3 /day to 8 mgd

[f] All SS (304 and 316) assumed as 18/8 SS (18 % Cr, 8 % Ni), with life cycle as described in Classen et al. (2009)

ability to provide indoor light sufficient for reading (or at an intensity of a certain number of lumens), for four hours per day over 10 years…" or "…for a total of 10,000 hours," etc. As a result, some instruction and practice in defining a functional unit is warranted for all audience levels, and it is helpful for students to begin all functional units with the phrase "the ability to…."

ISO methodology suggests a functional unit should have a magnitude, a duration, and qualitative descriptors. For this disinfection case study, a suggested functional unit is: "The ability to disinfect nitrified secondary effluent wastewater at an 8 million gallon per day (mgd) facility for 25 years sufficient to meet secondary discharge standards in the United States…" The instructor can tailor this with more or less detail sufficient for the audience (e.g., adding a peaking factor to guide design of the basin sizes), but students should be able to develop this skill in defining a functional unit.

The system boundaries in this example include selected materials for the upfront construction (concrete and reinforcing steel for all alternatives and an approximation of the material makeup of the UV equipment from Lee et al. (2012)), chemical inputs for the chemical alternatives, and electricity for the UV alternative. Because the system boundaries in this case study are influenced by the LCI(s) available to students, they are discussed below in the LCI section. Students can be asked to draw the system boundaries for the alternatives, or they can be provided to them. One reason for the choice of ISO methodology in this case study is the challenge students have in defining functional units, as discussed earlier. Certain elements, such as transportation of chemicals in two of the alternatives, are excluded from the system analyzed but may not be negligible. Alternative methods for addressing this inequality across alternatives could be introduced. However, with significant effort expended on the gateway task of defining the functional unit, addressing more advanced system boundary definitions using EIO-LCA or hybrid approaches would complicate the topic considerably and is probably best served in a follow-up second course of study.

2.4 Life cycle inventories

Depending on access to LCI data and software, the system boundaries will vary with regard to what is included. If a comprehensive tool such as SimaPro is available, including unit-level processes such as those in the ecoinvent database, system boundaries will be vast, extending back to raw material extraction and encompassing peripheral processes (roadways, fuel used in transportation, etc.). Without such access, the instructor may need to draw upon selected LCI flows (such as greenhouse gases, particulate matter, etc.) from the US LCI database or ELCD, recognizing the geographic specificity of each. The latter database is more extensive and detailed. System boundaries for the alternatives in this case study are illustrated in Fig. 1. Since primarily ecoinvent LCI entries were used in the case study and sodium bisulfite ($NaHSO_3$) was not available, sodium sulfite (Na_2SO_3) was used.

2.5 Life cycle impact assessments

Several learning objectives related to LCIA (classification, characterization, and normalization) are achieved by having the students perform LCA simulations. For understanding classification, the students must have some background in environmental phenomena such as understanding that CO_2 is a greenhouse gas (GHG) impacting climate, and that $PM_{2.5}$ is a respiratory hazard impacting human health. For non-technical audiences,

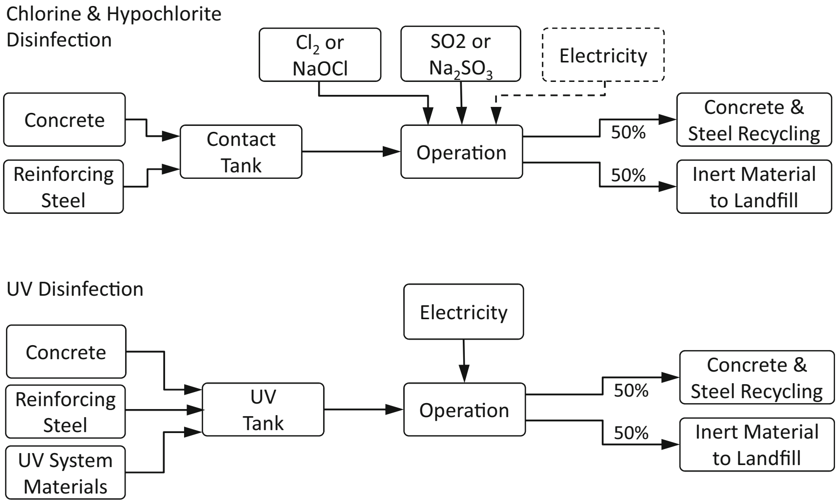


Fig. 1 System boundaries for disinfection alternatives. Electricity for Cl_2/SO_2 is assumed to be negligible and is not included but is included for $NaOCl$/Na_2SO_3 and UV

the analysis can be limited to a few selected impact categories such as these two. For understanding characterization, the global warming potential (GWP) of GHGs provides the simplest example, converting CO_2, CH_4, and N_2O into CO_2 equivalents (CO_{2eq}). Non-technical audiences are often familiar enough with the climate impacts of the first two of these and possibly also their relative 100-year GWP values. [For example, $CH_4 = \sim 25 \times CO_2$ in IPCC AR4 (Forster et al. 2007), now 28 × or 34 × CO_2 in AR5 without or with climate carbon feedback, respectively (Myhre et al. 2013).]

2.6 LCA model formulation and simulations

The LCA models used in this example were constructed in SimaPro 8.04.26, Multi-User educational version (PRé Consultants, Amersfoort, Netherlands; Earthshift, Huntington, VT, USA) using the NREL US LCI and ecoinvent 3 LCI databases. For the ecoinvent data, inputs were limited to the "Allocation, default" databases at the unit level (as opposed to the system level). While system level LCI flows decrease simulation time, the LCA model described here is relatively simple, and interpretation at levels 3 and 4 (Table 2) intended for technical students requires the ability to drill back to individual unit processes in order to track specific material and energy flows and attribute them to specific processes and/or life stages. Unit-level LCI allows this level of interpretation, and simulation times are quite reasonable (~10 min for the first simulation, <30 s for all subsequent simulations, assuming a 10Base-T or greater Ethernet network connection to the database server). Furthermore, this provides an opportunity to instruct students on the differences between unit level and system level LCA formulation.

In the LCA models, concrete was converted from a volumetric basis to mass basis to facilitate its accounting in waste handling scenarios. Waste scenarios were constructed to allow for 50 % recycling of both concrete and reinforcing steel at the end of life, with the remainder of material going to landfills as inert material. However, no credit for avoided products is included for the recycled materials; rather, only the avoidance of disposal is accounted for in the scenario described. For the baseline scenario, electricity was selected from the National Electric Reliability Corporation (NERC) region where Bucknell University is located (RFC). The US LCI electricity fuel mixtures included in SimaPro version 8.04 is the 2008 data. Table S.1 (Electronic Supplementary Material) presents information to aid in constructing the material processes, assemblies, and product stages used in the case study. The IMPACT 2002+ LCIA methodology (Jolliet et al., 2003) was selected because it has both midpoints and endpoints and the documentation is reasonably appropriate as a reading assignment during the course.

3 Results and discussion

The following LCA scenarios illustrate life cycle impact differences between the disinfection alternatives. It is recommended that, up through scenario 5, only the Cl_2/SO_2 and UV alternatives be compared. Once the students are comfortable with the process, the third alternative ($NaOCl/Na_2SO_3$) can be added. For each scenario, the assigned task is stated in italics, the expected results are discussed and referred to in associated figures, and finally a brief summary of that task's unique learning opportunities is provided.

3.1 Scenario 1: upfront construction materials only

Perform the LCA using just the upfront construction. Do the results appear as expected? The purpose of this scenario is twofold—to illustrate an intuitive result and also to set the stage for comparison with scenario 2, which is termed the "baseline scenario." Regulatory requirements specify 15 min of HRT for disinfection with a chlorine-based chemical, whereas UV disinfection is nearly instantaneous by comparison. Hence, the LCA impacts of capital facilities for chlorine disinfection are significantly greater than for UV, the latter of which only requires basin volume sufficient to contain the lamp modules; the materials of the UV equipment itself are less significant than the concrete and reinforcing steel. Based on normalized results at the midpoint level, students can identify the three impact categories that are most significant in the analysis: respiratory inorganics, global warming, and non-renewable energy depletion (Fig. 2a). While it is noted that the authors of the IMPACT 2002+ LCIA methodology do not recommend presenting normalized results at the midpoint level, due to the implicit 1:1 weighting inherent in such an approach (Jolliet et al. 2003), the author's experience in teaching LCA suggests this approach is helpful when students are first introduced to LCA and are attempting to identify significant impact categories. The author is careful to articulate to the students the value judgment of equal weighting inherent in this approach.

By inspecting the results, students can either brainstorm explanations for their observations or drill back into the contributions of individual unit processes. Given that the only material inputs are concrete, reinforcing steel, and UV system materials, some students may realize or be able to determine through research that cement and aggregate manufacturing requires input of energy and generates particulate matter emissions. Hence, they can incorporate this into their interpretation and recommendations: opportunities for reducing the life cycle impacts can be realized by minimizing concrete with common-wall construction, improving control of particulate emissions during manufacture of ingredients, or reducing energy input embodied in concrete. Furthermore, a more complete analysis of the construction scenario can be achieved by

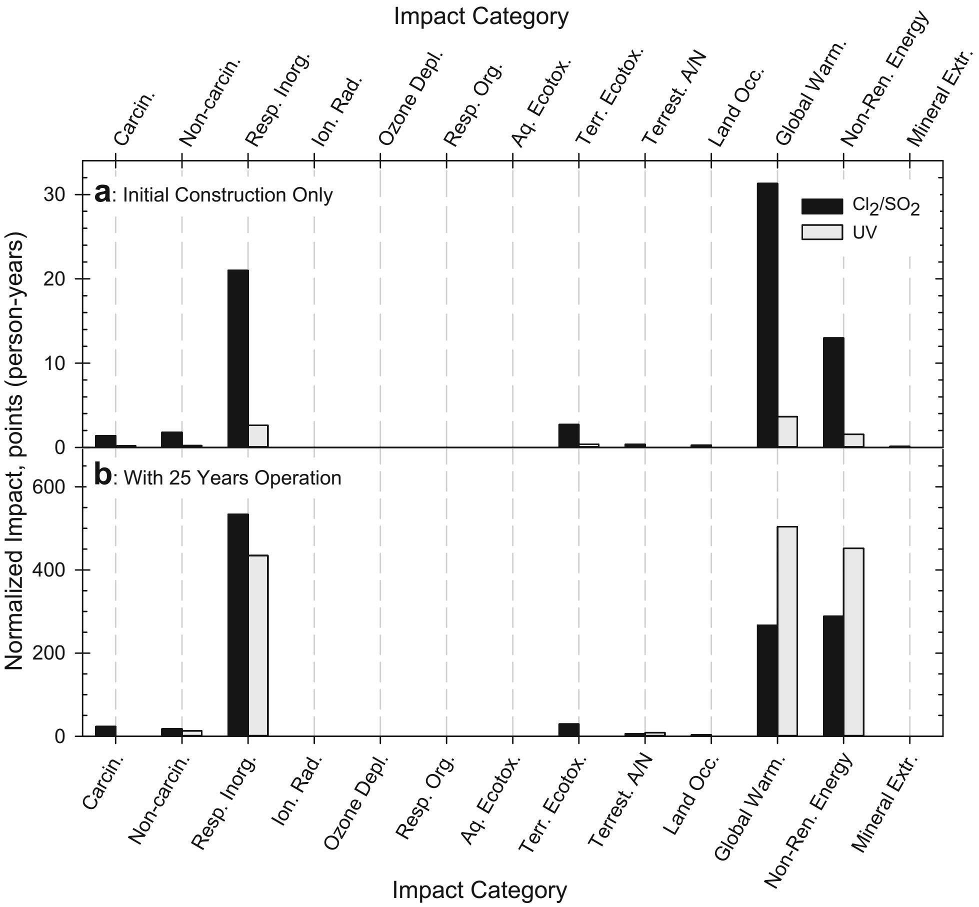


Fig. 2 LCA midpoint results for initial construction materials only (**a**) and baseline case: entire 25-year life cycle (**b**). LCIA methodology is IMPACT 2002+ V.2.1 v.1.02. Refer to the ESM for full names of impact categories

extending the system boundaries to include transportation of materials to the site, site work, etc., if desired by the instructor and/or within the capabilities of the students.

3.2 Scenario 2 (baseline): chlorine/sulfur dioxide and UV, 25-year design life

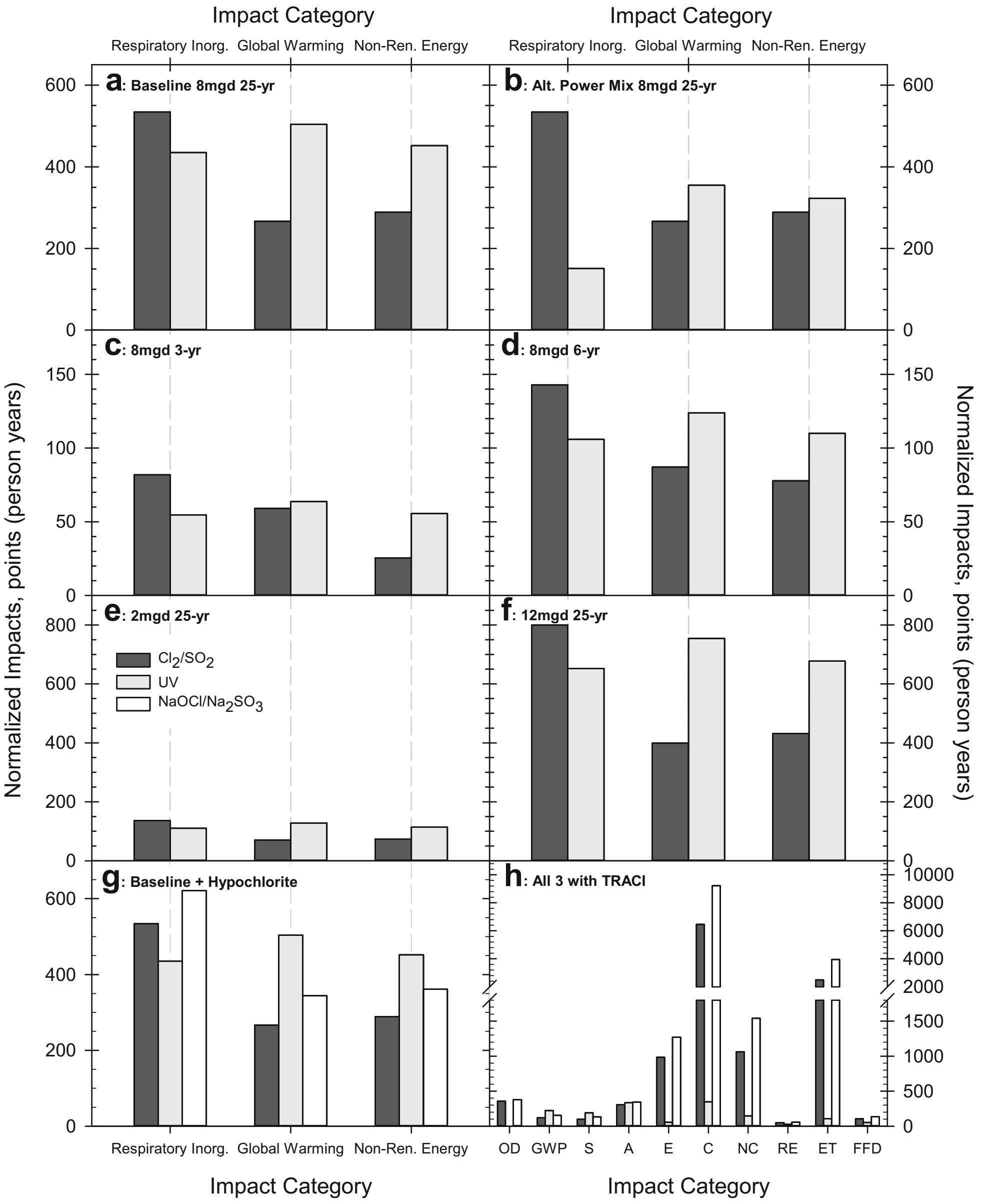
Perform the LCA including both initial capital facilities as well as operating and end-of-life impacts for a 25-year life. Present normalized results at the midpoint and endpoint levels and interpret the results. The results from this scenario illustrate the tradeoff between up front, initial impacts, and those realized over the operating phase of the life cycle. While the UV system has lower initial impacts, impacts associated with electricity consumption during operation more than compensate over the 25-year design life. Results shown in Fig. 2b.

Once again, students should explain their observations according to the intent of the course and the students' backgrounds. Knowing the electricity requirement, along with observing increased impacts in global warming and non-renewable energy categories suggest fossil fuel consumption and combustion for energy production cause these impacts. Hence, improvements in energy efficiency or upstream filtration to improve effluent transmittance could reduce energy inputs and lower environmental impacts for the UV alternative.

3.3 Scenario 3: alternative electricity fuel mix

Select an electricity unit process different from the one initially used. Evaluate the effect of fuel mixture (coal, natural gas, nuclear, renewables, etc.*) on the impacts observed in the LCA.* In this analysis, students should be encouraged to seek electricity grids with very different characteristics including both fossil-intensive and renewable-intensive fuel mixtures. With electricity comprising the majority of impacts for the UV alternative, the impact of fuel mixture is significant as can be seen from comparing Denmark's electricity grid, containing less coal and a larger fraction of renewables (Fig. 3b), with the more coal-intensive baseline US Region RFC (Fig. 3a). While the UV alternative still has higher impacts in two impact categories, the overall normalized single score that could be calculated shifts the outcome to the benefit of the UV alternative. The results of the analysis should contribute to the students' overall interpretation that the selection of the most favorable alternative can depend on the electricity fuel mix.

Fig. 3 LCA simulation results for scenarios 2 (panel **a**) through 7 (panel **h**) for significant midpoint categories. All scenarios use IMPACT 2002+ methodology except panel **h**, which uses TRACI v.2.1; TRACI impact categories are ozone depletion (*OD*), global warming potential (*GWP*), smog (*S*), acidification (*A*), eutrophication (*E*), carcinogens (*C*), non-carcinogens (*NC*), respiratory effects (*RE*), ecotoxicity (*ET*), and fossil fuel depletion (*FFD*)



3.4 Scenario 4: design life

Returning to the original electricity fuel mix, perform the LCA with only 3- and 6-year time horizons. At what point (in years) do the UV system's operating impacts negate any advantage it had in the beginning due to its lower capital impacts? At some point in the operating phase of the disinfection systems, the electricity consumption of the UV alternative causes its overall environmental impacts to surpass those of the chlorine system. By varying the operating lifetime, students can determine the point at which this occurs. Environmental impacts from these two operating durations can be seen in Fig. 3c, d. At approximately 5 years, depending on assumptions and LCIs used, the UV system's impacts appear to overtake those of the chlorine alternative. Students can even export numeric results obtained from different design life periods, perform linear regressions on the single score impacts versus time, and solve the two regressions simultaneously to determine the time at which the UV system's life cycle impacts overtake those of the chlorine system (approximately 4.9 years using these assumptions).

3.5 Scenario 5: design flow rate

Create design equations and parameters in your LCA to allow varying the design flow, using 2, 4, 8, and 12 mgd. Your model should scale both the tank construction materials as well as the chemical and electricity requirements.

Do the results of the LCA change substantially? This scenario requires either redesign of the concrete basin/channels or parameterization of the design flow and expressing the amounts of concrete, reinforcing steel, chemicals, UV equipment, and electricity as a function of the design flow. For the reader, these calculations can be found in the ESM, and a regression for each of these parameters as a function of flow rates has been developed. The instructor or the students can then use these equations to automatically scale material and energy inputs accordingly.

Relative LCA results do not change in this scenario as shown in Fig. 3e, f for 2 and 12 mgd, respectively; only the overall magnitude of the impacts increases or decreases with a concomitant change in flow. Perhaps the greatest value in this scenario is observing the value of parameterization in an LCA, as it facilitates rapid evaluation of many alternatives and scenarios without having to manually recalculate and change every design input. In subsequent engineering roles (graduate research, consulting, and design), this skill will serve students well.

3.6 Scenario 6: NaOCl/($NaHSO_3$ or Na_2SO_3) disinfection

Compare a third alternative—disinfection with sodium hypochlorite (liquid bleach). How does this new alternative compare with chlorine gas and UV disinfection? Incorporation of sodium hypochlorite for disinfection and either $NaHSO_3$ or Na_2SO_3 provides another alternative for comparison to the primary two options. Because $NaHSO_3$ was not available in the ecoinvent LCI, Na_2SO_3 was used in the case study. Results (Fig. 3g) indicate that impacts in all three significant impact categories are higher than those for Cl_2/SO_2 but follow the same trends. The author uses this scenario primarily to engage the students in discussions of non-environmental, non-economic factors. The conversion in recent decades of many chlorine gas-based disinfection systems to either UV or liquid bleach is driven by process safety and community safety considerations. Seemingly counterintuitive from the standpoint of the LCA results in Fig. 3g, students are asked to research the conversion from Cl_2 to NaOCl at DC Water's Blue Plains Advanced Wastewater Treatment Plant in 2001 following terrorist attacks in the USA. In this example, due to chlorine gas safety concerns in close proximity to the nation's capital, the utility completed a fast-track conversion from having six 90-t chlorine gas rail cars on-site to using liquid sodium hypochlorite for effluent disinfection (Hawkins 2011; Wastewater Treatment Works Security Act of 2006). This conversion was accomplished in 60 days (Hawkins 2011), a timeframe unheard of for a project of that scale. Through this exercise, students gain an understanding of and appreciation for the importance of non-cost, non-LCA factors in policy- and decision-making.

3.7 Scenario 7: vary selected LCIA methodology

Perform the LCA with a different methodology (use the North American TRACI model). Are there differences in the significant impact categories or in the preferred alternative? Students can observe the differences among LCIA methodologies by performing the same baseline analysis (plus hypochlorite alternative) with the North American LCIA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) (Bare et al. 2003; Bare 2011). Use of this second method allows students to examine the differences in number and types of impact categories included in different methods. A method from a different geographic region will also result in different normalization factors (TRACI = US factors v. IMPACT 2002+ = European factors) that can greatly impact the LCA outcomes (Fig. 3h).

Using TRACI, the most significant impact categories are somewhat different: carcinogens, non-carcinogens, and ecotoxicity dominate the impacts of chlorine and hypochlorite alternatives. Students can perform a network analysis on each alternative in these impact categories to determine the LCI flows/life stages that contribute to these categories. For instance, for Cl_2/SO_2, the primary life cycle component impacting all of those categories is the liquid chlorine supply chain. For hypochlorite, the health and ecotoxicity impacts appear to arise from LCI flows distributed throughout both chemicals' supply chains, including the manufacturing infrastructure; eutrophication impacts arise largely through the sodium hydroxide precursor chemical portion of the life cycle.

3.8 Scenario 8: illustrate effects of weighting

Choose three significant impact categories (midpoints), or use an LCIA methodology with three endpoints, and evaluate the effects of weighting on the outcome of the LCA. Illustrate these effects with a ternary plot. Because analysis of the case study with the IMPACT 2002+ model yields three significant impact categories, students can illustrate the effects of weighting on the LCA outcome using a ternary plot. Under the baseline scenario (2), only when non-renewable energy and global warming potential are weighted very low (less than approximately 30 % combined, corresponding to the lower right corner in Fig. 4) does the UV alternative have lower total impacts than the Cl_2/SO_2 alternative. The weighting evaluation is more accurately performed at the endpoint step. However, here (Fig. 4) it is shown with three midpoints, for continuity with the discussions above. Students should be encouraged to articulate these impacts and limitations in their interpretation of the LCA (learning objectives 8–10 in Table 1).

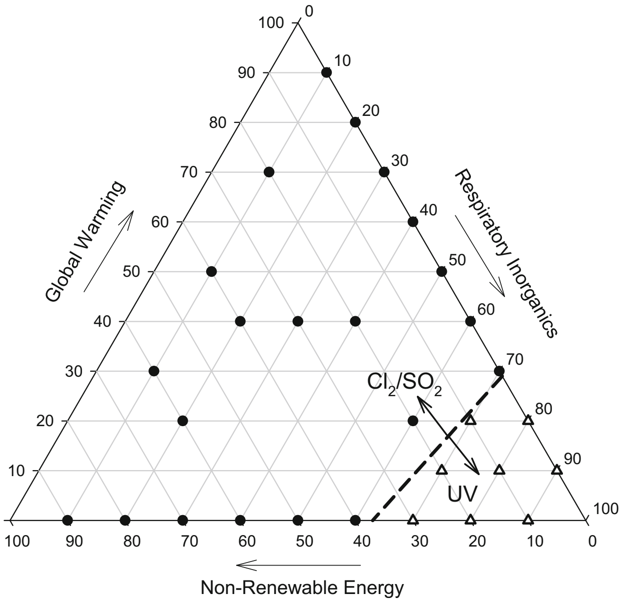


Fig. 4 Ternary plot illustrating the effects of weighting on determination of the lowest impact alternative. *Circles* represent weighting combinations where Cl_2/SO_2 has lower total (summed) impacts, and *triangles* represent weighting combinations where UV has lower total impacts, yielding the boundary shown with a *dashed line*. All axes in percent

Table 5 Example life cycle costing (LCC) results for disinfection alternatives

Cost component	Cl_2/SO_2	UV	$NaOCl/Na_2SO_3$
Capital costs[a]	\$284,000	\$447,000[b]	\$284,000
O and M costs[c]	\$48,500	\$28,200	\$110,000
Total costs	\$1,128,000	\$937,000	\$2,191,000

Results presented here should be considered an example only and should be modified using assumptions determined by the instructor and/or students

[a] Including concrete and steel (all alternatives) and UV equipment estimate (UV only). All alternatives are assumed to have a building of the same size associated with them, which is hence not included

[b] Includes \$400,000 estimate for UV equipment, estimated from Das (2002); see ESM

[c] $i = 3$ % per year, 25 years, assuming constant 8 mgd flow throughout, electricity = \$0.1019/kWh (EIA 2015)

3.9 Scenario 9: life cycle costing

Research costs for concrete, reinforcing steel, chemicals, and electricity and perform an engineering economic analysis, calculating net present worth costs associated with a 25-year life and a 3 % annual discount rate. Discuss the outcomes and compare them to the results of the LCA. Students who have had coursework in engineering economic analysis can be given or asked to research capital costs (e.g., RSMeans (2013) for concrete and reinforcing steel) and chemical costs in order to calculate net present value cost for comparing alternatives. With simplifying assumptions and costs (provided in the ESM; instructors are encouraged to find current and regional cost data for use), Table 5 illustrates a possible outcome of such an analysis. Using these LCC results in conjunction with the LCA results and non-cost, non-environmental factors (such as the safety and risk considerations discussed earlier), students can formulate recommendations as to the most desirable alternative by considering multiple facets of sustainability.

3.10 Interpretation and recommendations

Finally, make a recommendation on which option should be selected. Your recommendation should be supported by the LCA results, and you should discuss any qualifiers or caveats, such as how the system should be operated, region specificity, economic or social factors, etc. In this summative exercise, students should draw upon the results discussed above. It is expected that students will be able to make a recommendation based on total environmental impacts and to articulate the tradeoff between initial impacts and operating impacts, the impact of electricity fuel mix, safety and risk considerations, LCC and weighting results if performed, and other factors. This task should be assigned as a written prose response and should be assessed based on the level of the students' abilities. If the case study is presented at the introductory levels in Table 2, the instructor can describe factors beyond the environmental impacts that influence the decision.

3.11 Opportunities for extending the analysis

The adaptability of this case study cannot be overstated. For instance, a scenario can be envisioned with reclaimed water reuse, facilitating an alternative of UV disinfection but also supplemental chlorination or chloramination for maintaining a disinfectant residual in the reclaimed water distribution system. The economic analysis can be expanded for more detail or for flow that increases linearly with time up to the design capacity being realized at 25 years. System boundary changes could be explored, along with the use of alternate LCA methodologies, especially if access to advanced computational LCA tools is limited.

The topics of variability and uncertainty are, at present, only briefly addressed in this case study and in the discussion of LCA in the engineering course described in this work. Parameter distributions (uniform, triangular, normal, lognormal, etc.) and their descriptors (minimum, maximum, mode, standard deviation, etc.) for LCI entries are observed where available and discussed but not varied or modeled. Studies have demonstrated the strong bias that ignoring uncertainty can impart on an LCA and the interpretation of its results (Sills et al. 2013), so these are certainly important topics for LCA practitioners. Detailed exposure and hands-on practice manipulating these parameters is warranted in a course where LCA is the primary topical content or in a follow-on course to the one described here.

With regard to audience, additional credit/rigor for graduate students in the course can be facilitated by asking them to research the content of the case study (LCA comparison of disinfection alternatives) in the peer-reviewed literature and comparing published results (Das 2002; Lee et al. 2012) to their own. Finally, assignments associated with the case study are ideal for use as direct or indirect assessment tools for the engineering accreditation outcomes associated with sustainability and contemporary issues.

4 Summary and conclusions

The author's experience using this case study in engineering courses has been strongly positive to date. The characteristics of the two primary alternatives (Cl_2/SO_2 and UV) are ideally suited to illustrate tradeoffs between initial and ongoing environmental impacts, and the electricity consumption of UV disinfection illustrates the sensitivity of environmental impacts to the electricity fuel mix. One strong advantage of this case study is its adaptability: audiences new to both the content (disinfection) and the LCA process can understand the tradeoffs between initial and operational impacts, and highly advanced audiences can take the case study from design criteria all the way through complete LCA and LCC. The content is even appropriate for a senior design project, which could include contract drawings and specifications for the selected alternative. In the author's course, this LCA module is followed up first by discussions of resource economics, using the most significant impact categories from the LCA to illustrate market externalities, methods for valuation, and policy tools for internalizing externalities. In this way, LCA provides the gateway to sustainability aspects beyond just those environmental. After resource economics, the course moves into systems thinking, in which causal loop diagrams (CLDs) are presented, and students construct CLDs related to the nitrogen and phosphorus cycles and humans' imposition on both. Finally, the course concludes with a module on societal development indicators, in which the students read and critique worldviews, and they abandon gross domestic product (GDP) per capita in favor of metrics that more appropriately quantify human well-being. Again, the LCA portion of the course in general, and this case study in particular, provides both the context and the framework of systems thinking to facilitate these concepts of economic and societal well-being. It is the author's hope that by presenting this case study here, and offering the supporting information and calculations (Electronic Supplementary Material), readers can implement this example as an effective tool for teaching life cycle/systems thinking and the process of LCA, so that future professionals may envision, design, and create more sustainable societies.

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