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Cradle-to-gate sustainable target value design: integrating life cycle assessment and construction management for buildings

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ABSTRACT

Building stakeholders cannot easily quantify the environmental impacts of buildings as they accrue during construction. The goal of this work is to demonstrate a method to measure and manage the cradle-to-gate life cycle environmental impacts by linking environmental targets with modern construction management methods, to enable buildings to meet sustainable target values (STV). In this work, a construction activity-based computational framework was developed to enable stakeholders to reliably and efficiently construct cradle-to-gate life cycle models capturing environmental impacts including carbon and energy associated with material extraction, manufacture, transport to site, and construction. These models allow stakeholders to measure and manage impact accrual so as to not exceed STVs; without this framework, construction managers and other building stakeholders do not possess adequate environmental management tools to deliver projects consistently at or below STV. Specifically, the components developed are: (1) time dependent impact accrual budgets during construction and (2) impact measurement during construction. These benchmarks are used to determine whether a specific project is above or below target values, similar to methods for cost and schedule variance analysis. Two case studies were used to test this framework. This integration provides a life cycle assessment (LCA) modeling platform for management of environmental footprint during construction.

1. Introduction

In the United States, the building sector is responsible for approximately 41% of primary energy consumption and 40% of greenhouse gas emissions, while also contributing to acidification, eutrophication, smog, and solid waste emissions (U.S. EIA, 2011). Despite environmental concerns associated with energy consumption and greenhouse gas emissions, the US Department of Energy (DOE) projects that primary energy consumption and greenhouse gas emissions associated with buildings are expected to grow by 13% and 6% by 2020, respectively (U.S. EIA, 2011). This increase is in stark contrast to the fossil fuel based reduction proposed by the Challenge in order to avoid expected average global temperature increases between 2.0 °C and 2.4 °C (stabilized atmospheric CO_2e between 445 and 490 ppm) (IPCC, 2007). Architecture2030's timeline, which starts with a 70% reduction in 2015 and reaches a 100% reduction in 2030, combined with the fact that 75% of the built environment in the US will be new or renovated in the next quarter century (Architecture2030, 2011), represents an opportunity to create a less environmentally impactful building infrastructure.

Environmental impacts associated with buildings accrue throughout the life cycle phases of material extraction, transport to site, construction, use, and demolition. The cradle-to-gate impacts associated with buildings – those from material extraction, manufacturing, transport to site, and onsite construction – are often ignored. This is due to poor measurement methodology availability and the fact that they have historically been outweighed by operational impacts. Because these impacts have constituted a smaller proportion of life cycle impacts, literature has focused on reducing operational impacts and emission of harmful substances to the environment. However, these cradle-to-gate impacts are nontrivial and become a larger percentage of a building's total life cycle impacts as the use phase impacts decrease due to more efficient systems, onsite electricity generation, etc. (Faludi and Lepech, 2012). In the case of net-zero operational energy buildings, the cradle-to-gate impacts can represent the majority of impacts (Theirs and Peuportier, 2012). Construction managers need to be included in the sustainability discussion so that these cradle-to-

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gate impacts are effectively managed and reduced (Shen et al., 2010). In order to create environmentally sustainable buildings, the impacts of buildings at each stage of their life cycle, not just operation but including cradle-to-gate, must be quantified.

In order to manage these impacts, the methodology must include both measurement and a standard or target by which to establish what is 'sustainable.' Sustainable target value (STV) design has been recently proposed by Russell-Smith et al. (2015a; 2015b). The STV design methodology requires setting targets for environmental metrics such as global warming potential and primary energy for the life cycle of a building and using the STV software to predict design performance relative to these targets. The cradle-to-gate research presented in this paper describes a methodology to construct a building to meet a sustainability target. It operationalizes STV design by providing a process by which to develop sustainability budgets (or targets) for construction and to measure and manage the actual environmental impacts accrual during construction.

This work leverages life cycle assessment (LCA) and pre-existing construction management and control techniques. Together, these tools can provide a robust tool for modeling, measurement, and tracking of environmental impacts during the construction phase of a building life cycle to meet STVs. Specifically, the research integrates LCA with construction management methods in order to facilitate prediction, budgeting and control of environmental impacts of building materials, transport, and construction. The goal of this work is the development of a method to set quantitative environmental cradle-to-gate budgets and to measure and manage the accrual of cradle-to-gate environmental impacts over the course of construction.

1.1. Sustainable target value (STV) design

STV design, which has been developed by Russell-Smith et al. (2015a; 2015b), provides a method to reduce the environmental impacts of buildings throughout their life cycle by setting targets for environmental indicators and giving design teams the tools to explore building design performance as early as the design phase. The targets are set based on the ecological limit state or carrying capacity of the earth as defined by science and policy experts. For example, the global warming potential (GWP) and primary energy targets are based on scientific analysis performed by the Intergovernmental Panel on Climate Change (IPCC). The ozone depletion potential (ODP) and potable water targets are based on the Montreal Protocol and United States Energy Policy Act of 2005, respectively. In short, if buildings are designed to meet the STV targets, these performance levels could theoretically be supported by the planet's resources indefinitely. The STV target-setting methodology is generalizable; STV targets can be established for any environmental indicator for which a limit state has been defined.

The STV methodology combines life cycle assessment (LCA) and target value design (TVD) to rapidly produce more sustainable building designs. By establishing site-specific sustainability targets, this STV research has demonstrated that buildings can be designed to perform at higher environmental standards than those designed without a target in place. Results show that STV design implementation yielded building designs that met or surpassed the target in terms of environmental performance. However, designing to a target does not guarantee actual performance at or below the STV. To actually deliver a constructed facility that meets the STV design requires tools and methods to measure and manage impact accrual in real-time. With current techniques, this environmental impact accrual measurement is not possible. As a result, cradle-to-gate impacts are often ignored or estimated. This work proposes and demonstrates a novel framework, adapting current construction management techniques and integrating LCA, to construct a facility with a verified impact accrual profile that delivers on STV design.

1.2. Life cycle assessment approach for analyzing building impacts

LCA is an internationally standardized method of accounting for all inputs, outputs, and flows within a process, product, or system boundary to accurately quantify a comprehensive set of environmental, social, and economic indicators (Cucek et al., 2012; Finnveden et al., 2009). It considers all of the phases in a process, product, or system's life, from raw material extraction, processing, transportation to site, installation, to use, removal, and recycling or disposing. For built environments, these different stages include the raw material extraction for the different assembly components of the building (i.e. limestone mining and calcination for cement), the manufacturing, transport to site, construction and installation, the building's operational life, maintenance and retrofitting, and at the end of life, its demolition.

The international framework for conducting an LCA prescribes four stages, which include (1) definition of goal and scope, (2) life cycle inventory (LCI) analysis, (3) impact assessment, and (4) interpretation (U.S. EPA, 2012; ISO, 2006a; ISO, 2006b). The definition of goal and scope stage establishes the intended application and audience (goal), as well as the functional unit (reference basis for calculating inputs and outputs), system boundaries and life cycle phases for analysis (scope). In the LCI analysis, the relevant inputs and outputs for a given product or system are identified and quantified throughout its life cycle. The impact assessment stage evaluates the magnitude and significance of the product's or system's environmental impacts based on the LCI analysis. Lastly, conclusions and recommendations are drawn from the results based on the two previous stages. The purpose of the interpretation is to identify the major burdens, impacts, and potential areas for impact reduction.

Numerous LCA studies have investigated the sustainability impacts of constructed facilities; to date, most have found that operational impacts dominate life cycle impacts (Gambatese and Rajendran, 2005). Junnila and Horvath (2003), Junnila et al. (2006) and Scheuer et al. (2003) found that for commercial structures, over 90% of life cycle energy consumption and the majority of carbon dioxide emissions stem from the use phase of the building. For residential structures, Keoleian (1993) found that most impacts occur during the use phase. In a comprehensive review of 16 other studies, Sartori and Hestnes (2007) found significant impacts throughout the life cycle of constructed facilities, with strong correlation between total life cycle energy consumption and operating energy consumption.

Yet, even as operational impacts have historically dominated building life cycle impacts, the cradle-to-gate impacts are not insignificant. Blanchard and Reppe (1998), Keoleian et al. (2001), and Faludi and Lepech (2012) have examined residential structures that use highly energy efficient materials and building operation technologies, and have found that such technologies push impacts from the use phase onto the material production and construction phases. As building operation becomes more efficient and net-zero energy use buildings become more mainstream, the relative percentages of embodied impacts of materials and onsite construction impacts will grow (Mequignon et al., 2013; Peuportier et al., 2013). Further, studies show that the embodied impacts increase for these net zero buildings due to factors such as increased insulation, material and manufacturing intensive PV panels, and specialized construction techniques required for novel systems (Gustavsson and Joelsson, 2010; Theirs and Peuportier, 2012). Construction produces large environmental impacts that need to be measured and managed (Bilec et al., 2007; Ochoa et al., 2002; Sharrard et al., 2007). The limited construction phase specific research has focused primarily on construction waste management and off road vehicle emissions (Franklin Associates, 1998). There is a need to further quantify the environmental impacts of onsite construction activity.

LCA has been demonstrated as a useful tool for products including buildings and has been found to be valuable for quantified environmental management and for isolating which components and phases are most impactful (Basbagill et al., 2013; Guinee et al., 1993; Jeswani et al., 2010). This paper introduces a LCA methodology that can be used to determine a building project's cradle-to-gate impacts and to quantify which materials and activities are most impactful. The goal is to enable not only measurement but also management of sustainability impacts during construction by tracking the impacts associated with individual construction activities. From a cost perspective, construction management and project control methods are well-established for monetary measurement and management. This paper presents a parallel method, for environmental impacts, combining methods of construction management and control.

1.3. Construction management and project control methods

In this study, construction management and project control methods form the basis of the methodology into which LCA and STV are integrated. Construction management and project control methods are well-developed and widely accepted for construction cost management (Barrie and Paulson, 1984; Carr, 1993; Clark and Lorenzoni, 1978; Rasdork and Abudayyed, 1991). Effective, ongoing monitoring is a basic requirement for tracking and managing cost, time, and quality on a construction project. Project control ensures progress by measuring actual completion of work and comparing it to planned work. Analysis of the project's underperformance in terms of schedule, price, and level of quality leads to updated forecasts, which signify the need to take corrective actions. Important components of effective project controls include the early (planning phase) definition of appropriate scope breakdowns, useful performance metrics, a management scheme for measuring and reporting of performance, as well as accurate performance forecasting (De Marco et al., 2009; Ritz, 1994).

Construction processes are modeled for costing, scheduling, and planning based on individual construction activities. A key first step is identification of these activities. The construction industry, distinct from many other industries, has well-designed methods for decomposing the complexity of major multi-year projects into fundamental work items and tasks for use in detailed cost and schedule tracking (Winch, 2002). In order to do this, a work breakdown structure (WBS) is created based on MasterFormat to serve as the basis for progress measurement (Jung and Woo, 2004). MasterFormat is a widely used standard in the construction industry in the United States and Canada to format specifications for construction contract documents. Once the WBS and activities have been established, a construction schedule is prepared based on an activity precedence network. Each activity is assigned a duration, and the resources necessary for its execution are allocated at the activity start time. The project must be monitored and actual progress compared to the pre-determined schedule in order to control it. Many methods exist for monitoring effort and work completion. These methods include direct contact with an observer at the site, employee time cards, feedback from time-lapse photography for estimating project completion, checklists, and bar charts (Abeid and Arditi, 2002).

Similar methods are transferrable to environmental impact control. Whereas tools for high fidelity environmental impact control and process monitoring are limited, economic cost controls are highly developed and form the foundation of current construction management and operation practices. Variance from budgeted costs or schedules, whether positive or negative, is managed by construction superintendents to effectively meet predetermined cost and schedule targets. In order to methodically manage the reduction of environmental impacts of built facilities, it is necessary to link environmental goals with modern activity-based construction management methods. Time dependent impact budgets (like cost budgets) provide the basis for such project control. Specifically, two components are used: (1) time dependent impact accrual predictions for the construction phase, and (2) actual impact measurement during construction. Predicted impact accrual is compared to actual impact accrual as a benchmark for whether the project is above or below expectations, similar to a cost and schedule variance analysis.

2. The framework: activity-based environmental management for STV

In this research, LCA is integrated with construction management schedule variance analysis in order to facilitate the construction of sustainable buildings and deliver constructed facilities that meet STV design goals. In parallel to creating predicted and measured cost curves with the goal of keeping the construction project under a specified monetary target, the new objective is to leverage these tools to create environmental impact accrual curves with the goal of keeping the project under a specified environmental target set using STV design. This methodology gives building stakeholders a basis for continuous management and environmental impact control throughout the construction process.

The scope of the LCA includes the inputs to and outputs from the building construction, beginning with the extraction of the raw materials needed to assemble the building and ending with the completion of the construction activities. As such, an accurate and meaningful quantification of impacts will depend on a detailed understanding of the construction activities. These activities, and their temporal order, are determined based on the construction schedule and the precedence network.

The construction schedule is used to determine the timing of system and material processes, which are inextricably linked to quantifiable environmental impacts. The LCI for each of these activities serves as the link between activity and impact. A given activity's LCI includes the material (including the processing actions to take raw material from extraction to finished product), any transportation systems to bring the materials to the construction site, and the construction processes involving equipment or material use onsite. Human laborers are not included as part of the construction activities inventories; their commute transportation system use and their lunch consumptions, among other examples of impact, are out of the scope. Electricity used for jobsite trailers and lighting are also excluded.

Performing the detailed LCI analysis for each of the individual construction activities in the schedule serves as the necessary precursor to evaluating their impacts. The materials and processes that make up each activity are determined. These materials and processes are then modeled in an LCA software tool (in this case Pre's SimaPro and the EcoInvent v2.2 database (EcoInvent, 2010)) as individual materials and processes, but grouped into construction activities for analysis. This process makes it possible to determine which activities are environmentally impactful. It is important to highlight this distinction, which represents a departure from typical LCA. The analysis presented herein groups materials and processes into activities within the LCI, so that they are fully integrated with activity-based scheduling and management used in construction. Further, this method allows for investigation into material and process pieces constituting the activities to make specific proactive substitutions to reduce impacts.

There are a variety of impact assessment methods for conducting the impact assessment of an LCA. For the purpose of this research, the EcoIndicator 95 method was used to compute values for target environmental indicators, which include global warming potential (GWP), primary energy consumption, acidification potential, eutrophication potential, and carcinogenic emissions. EcoIndicator 95 was chosen to allow direct comparison to several other building LCA studies that have used the EcoIndicator 95 method.

Once the activities have been evaluated for these indicators and before construction begins, the predictive curve of impact accrual over the construction phase can be created. This is shown in Fig. 1. This curve illustrates the forecasted impact accrual versus time and is called the budget impact line (BIL). This step involves linking activity scheduling with impacts to produce cumulative impact functions over time. This link was used to create activity-based construction environmental impact budgets. For each activity, it is assumed that the impacts accrue linearly over the completion of the activity. For instance if 100 MJ primary energy is associated with producing and placing concrete and the activity duration is 4 days, 25 MJ are attributed daily. Once construction begins, the real time measurement of environmental impacts (based on physical rental agreements and work item logs) allows for the creation of the actual impact curve, called the actual impact line (AIL), which is shown in Fig. 1. The AIL is compared to the benchmark prediction (BIL) as the project continues. This comparison provides a quantified indication of performance with regards to environmental metrics and progress towards the overall environmental targets and projected impact budgets. The results from the preceding steps are used to manage the accrual of environmental footprint (e.g., CO_2e, SO_x, etc.) over the course of construction, analogous to construction cost control. The notable differences from cost control lie in the need for more detailed material, transportation, and equipment use information. Fig. 1 shows a sample footprint accrual for a hypothetical construction project over time.

BIL represents the budgeted impact accrued during construction. AIL represents actual impact accrued during construction. The dashed vertical line marks the end of construction. Implementing existing cost variance control management techniques, this type of figure is used to measure construction processes and facility operations in real-time to better ensure that environmental performance targets are met. AIL and BIL are analogous to cost variance

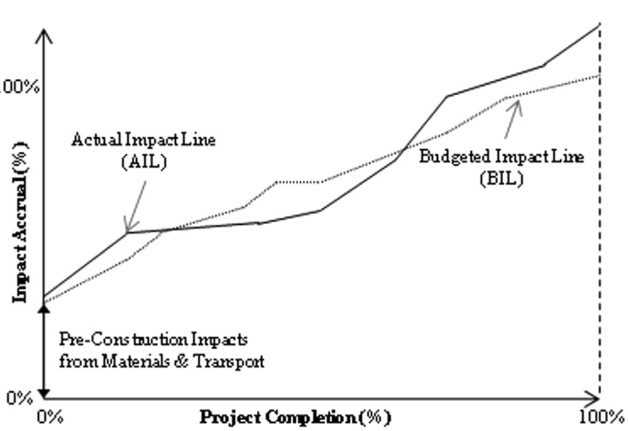

Fig. 1. Schematic view of impact accrual versus time.

figures prevalent in the construction industry for project cost management. From Fig. 1 it can be seen that at 50% completion, the actual impacts are less than the budgeted impacts. Thus, the project is either below environmental budget or behind schedule on construction completion. Based on this information, a construction manager can look at the schedule to determine the case and make adjustments if necessary. From Fig. 1, at 75% completion, measured impacts are greater than predicted impacts, thus the project is either ahead of schedule or above environmental budget. Again, further investigation allows for determination of the case and for adjustments to be made. Potential adjustments include sourcing more local materials, fuel switching in equipment, reducing machinery idling time, streamlining of equipment activities, and increasing recycling and reuse of materials.

3. Case studies

The framework discussed in the preceding section enables building stakeholders to quantify both budgeted and accrued environmental impacts in an effort to deliver STV designed buildings. Two case studies were conducted to demonstrate this framework; an infrastructure project and a building project. These case studies were selected to demonstrate the generality of the framework in two different project types within the construction industry. While the infrastructure case study evaluates only the framework for impact budgeting (BIL), the building project case study incorporates both the budgeted (BIL) and accrued (AIL) impact lines.

To conduct the inventory analysis for each study, material quantities, equipment types and usage, and transportation distances were collected and/or calculated. This process involved quantity takeoffs from construction documents for the infrastructure case study and quantity takeoffs from a BIM model and from conversations with the general contractor and subcontractors for the building case study. Construction drawings (hard copies) were used to determine the dimensions and quantity takeoffs for the infrastructure case. The BIM model, in combination with PDFs of structural drawings, was used to calculate the material quantities for the building case. RS Means MasterFormat crews were used to determine the equipment requirements. Hours of equipment usage were calculated using material quantities and RS Means productivity data.

For each case study, an individual activity's materials and processes were modeled into an LCA software database (the EcoInvent (2010) database housed within SimaPro) as an assembly by finding analogous materials and processes in existing or newly created LCI databases. In instances where an exact match did not exist for the material or process, an approximation or assumption was made. Details for materials, equipment, and transport methods, along with assumptions made for each of the two case studies, are provided below.

3.1. Infrastructure project case study

The first case study was an infrastructure project involving the rehabilitation of a steel girder bridge in southwest Michigan. The bridge is located on state highway M-89 where it crosses the Kalamazoo River between Heath and Valley townships. It is a 2-lane vehicle bridge with a reinforced concrete deck and spans 110 m. The project, Michigan Department of Transportation Project BHT 9903002, included partial demolition of the existing structure and bridge deck and addition of structural steel and new reinforced concrete decking. The specific construction activities, materials, and equipment are described below.

3.1.1. Goal and scope definition

The goal of the infrastructure project LCA was to test the activity-based LCA framework. A budget impact line (BIL) for this project was retrospectively calculated based on the completed construction documents. The project scope included the following activities: (1) concrete deck hydrodemolition, (2) placement of concrete overlay, (3) strengthening of steel girders by adding plate steel, (4) replacement of guardrail, (5) asphalt paving, (6) epoxy painting, (7) excavation, (8) removal of old drainage structures, and (9) installation of replacement drainage structures. The construction activities were determined from the general plan notes of the construction documents package. The documents included a summary of the project, technical notes on work to be done, and 2D renderings of the bridge and work. An example of how an activity was developed is described in the inventory analysis discussion. This infrastructure case was chosen based on the limited number and scope of activities and availability of construction documents and data.

3.1.2. Inventory analysis

The material types were taken from the construction document descriptions and labels. The material quantities were calculated based on length, area, and volume dimensions given on the drawings. Each activity identified above was matched with a corresponding MasterFormat activity and construction equipment was determined based on the crew listed. Only equipment use was included; human laborers were excluded from the analysis. For example, for the hydrodemolition activity, the 146 m^3 of concrete to be demolished was determined based on the length, width, and depth provided on the construction drawings. The only material input required was water. The corresponding MasterFormat code used was 030505100010 for selective concrete demolition, excluding saw cutting, torch cutting, loading and hauling. The crew for this code is B9 which includes a 250 CFM air compressor and a 60 pound pavement breaker. The equipment and materials were modeled in the LCA software, SimaPro, to determine the associated impacts: water was modeled as 'water, deionized at plant' and the compressor and pavement breaker were modeled as 'diesel, burned in building machine.' In this case, there are no materials transported to site, so transport is omitted. Summing the impacts from materials, transport, and equipment provides the total impact for this activity. For hydrodemolition, material impacts are 2.0×10^3 kg CO_2e and equipment impacts are 3.7×10^6 kg CO_2e. The total activity impact is divided by the duration (in days) to determine impact of an activity per day. For hydrodemolition, the global warming impacts per day are 9.5×10^4 kg CO_2e. Table 1 below shows the material quantities associated with the bridge rehabilitation project.

Table 1
Materials and quantity infrastructure project.

Material	Unit	Quantity
Bitumen	kg	68,025
Concrete	m^3	146
Epoxy coating	kg	8646
Formwork, Plywood	kg	548
Grout	kg	194,580
Iron, Sand casted	kg	844
PVC pipe	kg	63,950
Reinforcing steel	kg	7929
Riprap	tonne	1000
Sand	kg	768,800
Structural steel	kg	154,416
Timber	m^3	0.3
Water	kg	2,616,933

3.1.3. Impact assessment

Based on all the construction activities performed, the total impact of the designed work, in terms of life cycle GWP and primary energy consumption, was 4.4×10^6 CO_2e and 7.2×10^7 MJ (lower heating value), respectively. These totals include embodied impacts of materials, impacts from transporting materials to site, and impacts of onsite construction. Combining material, transportation and construction equipment impacts for each activity, project impacts were associated with specific tasks. The breakdown of activities and impacts is shown in Table 2.

3.1.4. Interpretation

Linking the activities shown in Table 2 with the construction schedule, accrual of environmental impacts can be plotted versus percent project completion. Theoretically, these links allow construction managers to pinpoint sources of impact and focus process improvements. This time-dependent budget for environmental impacts can be coupled with the Gantt chart to illustrate impact accrual over the course of activity completion (Fig. 2).

This tool provides a simple visualization of impact accrual and can guide project management during the construction phase. Further, when coupled with plots of actual accrual of impacts, it can inform project management and decision-making. This retrospective infrastructure case demonstrated that the activity-based LCA framework is feasible. To further investigate construction activity-based LCA as an impact management and control tool, a case involving both actual (AIL) and budgeted (BIL) impact lines was required. Therefore, a second case was undertaken focusing on a building erection project.

3.2. Building erection case study

A building project involving extensive retrofitting and rehabilitation of a football stadium was chosen as a case study to compare budgeted and actual environmental impact lines for selected construction activities. The project included work on the stadium structure and athletic field. It involved extensive seismic upgrades as well as preservation of historic elements of the original stadium structure. Activities associated with the construction of a new press box building, which provides broadcast support spaces and a multi-functional club space, were selected for this analysis. The structure is a seismic-resistant steel frame with glass and concrete façade. The specific activities analyzed for this case study are those associated with the assembly and erection of the structural steel for the press box. The methodology is scalable to the entire project provided widespread adoption within the construction management team.

3.2.1. Goal and scope definition

The goal of this case study was to test the framework's applicability in developing and comparing budgeted and actual environmental cradle-to-gate impacts. The activities include (1) erecting crawler crane, (2) erecting structural steel and safety deck for Northern portion of press box, (3) plumbing and aligning structural steel for Northern portion of press box, (4) bolting and welding structural steel for Northern portion of press box, (5) erecting structural steel and safety deck for Southern portion of press box, (6) plumbing and aligning structural steel for Southern portion of press box, (7) bolting and welding structural steel for Southern portion of press box, and (8) dismantling crawler crane. This project was chosen due to the detailed BIM model associated with the project. This particular portion of the project was chosen

Table 2
Construction activities and budgeted impacts for infrastructure project.

Construction activity	Duration (Days)	GWP (CO_2e)	Energy (MJ LHV)	Acidification (kg SO_2)	Eutrophication (kg PO_4)	Carcinogens (kg B(a)P)
Hydrodemolition	39	3.7×10^6	5.9×10^7	4.8×10^4	8.5×10^3	7.6×10^{-2}
Excavation	3	5.7×10^3	1.1×10^5	7.6×10^1	$1.4.10^1$	1.8×10^{-3}
Drain structure	2	1.8×10^5	4.3×10^6	9.2×10^2	7.5×10^1	2.2×10^{-4}
Structural steel	2	4.4×10^4	7.1×10^5	3.1×10^2	9.1×10^1	1.8×10^{-2}
Concrete overlay	12	3.3×10^5	1.7×10^6	1.6×10^3	1.6×10^2	6.6×10^{-3}
Epoxy painting	5	5.6×10^4	1.2×10^6	1.9×10^2	3.0×10^1	3.0×10^{-3}
Curb and gutter	1	3.1×10^2	1.9×10^3	6.9×10^{-1}	1.5×10^{-1}	9.2×10^{-6}
Paving	3	3.3×10^4	3.7×10^6	4.9×10^2	3.6×10^0	7.1×10^{-4}
Guardrail	1	1.2×10^4	2.1×10^5	7.6×10^1	2.6×10^1	4.6×10^{-3}
Totals	58[a]	4.4×10^6	7.2×10^7	5.2×10^4	8.9×10^3	1.1×10^{-1}

[a] Total duration is not a sum of all activity durations because work on some activities occurs simultaneously.

because it is limited in scope in terms of both number of activities and number of subcontractors. Further, the subcontractors were responsive to requests for material and transport data. Finally, the scheduled dates of the construction activities included changes due to weather, material, and other delays but the actual activities remained the same.

3.2.2. Inventory analysis

Table 3 lists the predicted and measured material quantities for the above listed activities. The BIM model, bidding documents, and subcontractor agreements were used to determine specific quantity takeoffs and associated material impacts. These sources were supplemented and interpreted by the general contractor. Purchase orders, change orders, and interactions with the general contractor and subcontractors provided the actual material quantities and associated impacts (i.e. transportation impacts). In parallel with the infrastructure case, the activities were matched with corresponding MasterFormat activities.

For each construction activity, budgeted impacts and actual impacts were calculated by associating the impacts of each construction activity with the construction schedule. The general contractor provided the preliminary schedule and weekly updated schedules. The construction impacts included the impacts associated with materials (listed above), transport, and onsite equipment. Transport data was either provided by the subcontractor, general contractor, or estimated based on material availability in region. The same transport methods were assumed for the predicted and measured impact calculations. The project activities were associated with the corresponding MasterFormat work codes. For predicted impacts, the MasterFormat data was used to determine which construction equipment was required and the productivity rate. Due to insufficient and inaccurate data on which equipment was actually used onsite, MasterFormat data was also used to calculate actual impacts. Combining material, transportation and construction equipment impacts for each activity, project impacts were associated with specific tasks for both predicted and measured scenarios.

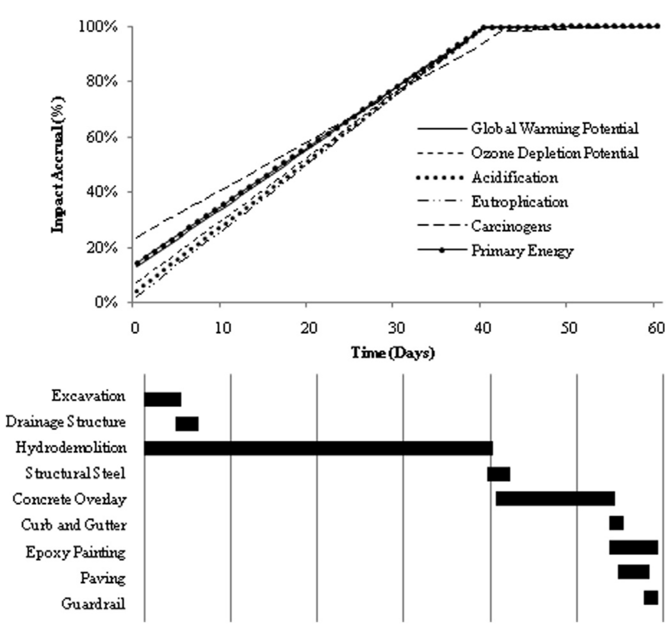

Fig. 2. Gantt chart and impact variance budget for infrastructure project.

Table 3
Materials and quantity takeoffs for building project.

Material	Unit	Quantity	
		Budgeted	Actual
Structural steel for columns and beams	kg	851,846	969,714
Stainless steel bolts	kg	1361	1538
Steel fasteners	kg	227	232
Steel for decking	kg	18,144	17,891

3.2.3. Impact assessment

The budgeted total impact of the work in terms of GWP and primary energy consumption was 1.21×10^6 kg CO_2e and 2.02×10^7 MJ (lower heating value), respectively. The actual total impact of the work in terms of GWP and primary energy consumption was 1.38×10^6 kg CO_2e and 2.29×10^7 MJ, respectively.

The budgeted impacts (used to generate BIL) associated with each construction activity are shown in Table 4 for GWP, energy consumption, acidification, eutrophication, and carcinogens. The measured impacts (used to generate AIL) associated with each construction activity are shown in Table 5.

3.2.4. Interpretation

Linking the activities shown in Table 4 with the approved contract construction schedule, accrual of environmental impacts was plotted versus time to produce the BIL. Linking the activities in Table 5 with the updated schedule (of actual work completed), accrual of environmental impacts was plotted versus time to produce AIL. Fig. 3 illustrates the budgeted (solid black) and actual (dashed gray) accrual of GWP plotted above the Gantt chart of budgeted and actual schedule for the included activities.

Fig. 3 demonstrates that the accrual of measured and predicted impacts can be plotted together to illustrate variance between the two lines for environmental impacts (in this case GWP). It shows that the measured scheduled start date of press box activities is

Table 4
Construction activities and budgeted impacts for building project.

Construction activity	Duration (Days)	GWP (kg CO_2e)	Energy (MJ LHV)	Acidification (kg SO_2)	Eutrophication (kg PO_4)	Carcinogens (kg B(a)P)
Crawler crane erection	3	7.15×10^0	1.28×10^2	6.28×10^{-2}	8.23×10^{-3}	4.21×10^{-7}
Structural steel erection (N)	12	6.03×10^5	1.01×10^7	2.26×10^3	1.38×10^3	1.26×10^{-1}
Plumbing & aligning (N)	12	2.96×10^{-1}	4.21×10^0	1.42×10^{-3}	2.36×10^{-4}	1.42×10^{-10}
Bolting & welding (N)	12	2.68×10^3	2.14×10^4	1.40×10^1	8.52×10^{-1}	1.24×10^{-4}
Structural steel erection (S)	12	6.03×10^5	1.01×10^7	2.26×10^3	1.38×10^3	1.26×10^{-1}
Plumbing & aligning (S)	12	2.96×10^{-1}	4.21×10^0	1.42×10^{-3}	2.36×10^{-4}	1.42×10^{-10}
Bolting & welding (S)	12	2.68×10^3	2.14×10^4	1.40×10^1	8.52×10^{-1}	1.24×10^{-4}
Crawler crane dismantling	3	4.29×10^0	7.66×10^1	3.77×10^{-2}	4.94×10^{-3}	2.53×10^{-7}
Totals	49[a]	1.12×10^6	2.02×10^7	4.54×10^3	2.77×10^3	2.52×10^{-1}

[a] Total duration is not a sum of all activity durations because work on some activities occurs simultaneously.

Table 5
Construction activities and actual impacts for building project.

Construction activity	Duration (Days)	GWP (kg CO_2e)	Energy (MJ LHV)	Acidification (kg SO_2)	Eutrophication (kg PO_4)	Carcinogens (kg B(a)P)
Crawler crane erection	3	7.15×10^0	1.28×10^2	6.28×10^{-2}	8.23×10^{-3}	4.21×10^{-7}
Structural steel erection (N)	14	6.85×10^5	1.14×10^7	2.56×10^3	1.57×10^3	1.43×10^{-1}
Plumbing & aligning (N)	10	2.96×10^{-1}	4.21×10^0	1.42×10^{-3}	2.36×10^{-4}	1.42×10^{-10}
Bolting & welding (N)	10	2.99×10^3	2.38×10^4	1.56×10^1	9.49×10^{-1}	1.39×10^{-4}
Structural steel erection (S)	10	6.85×10^5	1.14×10^7	2.56×10^3	1.57×10^3	1.43×10^{-1}
Plumbing & aligning (S)	10	2.96×10^{-1}	4.21×10^0	1.42×10^{-3}	2.36×10^{-4}	1.42×10^{-10}
Bolting & welding (S)	10	2.99×10^3	2.38×10^4	1.56×10^1	9.49×10^{-1}	1.39×10^{-4}
Crawler crane dismantling	3	4.29×10^0	7.66×10^1	3.77×10^{-2}	4.94×10^{-3}	2.53×10^{-7}
Totals	37[a]	1.38×10^6	2.29×10^7	5.16×10^3	3.14×10^3	2.86×10^{-1}

[a] Total duration is not a sum of all activity durations because work on some activities occurs simultaneously.

after the predicted date. This was due to a combination of weather, change orders, and design alterations. Fig. 3 also shows that total duration of press box related activities was compressed, resulting in a steeper AIL vs. BIL; the purpose was to save time in order to get the remainder of the project activities back on predicted schedule.

The total measured impacts are over budget compared to the budgeted impacts – this is due mainly to increases in the amount of structural steel used. The actual structural steel used for the press box was 117,868 kg greater than the budgeted steel due to a design change. The construction manager could use the tool to assess the

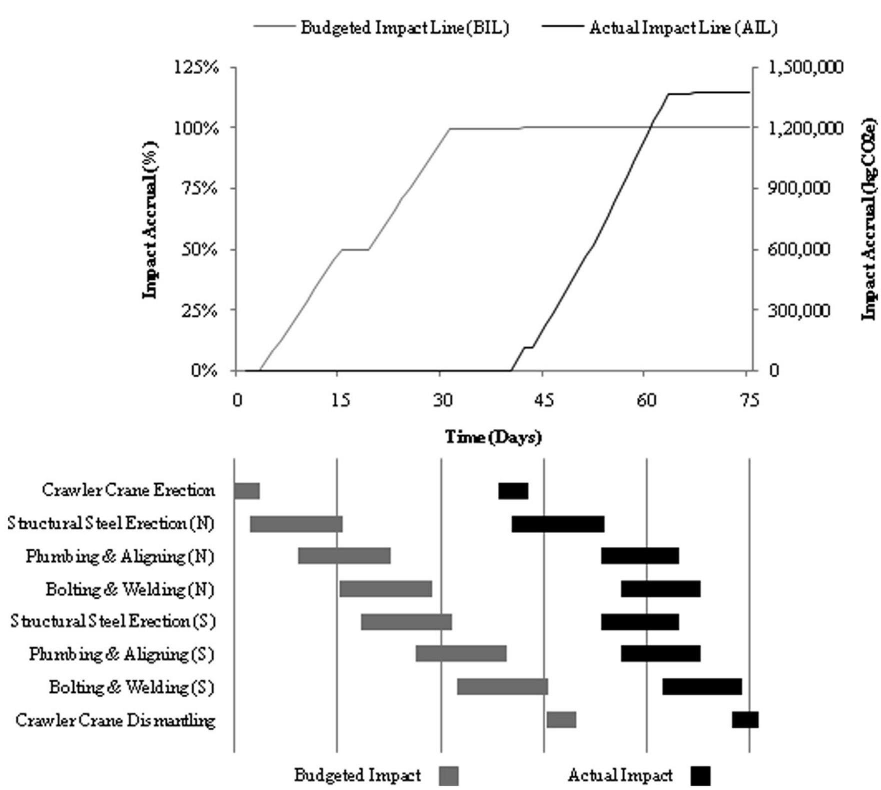

Fig. 3. Gantt chart and GWP variance for building project.

impacts of implementing impact-saving strategies. In this case, the construction manager explored biodiesel blends, alternate concrete mixes, and scheduling priorities in order to shift the AIL and stay closer to the budget. This visualization illustrates that environmental metrics can be measured, and theoretically managed, in parallel to cost in traditional construction management. This has the potential to be a useful tool for construction managers if measuring and managing environmental impacts is implemented more widely in the construction industry.

4. Discussion

The case study applications of STV for construction, the activity-based LCA framework, demonstrate that the predicted LCA impacts of materials, transport, and construction can be linked with the relevant construction activities. The building case shows that both budgeted (BIL) and actual (AIL) impacts can be quantified and compared and have the potential to be managed under this framework. Using both BIL and AIL provides a construction management tool for environmental impact management. When coupled with the Gantt chart, they can help visualize whether a project is ahead or behind schedule as well as above or below its environmental budget. It is important that this methodology leverages accepted construction management techniques already in place in the architectural, engineering, and construction (AEC) industries; previous work shows that lack of knowledge and expertise about environmental effects combined with lack of access to environmental data parallel to cost and performance data limits stakeholders' ability to achieve environmental performance objectives (Keoleian, 1993).

The case studies demonstrate that the methodology can be applied to budgets limiting carbon dioxide emissions or other environmental indicators. In the press box construction case, the budgeted impacts line (BIL) represents the budgeted accrual trend over the course of the project and ends at a final impact value. This final value could be likened to the monetary budget for a similar prediction of project cost. In either case, the performance of the final project – the actual impact line (AIL) – should end at or below this value if the project was designed and carried out as planned.

The power of this methodology lies in the ability of the building stakeholders to set more aggressive performance targets, or sustainable target values (STV), beyond those relating to cost control and in providing a way to manage performance to actually meet the targets. Previously, even with the goal of being sustainable, construction managers and other building stakeholders had no way to manage or verify performance in real-time during design and construction. Using the activity-based environmental management for STV framework, when provided with a building STV such as an embodied carbon dioxide emissions limit, a construction project can now manage the project such that the impacts of all of the activities accrue to a value within this limit. Thus, cradle-to-gate impacts can be verified to STV design targets. This also provides an avenue for future construction bidding based on both cost and environmental impact. When construction then takes place, the ongoing LCA provides an indication of where the project stands in relation to this goal at each construction phase.

This work extends the STV framework described in Russell-Smith et al. (2015a) beyond design and enables construction activity-based environmental management for STV. It contributes a previously lacking methodology to operationalize STV and produce constructed facilities with verified environmental profiles. Building to the STV facilitates the construction of buildings that actually perform within the boundaries of the STV targets. The STV methodology is used to break down the impacts into those from materials, transport to site, construction, and operation so that performance for each phase can be assessed and compared. This operationalization of STV builds upon existing management and control techniques for cost. It uses techniques common to building construction stakeholders, facilitating ease of adoption. This work, building to STV, provides a basic methodology to manage the production of buildings from cradle-to-gate with sustainable life cycle impacts.

5. Limitations

Several limitations exist in terms of the scope of this work. These limitations exist with respect to the lack of inclusion of the entire life cycle and with respect to the availability of data for the case studies. These limitations are discussed in more detail below.

From a life cycle standpoint, this work does not account for the full life cycle of a building; cradle to gate includes material extraction, material processing, transportation of materials to site, and construction processes. Cradle-to-gate excludes operation and end-of-life. The intent was to provide a method of quantifying the often ignored cradle-to-gate impacts. However, the literature to date shows that the majority of environmental impacts of buildings stem from the operation phase (Junnila et al., 2006; Keoleian et al., 2001). Minimizing the cradle-to-gate impacts would not necessarily achieve operational energy savings. Further, the end-of-life impacts of demolishing and reusing, recycling, or landfilling the components could mean ignoring the complications of disposing of hazardous materials or remediation of site as a result of pollutants. For instance, if asbestos-containing insulation is used in design and construction, there are major health and environmental impacts that must be dealt with at end-of-life. The activity-based cradle-to-gate life cycle assessment method was developed to address the previously often ignored cradle-to-gate impacts and to provide a method for construction stakeholders to understand and quantify impacts, leveraging tools methods with which they are familiar. This framework is a compliment to existing LCA frameworks which focus on the other life cycle phases. A consequence of the scope limitations of this work, is the opportunity for future work in integrating the various life cycle stage models into a holistic LCA model.

In terms of limitations with the case studies, there were several challenges faced in the application of the activity-based LCA framework. The most problematic was the availability of data. A detailed, complete BIM model can better provide a complete quantity takeoff and schedule for development of budgeted impact lines (BIL). However, the architecture, engineering, and construction (AEC) firms were unwilling to share these models in their entirety, so data had to be obtained by sending requests to members of the general contractor's BIM team for the building case study. The other significant data availability challenge was the accurate measurement of onsite equipment use. Up-to-date records of equipment rentals and usage were at times inaccurate or unavailable. Another limitation of this work is the applicability of data; since the LCI databases are largely populated with values from European or North American manufacturers and transportation authorities, the data tends to lose geographic fidelity.

6. Conclusion

This paper presents a life cycle assessment (LCA) framework for management and control of environmental impacts of constructing a building or infrastructure facility to meet sustainable target value (STV) design targets. It builds on existing construction management techniques to produce a method of accounting, managing, and controlling environmental impacts of construction projects. Coupling environmental impacts of construction activities determined using LCA with construction schedules can successfully produce time-dependent environmental impact budgets that form the basis for management of variance between predicted environmental impacts and measured environmental impacts of constructed facilities. This is demonstrated using a case study of select construction activities from a larger construction project.

The framework produces environmental impact accrual timelines facilitating improved sustainability-oriented project management during the construction of a facility and offers unique analysis opportunities to examine the managerial tradeoffs between construction decisions. It enables designers, contractors, and engineers to manage designed and actual environmental impacts and make more informed decisions from cradle-to-gate in order to meet STV. Future research will further develop tools necessary to track actual environmental emissions from onsite equipment usage, explore integration of LCA and building information modeling, monitor actual facility material consumption, and expand the breadth of activities used to demonstrate the framework to meet STV design targets.

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