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TOPICAL REVIEW

Taxonomy of uncertainty in environmental life cycle assessment of infrastructure projects

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Abstract

Environmental life cycle assessment (LCA) is increasingly being used to evaluate infrastructure products and to inform their funding, design and construction. As such, recognition of study limitations and consideration of uncertainty are needed; however, most infrastructure LCAs still report deterministic values. Compared to other LCA subfields, infrastructure LCA has developed relatively recently and lags in adopting uncertainty analysis. This paper presents four broad categories of infrastructure LCA uncertainty. These contain 11 drivers focusing on differences between infrastructure and manufactured products. Identified categories and drivers are: application of ISO 14040/14044 standards (functional unit, reference flow, boundaries of analysis); spatiotemporal realities underlying physical construction (geography, local context, manufacturing time); nature of the construction industry (repetition of production, scale, and division of responsibilities); and characteristics of infrastructure projects (agglomeration of other products, and recurring embodied energy). Infrastructure products are typically large, one-off projects with no two being exactly alike in terms of form, function, temporal or spatial context. As a result, strong variability between products is the norm and much of the uncertainty is irreducible. Given the inability to make significant changes to an infrastructure project ex-post and the unique nature of infrastructure, ex-ante analysis is of particular importance. This paper articulates the key drivers of infrastructure specific LCA uncertainty laying the foundation for future refinement of uncertainty consideration for infrastructure. As LCA becomes an increasingly influential tool in decision making for infrastructure, uncertainty analysis must be standard practice, or we risk undermining the fundamental goal of reduced real-world negative environmental impacts.

1. Introduction

Environmental life cycle assessment (LCA) is increasingly being used to evaluate infrastructure products and to inform their funding, design and construction (Province of Ontario 2017, State of California 2017, City of Vancouver 2018, 2019, Infrastructure Canada 2019, Klimatkalkyl 2019). With increasing use in regulation and growing reliance on infrastructure-specific LCA standards (BSI 2010, BSI 2011 and BSI 2016), there is a need to articulate the confidence with which results are known and to recognize key drivers of the uncertainty and variability across infrastructure LCA. In this paper 'infrastructure' includes both vertical infrastructure (e.g. buildings) and horizontal infrastructure (e.g. roads, bridges, tunnels). We focus on civil infrastructure (e.g. sewers, roads, buildings) though much of the discussion can apply to other infrastructure systems (e.g. telecommunications, electricity networks).

While analysis of uncertainty and communication of uncertainty in results is accepted best practice in LCA, to date, the majority of infrastructure LCAs provide single value assessments (Chester and Horvath 2009, Iddon and Firth 2013, Hanson and Noland 2015, De Wolf *et al* 2016); the word 'uncertainty', for example, does not appear in the EN15978:2011 standard. These deterministic assessments omit explicit communication of the uncertain nature of LCA, which is critical to proper interpretation of results (Lloyd and Ries 2007, Williams *et al* 2009, Zhang *et al* 2019). Decisions based on a single value deterministic assessment can misdirect infrastructure investment. As infrastructure LCA transitions from an academic discipline toward having real-world influence on infrastructure decision-making, recognition of study limitations and consideration of uncertainty are necessary (Mendoza Beltran *et al* 2018b).

Infrastructure LCA has developed relatively recently and lags in adopting uncertainty approaches common in other LCA subfields (e.g. fuels). LCA began as a process for evaluating the environmental credentials of consumer products (e.g. Coca Cola bottles and milk cartons); it has since been applied to increasingly large and complex products and systems like automobiles, building materials, and waste processing (Guinee *et al* 2011). The extension of LCA to infrastructure arguably stretches the ability of ISO standard LCA to capture the realities and complexities of these projects. LCA of whole infrastructure projects is only now starting to seriously address uncertainty. We argue that infrastructure projects present unique challenges for LCA and associated uncertainty, stemming from the combined impacts of multiple deviations from traditional consumer product manufacturing. Assessing uncertainty in infrastructure LCA has extra complexity related to the individuality of each project: its size, the time to design and construct, and the accumulated uncertainty inherent in being a system of sub-products (e.g. concrete, steel, copper, electricity, diesel). These features point to potentially substantial uncertainty in infrastructure LCA and the need for new sector-specific approaches.

A key challenge is that infrastructure is produced in far smaller quantities than common consumer products, leading to a lack of databases to facilitate LCA. For example, existing LCA databases may include entries for typical plastic packaging, but there can be no accurate standard equivalent for a 'typical' building or bridge. At the same time, compared to other complex products, infrastructure is ubiquitous; we build many more buildings, for example, than oil fields, ferries or jumbo jets. As ubiquitous, complex products with outsized environmental impacts, infrastructure requires subfield specific consideration of LCA, life cycle thinking and LCA uncertainty. We provide a framing of the distinct drivers of uncertainty in the life cycle environmental impact of infrastructure.

Full LCA of an infrastructure project includes assessment of the materials and energy used in mining, manufacturing and transportation to site, on site energy use, operation, and demolition/disposal/reuse. We focus on assessments of design and construction processes. The operation and demolition phases create further complexity and uncertainty as they extend over even longer time periods and can occur far in the future in different socio-technical environments than exist today (Gantner *et al* 2018). The additional uncertainty inherent in these long timelines is related to but outside the scope of this paper.

Section 2 provides a background from the literature of infrastructure LCA and considerations of uncertainty in LCA. Section 3 presents important drivers of uncertainty in infrastructure LCA and their deviation from manufactured products. We discuss the sources of uncertainty in infrastructure and categorize their impacts. Section 4 explores implications of these drivers with qualitative and quantitative examples, followed by a conclusion in section 5. This paper articulates the key drivers of infrastructure specific LCA uncertainty, laying the foundation for inclusion, and consistent approaches to, uncertainty as LCA becomes an increasingly influential tool in decision making for infrastructure. The drivers of infrastructure LCA uncertainty categorized in this paper identify important differences between infrastructure projects and manufactured products for which LCA is most attuned. Wrestling with these uncertainties is an important aspect of accurately and clearly communicating infrastructure LCA. The irreducible nature of many of the uncertainties could necessitate a move beyond strict LCA toward broader application of life cycle thinking to infrastructure.

2. Literature review

Research on the energy intensity and associated environmental impacts of infrastructure attracted research attention starting in the 1970s (Hannon *et al* 1977). Early findings indicated that the environmental impacts of construction materials and construction energy paled in comparison to operational energy and, as such, received comparatively little academic, government or industry attention for the rest of the 20th century (Cole and Rousseau 1992, Cole 1999). With growing attention to the consequences and implications of global climate change and significant progress reducing negative environmental impacts of infrastructure operation, increasing attention has been paid to embodied impacts and cradle-to-gate LCA for infrastructure in the 21st century. For instance, a search for life cycle assessment, greenhouse gas emissions, and buildings finds nine relevant documents in 1995 and 990 in 2018 (the last full year before writing). Switching the term 'buildings' for 'infrastructure' finds three relevant documents in 1995 and 791 in 2018.

Existing research has investigated the design and construction (cradle-to-gate) impacts of buildings ranging from single family homes to large multistory buildings and institutional buildings, like libraries and hospitals (Keoleian *et al* 2001, Iddon and Firth 2013, De Wolf *et al* 2016, De Wolf *et al* 2017b, Ding

2018, Pomponi and Moncaster 2018). Modern findings indicate that the design and construction impacts of buildings can be 50% or more of the total life cycle impact (Skullestad *et al* 2016). LCA also been applied to horizontal infrastructure; roads (Hughes 2012, Hanson and Noland 2015, Noland and Hanson 2015), bridges (Krantz *et al* 2015), rail lines (Chester and Cano 2016, Hanson *et al* 2016, Saxe *et al* Saxe, et al., 2017a), water infrastructure (Piratla *et al* 2012), and components of infrastructure construction (Soga *et al* 2011, Xu *et al* 2019) have been investigated. In addition to whole project and/or component assemblies, there is a large body of literature on the environmental impacts of construction materials (Hoxha *et al* 2014, 2017, Lasvaux *et al* 2016), a key background system for whole project assessment. While there is an increasing use of LCA and other industrial ecology tools to study the environmental impacts of the built world, infrastructure LCA is still relatively early in its evolution and struggles with challenges related to the complex nature of infrastructure products. These challenges include access to data, diverging approaches among researchers, functional unit definition, properly defining boundaries, extrapolating from case studies to the sector as a whole, and the development of infrastructure tailored approaches to LCA.

Since its inception, the field of LCA struggled with a potential disconnect between modeled and real-world impacts. In the 'decades of conception' between 1970 and 1990 (Guinee *et al* 2011), this tension was manifest in diverging approaches that led to poor inter-comparability of results and competing claims of environmental preferability. With the advent of a standard framework first laid out by the International Organization for Standardization (ISO) in 1997, attention shifted toward recognizing limitations of LCA results—initially through clear statements of assumptions and data quality requirements (ISO 1997), and subsequently by adding a requirement for explicit analysis of sensitivity and uncertainty among comparative assertions intended for public disclosure (ISO 2006). Today, it is widely recognized that appropriate use of LCA results requires practitioners to convey the confidence with which those results are known (e.g. Groen *et al* 2014, Hellweg and i Canals 2014, Groen and Heijungs 2016). Thus, even while many LCA continue to produce only deterministic estimates, there has been a parallel proliferation of techniques for uncertainty analysis, ranging from the use of simple intervals and scenarios, up to full stochastic analysis using Monte Carlo simulation. Various references provide descriptions of the most common uncertainty techniques (Matthews *et al* 2014, Igos *et al* 2019), with others providing: more detail on advanced probabilistic techniques (Groen *et al* 2014); broader survey of uncertainty analysis applications (Lloyd and Ries 2007); proposals to extend LCA uncertainty methods using data analytics (Ziyadi and Al-Qadi 2019); and critical review of statistical techniques applied to interpreting LCA results in a comparative context (Mendoza Beltran *et al* 2018a). However, while considerations of uncertainty have become more common in other LCA sub-fields (e.g. fuels), the vast majority of existing infrastructure LCA have provided discrete quantification with little consideration of uncertainty. In a recent review of the published studies, less than 25% incorporated uncertainty into LCA of buildings (Richardson *et al* 2018).

The needs and benefits of more widespread inclusion of uncertainty assessment in infrastructure LCA can be illustrated by looking at the evolution of uncertainty treatment in the large body of literature on LCA of energy and fuels. Early LCA of energy and fuels were largely deterministic, occasionally providing some treatment of uncertainty through the use of ranges or bounding scenarios (e.g. Deluchi 1991, Bell *et al* 1995, Furuholt 1995, Lave *et al* 2000, MacLean *et al* 2000). Subsequent work provided more comprehensive treatment of uncertainty in inputs/emissions from within fuel product systems (e.g. Venkatesh *et al* 2011a, 2011b, Hong 2012), later expanding to uncertainty in producer/project specific analyses (e.g. Vafi and Brandt 2014, Masnadi *et al* 2018, Sleep *et al* 2018), uncertainty among LCA impact characterization factors (e.g. Abrahams *et al* 2015, Posen *et al* 2015), and even uncertainty within indirect market-mediated consequences of fuel use (e.g. Plevin *et al* 2010, 2015, Rajagopal and Plevin 2013). Evidence from these studies and others suggests that failure to consider uncertainty can lead to suboptimal or counterproductive policy decisions (Mullins *et al* 2011, Plevin *et al* 2014). There are now sufficient investigations of LCA of energy and fuels to warrant detailed meta-analyses and harmonization studies (e.g. Brandt 2012, Heath and Mann 2012, Menten *et al* 2013) that expose key sources of uncertainty/variability across studies. Indeed, the wide body of literature on fuels and energy has enabled practitioners to identify key sources of emissions and associated uncertainties that were historically overlooked. Such developments suggest the potential for characterization of sector-specific uncertainty in LCA to enrich our understanding of environmental impacts of different products/systems.

Infrastructure LCA research has recently seen an accelerating, but still early stage adoption of uncertainty analysis. Liu *et al* (2017) reported that uncertainty in concrete GHG intensity and LCA system boundaries impact the life cycle GHG emissions from road construction by up to 35%. Hong *et al* (2017) provided an overview of approaches to parameter uncertainty including data quality index, contribution analysis, Monte Carlo simulation, and parameter categorization. They found that key construction activities have uncertainties ranging from 15% to 20%. Richardson *et al* (2018) examined the embodied GHG uncertainty in two alternative supermarket designs focusing on material substitution between steel and glulam. Ott and Ebert (2019) highlighted uncertainties due to life cycle stage inclusion for wood buildings. Larsson Ivanov *et al* (2019) highlighted the importance of considering service life. Other research investigated the challenges in accurately quantifying materials used in construction (Hoxha *et al* 2014, Nahangi *et al* 2020) and the variation in impact intensity of construction materials (Häfliger *et al* 2017, Hoxha *et al* 2017, Pomponi and Moncaster 2018). The UK standard PAS 2080- Carbon Management in Infrastructure requires considerations of uncertainty (BSI 2016). Overall, uncertainty analysis in infrastructure LCA has focused on two sources of uncertainty: (1) uncertainty in quantification of materials, particularly when predicting construction inputs from the early design phase; and (2) the uncertainty in material choices and the environmental impact intensity of those materials. These sources of uncertainty have been examined for single family buildings (Hester *et al* 2018, Tecchio *et al* 2018), multifamily residential buildings (Hollberg and Ruth 2016, Cavalliere *et al* 2019), and multi-unit buildings (Röck *et al* 2018).

While explicit consideration of uncertainty in infrastructure projects in LCA continues to be the exception, there is a large body of knowledge outside of the industrial ecology literature that discusses the consequential impacts of infrastructure development. Harnessing this other literature may enable a more complete accounting of emissions and uncertainty than has been possible elsewhere in LCA. This includes geography, planning, and civil engineering literature examining the economic, land use, and behavioral implications of infrastructure projects (Cervero and Kockelman 1997, Ewing and Cervero 2010, Cervero and Guerra 2011, Kimball *et al* 2013, Nichols and Kockelman 2014, Saxe *et al* 2017a).

To date, there has not been a systematic analysis of drivers of uncertainty in infrastructure, which, we argue are qualitatively and quantitatively different from uncertainty in the rest of LCA given the scale, temporal and spatial context of such projects. This paper provides an overview of these drivers, focusing on what makes infrastructure provision unique, to inform LCA practitioners and users in recognizing and thereby managing these uncertainties.

Multiple authors have proposed typologies of uncertainty within LCA (Huijbregts 1998, Heijungs and Huijbregts 2004, Lloyd and Ries 2007, Williams *et al* 2009). In this paper, we most closely follow the framing from Huijbregts (1998), dividing uncertainty and variability into six categories:

- Parametric uncertainty, which relates to uncertainty in observed or measured values, including due to inaccurate/imprecise measurements, unrepresentative data, or missing data
- Uncertainty due to choices, which arises due to normative decisions such as in regard to functional unit or system boundary
- Model uncertainty, which relates to uncertainty in mathematical relationships or fundamental model structure
- Spatial variability, which refers to variability brought about by differences in geographic context
- Temporal variability, which refers to variability brought about by differences in the time/timescale of analysis
- Variability between sources and objects, which reflects other inherent differences between similar processes

Infrastructure products are typically large, one-off projects with no two being exactly alike in terms of form, function, temporal or spatial context. As a result, strong variability between products is the norm. Table 1, below, highlights the characteristics of infrastructure products and their differences from manufactured products. Predicting life cycle environmental impacts during design or early construction phases is thus hampered by a lack of appropriate historical data, creating a direct link between ex-post variability, and ex-ante uncertainty. Given the inability to make significant changes to an infrastructure project ex-post and the unique nature of infrastructure, ex-ante analysis is of particular importance.

3. Drivers of uncertainty in infrastructure provision

Moving to deeper consideration of uncertainty in infrastructure will require adopting and adapting tools and approaches used in other fields (e.g. Monte Carlo analysis). It also involves a consideration of the nature of infrastructure products, their construction process and the uncertainties inherent and specialized to these systems. The construction processes of infrastructure stretch the traditional LCA framework—originally developed for manufactured products—and add system-specific uncertainties to LCA. Table 1 discusses built environment-specific uncertainty drivers and notes differences between construction process and traditional manufacturing in a factory. The final column of table 1 outlines salient ways in which these drivers contribute toward uncertainty across the categories outlined by Huijbregts (1998). A simplified presentation of the uncertainty taxonomy is presented in figure 1.

The uncertainty drivers listed in table 1 fit broadly into four categories: application of ISO 14040/14044 standards (functional unit, reference flow, boundaries of analysis); spatiotemporal realities underlying physical construction (geography, local context, manufacturing time); nature of the construction industry (repetition of production, scale

Table 1. Differences in uncertainty between infrastructure projects and manufactured products LCA.

	Manufactured products/fuels	What makes infrastructure projects different	Implications for uncertainty of infrastructure projects
Application of ISO Standards			
Functional unit	1 product; usually easy to specify function (e.g. can contain x ml of water, or y kWh of electricity); similar functional units are usually analogous (e.g. x ml water vs x ml juice)	Multifunctional; similar functional units may be fundamentally different (e.g. bridge crossing shallow river may require fundamentally different structure than bridge crossing open strait). Buildings of the same size and shape can have very different purposes and associated internal fit-out (hospital vs library vs factory)	Uncertainty due to choices: • Challenges with inter-comparability • Difficulty establishing baseline/benchmarks for comparison • Product lifetime variable, and often poorly specified; interacts with maintenance/rehabilitation emissions Source/object variability: • Introduces potentially spurious variation when 'buildings' or building-types are all grouped together
Reference flow	Often clearly defined (e.g. 1 water bottle)	Cannot be simplified into single unit (e.g. m^2 of building is insufficient because different functions require different design loads, e.g. science lab vs condo building)	Source/object variability: • Wide variety of reference flows may be used for normalizing inputs/outputs
System boundaries	One-time auxiliary activities (e.g. plant construction) usually not important contributors to total emissions. Each unit reasonably viewed as price-taker Behavioral implications often limited to use of the product in question	Construction usually requires auxiliary work (e.g. utility relocations, temporary works, construction of facilitating infrastructure, power lines for a power plant). Can consume enough materials in one unit to influence regional materials availability (e.g. subway construction) Has potential to fundamentally shift lifestyle, and influence unrelated systems	Uncertainty due to choices: • Difficult to specify system boundary (boundaries inconsistent between assessment) • Need to include one-time processes • Consequential impacts often dominate (e.g. material supply & demand shifts are the norm; wide scale changes to user behavior extend beyond use of the product) • Horizon of analysis influences material quantities (e.g. maintenance/refurbishment) • Boundaries are often set based on available data Parametric uncertainty: • Material quantities heavily dependent on boundary selection Model uncertainty: • To what extent are consequential impacts considered? Can they reasonably be omitted?

Table 1. Continued.

	Manufactured products/fuels	What makes infrastructure projects different	Implications for uncertainty of infrastructure projects
Spatiotemporal Realities Underlying Physical Construction			
Geography	Affects electric grid, transportation distances and impact on local population; usually does not affect fundamental manufacturing/delivery process	Design codes vary across regions Material availability varies by region Changes structural loading based on weather, climate and seismic conditions Many processes are seasonal (e.g. concrete curing in heated tents in cold environments)	Source/object variability: • Fundamental nature of the product varies across regions, hampering comparability • Material and sub-component availability varies Temporal/spatial variability: • Time and location are well specified for a given project • Need for climate-specific designs • Variability due to geography is inseparable from parametric uncertainty (inputs required) due to changing product characteristics
Local context	Typically used to determine location of plant (e.g. close to water source) rather than process employed	Noise ordinances influence construction methods Site layout influences available construction methods and material availability (e.g. ability to stockpile, local materials) Neighbours (NIMBY) influence what gets built Site layout and project time/budget constraints affect equipment choices Site conditions (e.g. soil type) and weather affect daily operations Changes in ground capacity based on soil/rock type Availability of local construction teams varies, affecting operating experience and equipment selection	Temporal/spatial variability: • Time and location are well specified for a given project • Past assessments have limited usefulness as proxy • Unpredictability of weather; seasonality can affect emissions Parametric uncertainty: • Key inputs such as weather, worker skill are unknowable during design phase Model uncertainty: • There exists a range of techniques for predictive modeling of construction processes
Manufacturing/ Construction time	Measured in days to weeks	Measured in years to decades	Temporal/spatial variability: • Variability of background systems with time (e.g. changing impact factor of electricity) within a single unit • Product design evolves over time—need for repeated/step-wise LCA? • Difficult to foresee fate of components and materials at end-of-life Parametric uncertainty: • Data collection is more time consuming and less likely to be complete • Actors change, hindering data collection Model uncertainty: • Actors change, hindering understanding of entire process

Table 1. Continued.

	Manufactured products/fuels	What makes infrastructure projects different	Implications for uncertainty of infrastructure projects
Nature of the Industry			
Repetition of production process	Same process applied repeatedly over thousands of units	Number of projects by manufacturer (e.g. architect, engineer, contractor) measured in the 10 s per year, rarely are any two identical.	Parametric uncertainty: • Less historic data to draw from (data gaps) • Cannot collect multiple data points to establish uncertainty bounds • Input characteristics differ between projects, e.g. type of concrete (data unrepresentativeness) Model uncertainty: • Relationship between design and quantities variable/poorly established • Analysis most useful before product fully designed; pilot scale testing not available • One-off disruptions (e.g. rework) may substantially influence LCA results (i.e. temporary disruption not amortized over many units) Source/object variability: • Less relevant—projects often analyzed individually Uncertainty due to choices: • Limited ability to use prior work hampers extension to system boundaries in later work
Scale—number of plants, number of construction sites	Analysis of first-of a kind (FOAK) or nth of a kind	Construction methods mature, but individual sites are always first of a kind; individual companies develop nth of a kind expertise on types of infrastructure (i.e. always a mix of FOAK and nth) One building is not representative of all buildings. Varies by designer, contractors, local conditions (e.g. ground conditions). One bridge does not represent all bridges, varies in length and size, height, wind loads.	Source/object variability: • No convergence among estimates Uncertainty due to choices: • Difficulty establishing baseline/benchmarks for comparison

Table 1. Continued.

	Manufactured products/fuels	What makes infrastructure projects different	Implications for uncertainty of infrastructure projects
Division of responsibilities	Single manufacturer	Multiple manufacturers and separate assembler	Parametric uncertainty: • Lack of central data source exacerbates data gaps • Disparate sources of information that do not agree (BOQ, BIM, Estimates) Model uncertainty: • Large potential for inconsistency in data collection protocols and assumed model relationships • No actor understands entire process Source/object variability • Often required to use proxy data from an actor (e.g. contractor) that may not be representative of all actors.
Nature of the product/project			
Agglomeration of products	May contain few components (e.g. only plastic for a water bottle) or multiple components (e.g. vehicle parts for a car)	Usually contains a large number of components (e.g. concrete, steel, glass, asphalt, HVAC systems)	Parametric uncertainty: • Data gaps and challenges collecting data • Joint uncertainty compounded by large number of inputs • Potential for parametric uncertainties to scale superlinearly (as product of quantity and impact factor uncertainties) Uncertainty due to choices: • Large number of subsystems may necessitate aggressive system boundary cut-off rules Model uncertainty: • Lack of centralized control; relationship between components less well understood • Low ability for individual actor to change process (i.e. reduce emissions or reduce uncertainty) • Internally consistent, bottom-up modeling for all components/processes is prohibitive
Recurring embodied impacts	Products are manufactured once per life with limited future material replacement expected (e.g. clothing, water bottle) or some future material replacement (e.g. transportation vehicle)	Recurring input of materials and manufacturing energy into the life product to maintain function (e.g. roof maintenance in a building, repaving of a road).	Parametric uncertainty: • Data collection is never complete, initial calculations of material use become increasingly inaccurate with time Uncertainty due to choices: • Difficult to specify temporal system boundary (when does manufacturing end?) Model uncertainty: • Full ex-post study not feasible on human time scales.

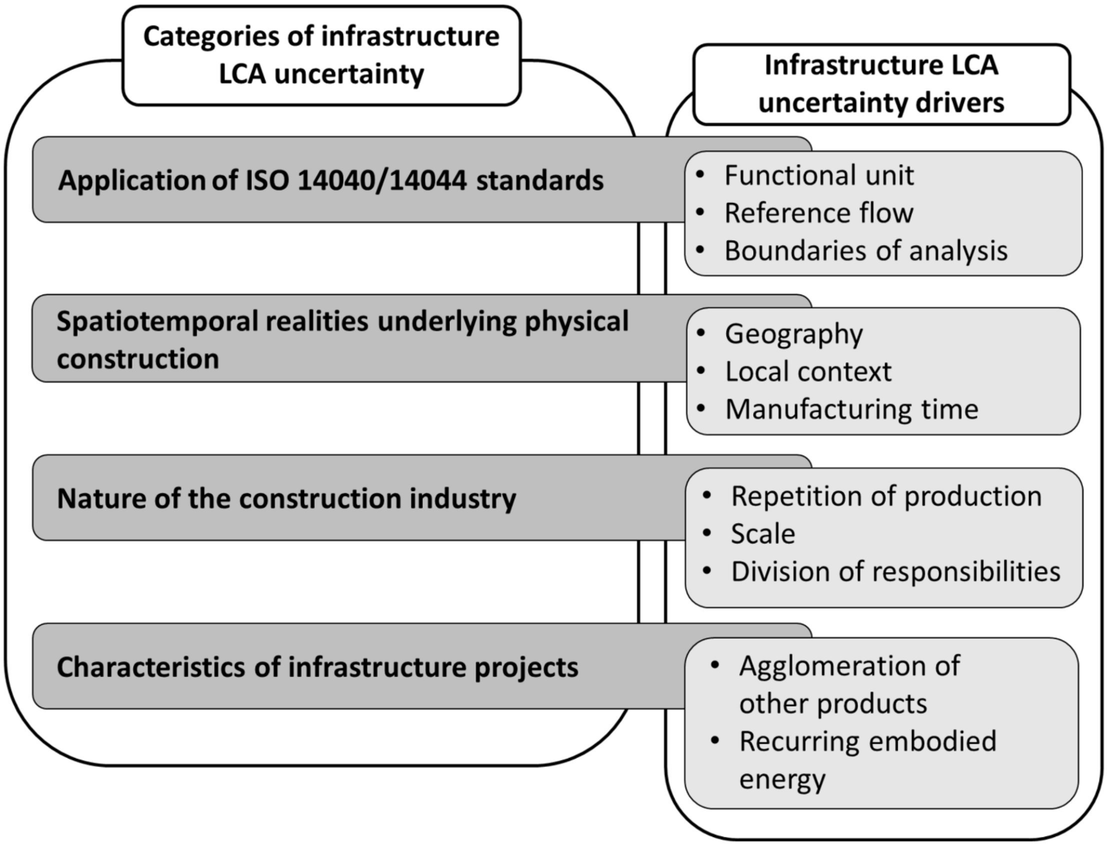

Figure 1. Categories and drivers of infrastructure LCA uncertainty.

and division of responsibilities); and nature of infrastructure products (agglomeration of other products, and recurring embodied energy). While categories and drivers presented in the table are intended to highlight key differences between LCA of infrastructure products and typical manufactured products, they are not necessarily exhaustive, nor are individual drivers intended to be unique to infrastructure delivery. Taken together, however, these drivers suggest a need for greater recognition of the challenges involved in infrastructure LCA, and sub-field specific uncertainty analysis. As such, table 1 provides an illustrative discussion of each outlined driver.

4. Discussion of infrastructure LCA uncertainty drivers

This section elaborates on table 1. For each driver, we provide illustrative examples of uncertainty with quantitative and qualitative examples from the literature. These examples draw from a range of infrastructure products based on data availability and to highlight the diversity of uncertainty considerations for infrastructure.

4.1. Functional unit and reference flow

Defining a functional unit and reference flow are critical elements to the goal and scope phase of any LCA (ISO 2006). A functional unit describes the service(s), including the time horizon, the system provides as distinguished from the physical system. When defining the study scope, it is critical to determine the relevant functions as not all product functions may be of equal relevance, and the different options for fulfilling the functions (Weidema *et al* 2004). The reference flow describes the physical inputs/outputs required to provide the service(s) described by the functional unit. For manufactured products, the system is typically more straightforward to define. Manufactured products/processes are often uni-functional (e.g. chopsticks, pencil), or have a small subset of defined functions (e.g. laundry detergent bottle, which contains and protects the detergent during distribution and use). In contrast, many infrastructure products are inherently multi-functional (e.g. buildings, tunnels and bridges) and with reference flows that would be impossible to define rigorously in the absence of detailed construction plans. As infrastructure projects are comprised of a multitude of other products (e.g. rebar, pumps), the reference flows would consist of the material list of the building or bridge project.

Regarding the multifunctional nature of infrastructure products, the minimum living space is defined as 165 square feet (~15.3 m^2) per person (U.S. Department of Housing and Urban Development 2007) but in many countries and socio-economic groups far larger apartments or houses are common, indicating that they provide more than the basic function. Living spaces are inherently multi-purpose; providing shelter, space for entertaining and recreation, home offices and home daycares, as well as social signaling of aspects such as wealth. Multi-functionality is common in infrastructure products. The concept of Complete Streets (City of Toronto 2019) is another example of the multi-functionality of construction products in that roads should do a lot more than facilitate the movement of motorized vehicles. Throughout much of the 20th Century, there was little attention to streets having multiple functions, including safety and accessibility for all users, facilitating non-motorized forms of transport such as walking and biking and a focus on more liveable neighbourhoods that include shopping, trees, sidewalk cafes, space for utilities, etc The image of transport infrastructure as only about moving people is commonly manifest in functional units that focus of vehicle or person kilometer travelled, overlooking the multifunctionality of the project.

Another distinguishing feature of infrastructure projects compared to many others, and one that complicates the definition of functional units, is that due to their often long service lives, their form and/or functions may change over that life. These changes may have major implications for the selection of appropriate functional units. For example, the retrofit of a century old industrial facility used for manufacturing clay bricks was analyzed (Opher *et al* 2019). The kiln building has been converted into an event and educational space with the aim of achieving carbon neutral operations for the site (Evergreen 2019). Functional units appropriate for representing the function of the original brick plant building would not appropriately represent the function of the event space retrofit building. Overall, in many LCAs of infrastructure projects, functional units are not considered or are confounded with the reference flow. Rather than focusing on the service it provides, authors often resort to a simplified reference flow, such as the product itself as a house (Ghattas *et al* 2013), subway system (Saxe *et al* 2017b), manhole, concrete pipe, or other precast concrete infrastructure product with an average service life of 100 years (Hershfield *et al* 2010), or one m^2 of floor area (Ghattas *et al* 2013). Other authors examined multiple options that inadequately captured the multi-function nature of the systems. Examples show different results when normalizing by m^2 living space, m^2 of function-based space (e.g. bedroom, garage), per dollar of construction cost, and per person (Zhang *et al* 2014, Norman *et al* 2016).

Several implications result from the challenges of defining functional units in construction product LCAs. Approaches where a functional unit is not specified or a reference flow is used as a proxy inherently overlook critical questions around how the building or road, for example, is used, which has a multitude of implications for the utility of the study and its ability to inform decision making. Uncertainties associated with the functional unit and reference flow definitions may arise due to conceptual errors, such as not taking into account relevant information, taking into account irrelevant information, and/or incorrectly identifying the relevant market segment (Weidema *et al* 2004). For instance, if a heated sidewalk were thought to be required for an application and this information were considered in specifying the functional unit but then in reality the heating was not required, then the functional unit would have been defined incorrectly and the life cycle impacts likely overstated compared to not including heating in the specification. Considering the above discussion of the challenges of multi-functionality of many construction products and their often-changing uses over their lifetimes, the likelihood of conceptual errors in defining the functional unit is likely higher than for many other products.

In any comparative study of products, the functional unit must be the same for all products being compared. While a common functional unit could be used for buildings and this would, in principle, satisfy the requirement for comparison, if the actual functions of the building were different or changed over their service life, then the study insights could be misleading and result in suboptimal decisions. In inter-study comparisons, differing functional units cause many challenges, the same is the case for setting benchmarks (e.g. product must meet a target GHG intensity) and as above, could lead to misleading insights and suboptimal decisions such as selecting an option that was actually worse for the environment and society. Overall, more effort needs to be focused on methods that guide the selection of appropriate functional units for construction products and a better understanding of the implications of the selected units on the results of a study. Transparency and comprehensive documentation of the process, including the implications of using alternative functional units and reference flows, will be critical for giving confidence to this process and study results.

4.2. Boundaries of analysis

Drawing boundaries of analysis around infrastructure products is a challenge and introduces uncertainty due to the interconnected nature of both physical and social systems. On the physical side, the development of new infrastructure products necessitates the construction of supporting infrastructure. A new building will require transport and utility connections or upgrades. Enough new homes will require a new school. A new energy generation facility often requires new transmission capability. Due to the physical disruption needed to manufacture infrastructure products, construction itself can disrupt the function of adjacent systems. Examples include traffic interruptions due to construction blockages

(Hanson and Noland 2015), or loss of water and energy service proximal to construction activities. For large infrastructure projects, the scale of material consumption can affect material markets. Further, temporary works of these projects can result in substantial impact, requiring additional attention in LCA compared with manufactured product systems where one-time processes tend to fall below LCA cutoff rules when accounting for the marginal impact over a large number of products.

On the social side, the development of new construction products can have strong implications on the behaviours of people who interact with them. A new highway incentivises more driving and more development at the urban edge (Baum-Snow 2007). A change in the size of homes incentivises a change in other consumption patterns such as energy use, furniture, or food storage. Residential energy retrofitting can lead to gentrification and displacement (Bouzarovski *et al* 2018). Across the literature, boundaries for the LCA of the infrastructure have been defined in different ways. In transport infrastructure LCA, for example, boundaries range from embodied materials only to the consequential impacts of construction (Nahlik and Chester 2014, Hanson *et al* 2016). This introduces substantial uncertainty due to choices into LCA of infrastructure, leading to inconsistencies that hinder comparisons across studies. The highly consequential nature of infrastructure decisions also makes indirect (market- and behavior-driven) impacts problematic to ignore (Plevin *et al* 2014), even though their inclusion is challenging and their uncertainty bounds are wide (Suh and Yang 2014).

4.3. Geography

A reflection of the unique nature of infrastructure projects (elaborated further in section 4.4) is the influence of local construction traditions, architectural trends, history, climate, and material availability (Gontia *et al* 2018). These influence the types and intensity of materials used for construction in different locations (Kleemann *et al* 2017, Gontia *et al* 2018, Ortlepp *et al* 2018). As an example of the influence of geography on constructed projects, we examine the inter-country difference in material intensity (MI) of buildings as reported in Heeren and Fishman (Heeren and Fishman 2019). MI is responsible for the majority of embodied environmental impacts in infrastructure products (Chester and Horvath 2009, De Wolf *et al* 2016). The database consists of 301 building case studies of different occupancy types (residential, commercial, industrial, mix-used buildings) from 21 countries. We focus on residential buildings as they represent more than 75% of the buildings in the database. Looking at countries with at least 10 data points each (Austria, Germany, Japan, Norway, and Sweden) illustrates meaningful differences in MIs.

As illustrated in figure 2, large variations between countries exist in the mean material intensities for both concrete and wood. The average MI for concrete ranges between 203 kg m^{-2} (Japan) and 666 kg m^{-2} (Austria), and for wood between 26 kg m^{-2} (Germany) and 75 kg m^{-2} (Norway). These findings are significant at a 95% confidence level using the Kruskal-Wallis test, which suggests that there are differences in the material intensity distributions between the countries based on a p-value of 0.002 for concrete and 0.001 for wood (see table S1.2 of the supplementary information (SI), which can be found online at stacks.iop.org/ERL/15/083003/mmedia). More information can be found in the SI regarding the descriptive statistics of the dataset and the results of the Kruskal-Wallis test and pairwise comparisons of the countries.

The causes of these differences stem from local history and conditions. For example, to speed reconstruction in the 1950s, Austria and Germany shifted much of their residential construction from masonry (brick and mortar) to concrete prefabrication (Wien 2006, Amtmann 2010, Pugh 2015). The low wood MI in both countries relative to the others can be attributed to the restricted use of this material for fittings and installations (Kleemann *et al* 2017, Ortlepp *et al* 2018). By contrast, the large availability of wood in Nordic countries and in Japan resulted in most residential buildings being constructed with wood (Tanikawa *et al* 2014, Gontia *et al* 2018).

These results infer that geography leads to inherent variability in infrastructure construction. This type of variability can occur on even smaller geographical scales where local materials or history strongly influence construction. As a result, seemingly equivalent products may be built in different ways depending on their location. The influence of geography on building MIs also increases parametric uncertainty whenever proxy data are required, as there can be a strong influence from local geography.

4.4. Local context

Going beyond the general region (section 4.3), there are numerous local conditions that affect the construction process and associated environmental impacts. These include the specific location of the site (within an urban core or on the periphery), the perceptions and sensitivity of neighbours to construction, the size of the site and the ground conditions (e.g. soil or rock, clay or sand), daily weather variations, and more.

As an example of the impact of local context, we discuss the GHG emissions of onsite equipment used for the construction of infrastructure products. Local climate and weather effects such as precipitation, temperature, and humidity affect worker efficiency, equipment operating efficiency, and average engine load, all of which lead to fluctuations in equipment emissions (Koehn and Brown 1985, Cole 1999,

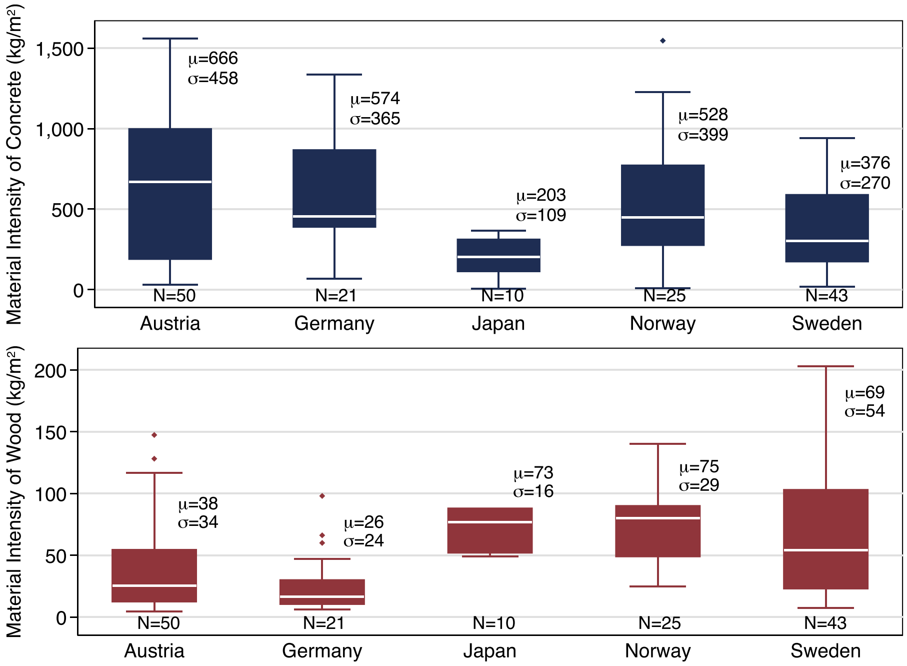

Figure 2. Box plots of concrete and wood material intensities of residential buildings in Austria, Germany, Japan, Norway, and Sweden (data from Heeren and Fishman 2019). Box plots show the median and the inter-quantile range of the material intensities. N is the number of case studies in each country, μ denotes the mean and σ represents the standard deviation of material intensity.

Shahin *et al* 2011, Devi and Palaniappan 2017). Site altitude impacts engine performance, with higher altitudes reducing fuel efficiency and increasing emissions (Caterpillar 2017, Fan 2017). Adjacent population and infrastructure affect hauling distances; road traffic obstructions similarly affect hauling time/speed, scheduling, and site layout restrictions (Ahn and Lee 2013, Devi and Palaniappan 2017); and, site size or compactness affect equipment idling rates (Hagerty 2011, Ahn and Lee 2013). Soil type influences the extent of environmental impacts. For example, denser, wetter soils require more time and higher engine loads to excavate (Lewis and Hajji 2013, Forsythe and Ding 2014, Trani *et al* 2016, Devi and Palaniappan 2017), and solid rock requires drilling—further increasing fuel use and emissions (Devi and Palaniappan 2017). Additionally, temporary works and foundation construction requirements are adapted to address soil types and water table elevations. These impacts vary from project to project, even if the final constructed products are expected to be similar. As with other drivers of infrastructure projects, this further increases the uncertainty of LCA. This has a profound impact on parametric uncertainty—particularly as many of these key inputs (e.g. worker skill) cannot be known prior to construction, or are not considered part of design plans (e.g. equipment selection).

For example, figure 3 illustrates site condition variations on emissions from excavation operations—often a substantial contributor to construction environmental impacts (Sandanayake *et al* 2016, Seo *et al* 2016, Trani *et al* 2016, Liu *et al* 2017). Many of the factors shown in the table are related directly to site conditions such as soil type, temperature, hauling distance, others are implicitly constrained by site layout (e.g. fleet size), and others are more closely related to decisions made at individual sites (see section 4.7). Results vary by up to an order of magnitude, both between studies, and associated with variation in some specific site conditions such as soil type.

Given the high variation in energy use and emissions associated with local context, the need for predictive modeling has led to the use of several techniques. Typical methods include: Multi-Linear Regression models (Lewis 2009, Hajji and Lewis 2013, Hajji 2015, Jassim *et al* 2017), Discrete Event Simulation models (Ahn *et al* 2010a, 2010b, Li and Lei 2010, Pan 2011, Jassim *et al* 2018), and Artificial Neural Networks (Ok and Sinha 2006, Jassim *et al* 2017, 2018). The proliferation of methods and models, each using different inputs, introduces a further layer of model uncertainty in embodied GHG emissions accounting.

4.5. Construction time vs manufacturing time

Constructing infrastructure products is inherently time consuming. Projects can range from months to a decade or more, depending on their complexity, size, location, material, energy, and labour requirement. In 2018, the average time to construct a multifamily building with more than 20 units in the U.S. was 17.4 months after obtaining authorization (U.S. Census Bureau 2019). This does not include the time to conceptualize, design, assess environmental impacts, and consult affected communities.

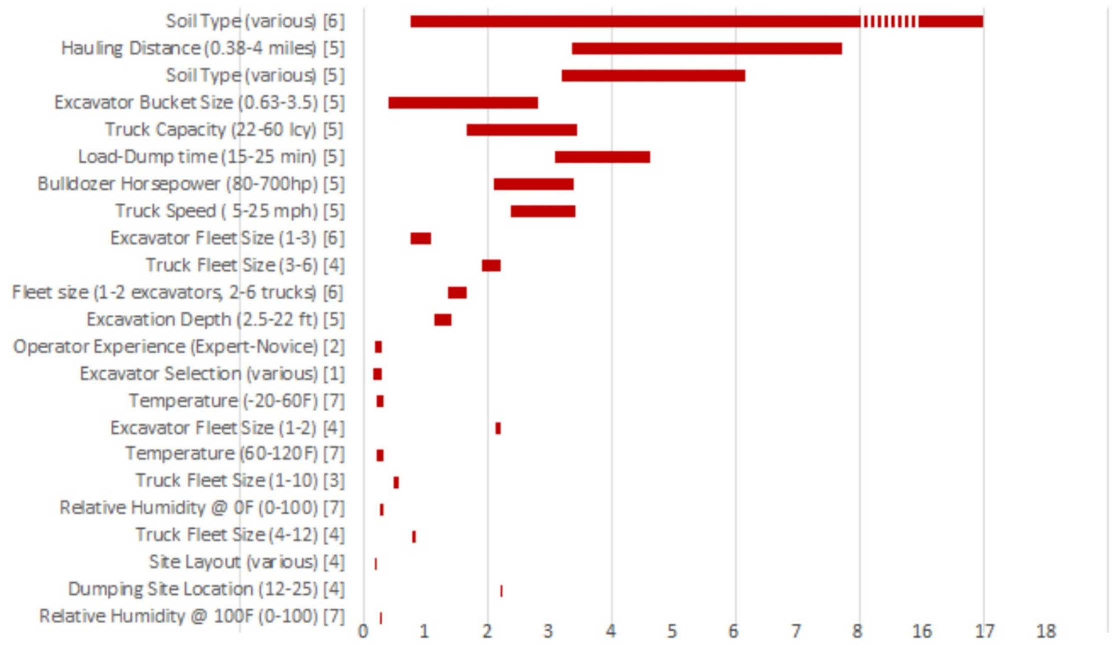

Figure 3. Impacts of selected project-specific management decisions and local conditions on the GHG intensity of soil excavation. Results are ordered according to the total range in predicted/observed emissions intensity. Categories that appear multiple times represent results from different case studies. Results presented are based on: [1] (Lewis 2009, Caterpillar 2017); [2] (Hughes and Jiang 2010); [3] (Carmichael et al 2012); [4] (Ahn and Lee 2013); [5] (Hajji 2015); [6] (Devi and Palaniappan 2017); [7] (Koehn and Brown 1985).

In transportation projects, time from initial idea to opening is measured in decades and is often more than 50 years including a decade of construction.

During the execution of the project, changes may occur in production technologies, market conditions, weather conditions, and input transportation logistics that affect the calculation of the emission factors associated with the materials, fuels and equipment used on the construction site. As a tangible example, electricity is a major contributor to the environmental impact of construction, including some materials (e.g. steel) and construction-site operations. Emissions associated with electricity production are subject to potentially large intra- and inter-annual variations, due to changes in the mix of grid electricity sources.

Figure 4 illustrates the change in GHG intensity with time for 12 construction materials, with a range on dependence on electricity for their manufacturing. table S2.1 in section 2 of the SI lists the specific matches within the Ecoinvent v3.5 database (Weidema B P *et al* 2018) for each material (e.g. Concrete Architectural = Concrete, 25 MPa CA-QC | concrete production). For each material, we substitute the default upstream electricity mix with monthly values of U.S. electricity GHG intensity from 2001 through 2018 (Carnegie Mellon 2019), as described in section 2 of the SI (tables S2.1–S2.10), and calculate the embodied GHG of the material with time.

As shown in figure 4, large variations are observed over time for the impacts of construction materials such as zinc, aluminum, steel, and copper, with far smaller variations in the emissions from concrete, which is less electricity intensive. Over a construction period from 2013–2015, steel GHG emissions would have differed by up to 11% from a high of 1016 kg CO_2e in February 2014, to a low of 909 kg CO_2e kg^{-1} steel in December 2015.

Extrapolating to a full building, figure 5 illustrates the percentage variations of the embodied GHG of non-residential buildings with typical materials compositions from China, Europe and North America (table S2.11 in the SI) due to monthly (area) and 18 month moving average (lines) variations in U.S. electricity emissions (2001–2018). Buildings with the North American composition are subject to higher inter- and intra-annual variation due to their higher average steel content (45%) compared to Europe (18%) and China (10%). Given that construction can take place over multiple years and may not be evenly distributed throughout the year (e.g. slower progress in winter months in cold climates), the use of a single average emission factor can introduce considerable false-precision in embodied emissions estimates, especially for metal-intensive buildings.

Electricity is one example of a system that will change over the long manufacturing time of infrastructure products. The environmental impacts of fuels, manufacturing processes, availability of materials, and other systems can similarly change especially on long projects. As such, the bigger the project and the longer its predicted construction time, the greater the uncertainty is likely to be. In a similar vein, planning stage assessments can be completed years

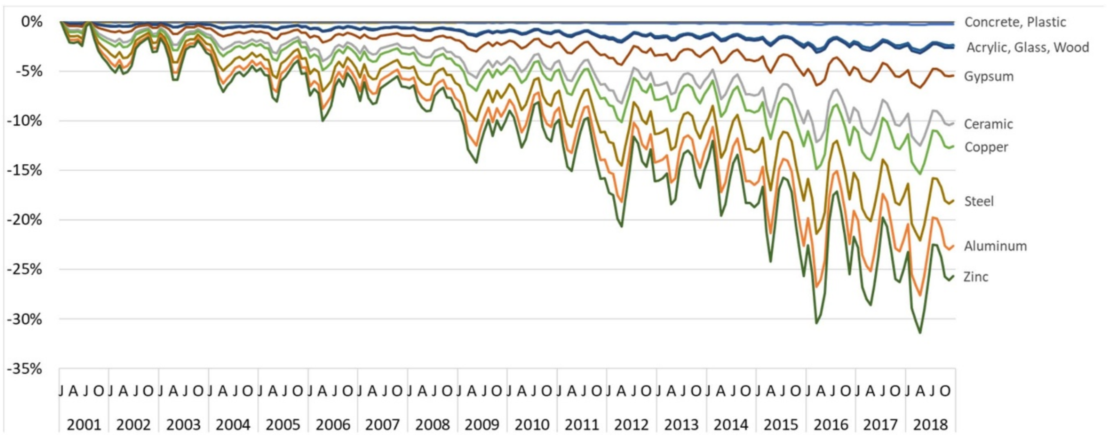

Figure 4. Percentage variation in the life cycle greenhouse gas emissions of construction materials due to monthly variations in the emissions of electricity generation in the U.S. (2001–2018).

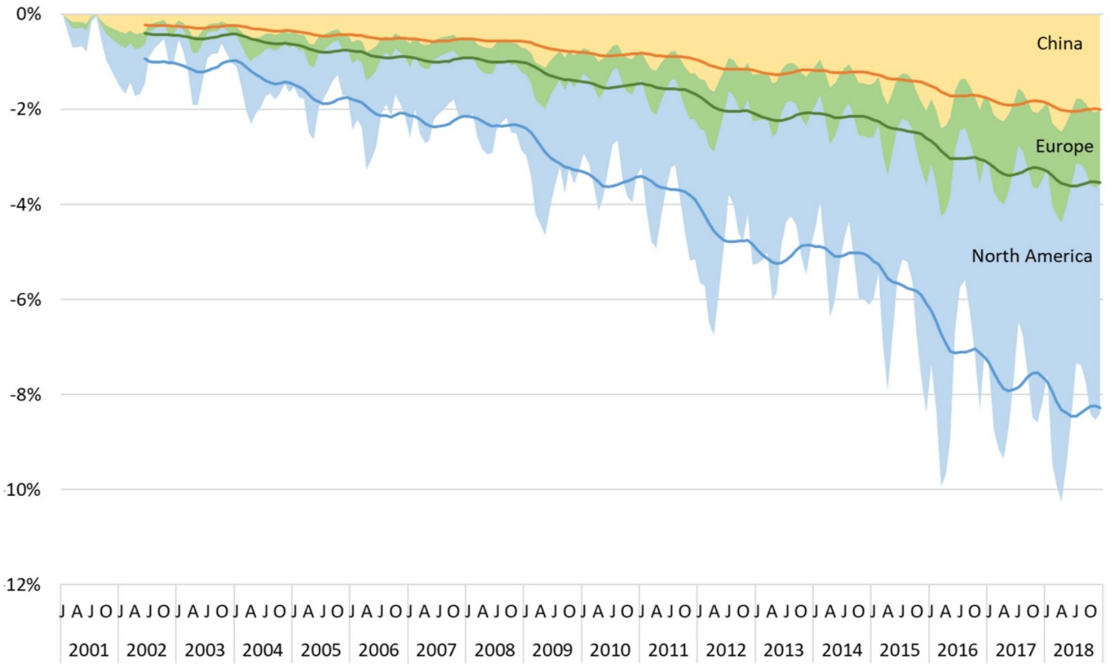

Figure 5. Percentage variation of the embodied carbon of non-residential buildings with typical materials compositions from China, Europe and North America due to monthly (area) and 18 month moving averages (lines) variations in the emissions of the electricity generation in the U.S. (2001–2018). The figure is illustrative, and so Chinese and European electricity sources were not considered.

before construction starts, thereby magnifying this impact.

Beyond changes to the background systems, the long planning period for infrastructure projects often leads to significant changes in the project scope and design features (Flyvbjerg 2014, Siemiatycki 2015). Modifications to the original scope and design of an infrastructure project can happen across the design and construction process, even years to decades after the original concept was established (Rider 2019). These changes can result in substantial differences in the product and consequently its GHG emissions, and often leads to rework or revision of works that result in cost overruns and delays (Desai and Pitroda 2015), further influencing the LCA results.

4.6. Repetition of production process

Manufactured products are generally produced in large numbers using repetitive steps, infrastructure projects by contrast are repeated less often. For example, in 2010, 2.8 million passenger cars were manufactured in the U.S; in the same year, 5917 highway bridges were built (OICA 2010, U.S. Department of Transportation 2013). In terms of LCA of infrastructure products, the scale of production is a limiting factor that makes it difficult to obtain numerous data points. As there are too few of the same product built within a suitably recent time to study and compare, it is very challenging to develop a database of infrastructure LCA to draw from for new product LCA analysis. Given the small number

Table 2. Characteristics of new single-family houses completed in U.S. in 2016 (U.S. Department of Commerce 2016) and the variation in cradle-to-gate embodied GHGs for primary exterior wall materials and framing materials.

	Primary exterior wall material					Framing material	
	Vinyl siding	Stucco	Brick	Fiber cement	Wood	Wood	Concrete
Building material (% of houses containing the material)*	27%	24%	22%	20%	5%	91%	8%
Cradle-to-gate embodied GHG (kg CO_{2e}/kg)**	1.83	0.091	0.454	0.679	0.168–0.369	0.168–0.369	0.121–0.135

*2% of the primary exterior wall material and 1% of the framing material are other materials that are not accounted for in the calculations.**From U.S. Life Cycle Inventory (LCI) Database (U.S. Life Cycle Inventory Database 2012), Ecoinvent v3.5 (Weidema B P *et al* 2018), ICE Database v3.0 (The Inventory of Carbon and Energy 2019), Environmental Product Declaration (EPD) from American Wood Council (AWC) and Canadian Wood Council (CWC) (AWC and CWC 2013a, 2013b), and EPD from (epddenmark 2016).

of products created, infrastructure LCA has to be tailored to the specific building, bridge, or tunnel being studied. As such ex-post LCA, when data is theoretically available, is of reduced value; it is too late to change the specific infrastructure product and only loosely predictive of future projects. As such, uncertainty for infrastructure LCA is unusually aleatory.

The large variation of infrastructure projects can be illustrated by residential buildings. Large cities have hundreds of thousands of buildings, more than numerically sufficient to allow for comparison and development of a background database. On closer examination, however, residential building in urban areas vary significantly in terms of type, age, size, material, function, and appearance (Meijer *et al* 2009, Tian and Choudhary 2011, Ghiassi *et al* 2017). Table 2 illustrates characteristics of 738 000 single-family houses completed in the U.S. in 2016 in terms of the percentage of houses containing the types of primary exterior wall material and framing material in the first row (U.S. Department of Commerce 2016), and the variation in cradle-to-gate embodied GHGs of these materials are calculated in the second row.

Other factors that impact the repeatedness of infrastructure projects include building codes and standards change through time (Martin *et al* 2015) disconnecting new buildings from any data gathering on older buildings built using a different code.

4.7. Scale of production

Unlike manufactured items that are produced in the same factory setting using the same technique, equipment, and personnel, constructed facilities are uniquely designed and built, adapted to site conditions, and customized to have the desired appearance and functions (Halpin and Senior 2001, Pilateris and McCabe 2003, De Wilde 2014). Due to these characteristics, there is uncertainty in material and energy use in construction, as the design and construction processes vary considerably from site to site. Previous research outlined environmental implications regarding CO_2 and local area pollutant emissions associated with on-site decisions as discussed in section 4.4.

As a result of project-specific decisions, the production of infrastructure products is similar to one-of-a-kind production where there is a high level of customization, low level of repetitiveness, large uncertainties, and complicated and dynamic supply chains (Tu and Dean 2011). It also shows similarities to the environmental assessments of emerging technologies that are at the pilot or lab scale. In the earlier stages of development, these products have limited reliable data and higher uncertainty for LCA (Sharp and Miller 2016, Cucurachi *et al* 2018, Bergerson *et al* 2019) . Even though companies gain experience by building the same type of projects, each site will have a different design and construction team, owner, design requirements, and site conditions. For example, bridges vary with respect to their style, length, height, and effective loads. As such, estimates of material and energy use do not converge and there is a lack of historical data that can be used to establish baselines or benchmarks for comparison when conducting an LCA. Instead, we use comparable or similar projects (De Wolf *et al* 2016) to establish benchmarks, but due to the wide variations that exist, uncertainty persists and the applicability of these benchmarks are limited with wide uncertainty.

There are initiatives to move site construction to standardized manufacturing facility production and include more precast, factory-manufactured, components. For example, modular buildings, units and components are made at off-site factories and transported and assembled on-site. This is favorable where repetitive units are needed such as in hotels, schools, hospitals, and offices (Ferdous *et al* 2019). Mass housing and small-scale works also include repetition. However, the one-off nature of the construction industry remains stronger in megaprojects, such as subways and airport terminals (Kwofie *et al* 2014, Brockmann *et al* 2016). A large body of literature is investigating the ability of prefabrication to reduce embodied emissions in construction, but the findings are not clear (Mao *et al* 2013, Teng et al 2018, Tavares et al 2019). By improving data collection, prefabrication might decrease the uncertainty in construction through repetition, implications for reduced uncertainty requires further study.

4.8. Division of responsibility

Project teams are typically created to deliver a particular project and disbanded after construction is complete (Halpin and Senior 2001, Yang et al 2011, Yusof et al 2016). This reduces the sharing of knowledge and best practices gained in previous projects, and transferring professional knowledge to organizational knowledge for reuse in future projects (Dave and Koskela 2009, Flyvbjerg 2014, Yusof et al 2016, Wang and Meng 2019). Typically, the key parties involved in the delivery of an infrastructure project are the client, designer, contractor and subcontractors. Each party brings their own objectives, interests, and cultures to the construction process (Arditi and Alavipour 2019). Hence, the extent to which a party comprehends the boundaries of a construction project depends upon its role in the project. Division of data follows division of responsibility, which is usually not shared vertically. The owner for instance has little knowledge of the quantities of materials used in construction; the subcontractor focuses on one specific task (e.g. concrete forming) and has little insight into the rest of the construction process. Due to the fragmented nature of the infrastructure industry, there is generally no central data source in construction projects. Within the industry, there is a tendency to protect company-specific data. For example, data on waste and site energy use is difficult to obtain from subcontractors (Moncaster and Symons 2013). Also, the available sources of information, such as building information models, bills of quantity, and cost estimates are prepared by different members of the larger construction team, using different methods and are commonly not fully in agreement. This lack of coherent data is a widely cited challenge in infrastructure LCA and introduces an inherent uncertainty as data gaps are common.

Overall, the division of responsibilities within construction products challenges the detailed data needs of high quality LCA. This uncertainty is irreducible without changing the structure of the industry or its data sharing practices.

4.9. Agglomeration of products

Infrastructure projects are large and multifaceted, with the end-product being larger and more environmentally impactful than nearly any other single product to which LCA is applied. As a result of both the division of responsibilities (section 4.8) and the sheer scale of the product, it is often necessary to model infrastructure as a sum of other products—many of which have incomplete data. By way of comparison, LCA of chemical products is often linked with process modeling in which each manufacturing stage is modeled individually using a bottom-up methodology (Garcia and You 2015, Montazeri and Eckelman 2016, Khojasteh Salkuyeh et al 2017), or collected from the manufacturers (Franklin Associates 2011). In contrast, infrastructure LCA is often forced to rely on aggregate results from other studies for entire systems found within the product. In a study of a metro line, Saxe and Guthrie (2019) relied on Chester and Horvath (2009) for estimates of the material intensity of entire surface level transit stations (Chester and Horvath 2009, Saxe and Guthrie 2019); Chester and Horvath (2009) similarly took the entire train vehicle as a single input from an LCA database (Chester and Horvath 2009). Infrastructure LCA must then accept some uncertainty stemming from the variability between sources and objects since the modeled system is unlikely to be identical to the new one as well as from any inconsistency between assumptions across prior studies (model uncertainty). Moreover, the uncertainty in infrastructure LCA unavoidably encompasses uncertainties within the LCA of its many components.

Agglomeration uncertainty is further exacerbated when the scale of the project requires the scope of input quantities to be limited. For example, it is common for LCA of infrastructure to focus only on structural materials (De Wolf et al 2017a). Similarly, emission factors often have to be approximated because the exact identity of inputs is unknown. With increased reliance on performance specifications (Lobo et al 2006, Alexander et al 2010) for example, there is little information available about material components such as concrete mix designs. We contend that these added uncertainties are a direct result of the large-scale of infrastructure projects, which represent an agglomeration of other products.

As a result of the many inputs to an infrastructure project and the uncertainty on both quantities and impact factors like GHG intensity, it is also possible for uncertainty to scale in a superlinear fashion. Simplistically, a life cycle inventory results from multiplying input quantities by their respective impact factors. In many other LCA subfields, it is common for either uncertainty of quantity or impact factors to dominate. For example, the dominant variability in grid electricity production is the relative input from energy sources such as coal vs renewables rather than uncertainty on the impact factors for each source (Weber et al 2010). The dominant variability in freight transport by diesel truck is fuel use per t-km related to cargo capacity utilization rate and drive cycle (e.g. Zhou et al 2017) rather than uncertainty in the impact factors for diesel (e.g. Venkatesh et al 2011a). Equivalently, consumer product manufacturers typically know their inputs per unit product, with uncertainty stemming primarily from the impact factors for these inputs. Infrastructure projects exhibit large parametric uncertainty in both input quantities (Hoxha *et al* 2014, Nahangi *et al* 2020) and impact factors (Häfliger *et al* 2017, Hoxha *et al* 2017, De Wolf *et al* 2017a, Pomponi and Moncaster 2018), both of which are (usually) strictly positive—leading to superlinear uncertainty when they are multiplied.

4.10. Recurring embodied energy

Finally, where in many products there is a clear end to the manufacturing stage, infrastructure products are often 're-manufactured' in the middle of their service life without changing function (e.g. repaving a road) (Makarchuk and Saxe 2019, Saxe S and Kasraian D 2020). While ongoing maintenance is not unique to infrastructure, it differs by scale and by levels of uncertainty compared with simpler, shorter-lived products. Other products' upkeep usually involves a small set of pre-defined maintenance activities such as cleaning filters and replacing refrigerant in air conditioners, but maintenance of an infrastructure project typically includes major efforts related to its numerous components and their interdependencies. For example, a burst pipe might result in damaged floor boards or allow faulty electric wiring to cause a fire. Depending on the facility, a significant portion of the overall materials (up to more than 100%) may be replaced during its lifetime. Refurbishments, as well as most maintenance activities, may take on different forms within presently used practices. Recurring embodied energy may add up to between 21% and 44% of a building's life cycle (excluding end of life) embodied energy (Dixit 2019). Within 38 years, recurring embodied energy nearly doubled the embodied GHG of a streetcar line in Toronto (Makarchuk and Saxe 2019). The uncertainty regarding these activities is further enhanced if they operate for decades and are likely to evolve. The ongoing need for maintenance and refurbishment leads to parametric uncertainty regarding the scale of future maintenance operations. For example, any assessment based on initial construction will be inaccurate as to full material needs. The total quantity and timeline of materials will be unknowable and sensitive to future weather, unforeseen events and decisions about deferred maintenance. This connects to model uncertainty and how maintenance schedules are predicted, for example with use, atmospheric chemistry, and weather (e.g. freeze thaw cycles) all affecting maintenance and future input of materials.

5. Discussions and conclusions

We opened this paper by proposing that the nature of infrastructure projects, and the limited considerations of uncertainty to date in infrastructure LCA, necessitate a detailed consideration of infrastructure uncertainty drivers. We identified four broad categories of infrastructure LCA uncertainty and 11 drivers where there are important differences between infrastructure products and the manufactured products for which LCA was originally developed and for which common uncertainty methods are most often applied: application of ISO 14040/14044 standards (functional unit, reference flow, boundaries of analysis); spatiotemporal realities underlying physical construction (geography, local context, manufacturing time); nature of the construction industry (repetition of production, scale, and division of responsibilities); and nature of infrastructure products (agglomeration of products, and recurring embodied energy). We provided a mostly qualitative and example driven discussion of the potential impact of these drivers, illustrating their importance and highlighting that they should be considered in infrastructure LCA. Future work is needed to develop and agree on approaches for quantifying and communicating these uncertainties—potentially necessitating a move beyond strict LCA toward broader application of life cycle thinking to infrastructure.

Some of the uncertainties identified are irreducible (functional unit, local context); others are sensitive to changes in the construction industry (division of responsibilities), changes in the approach to infrastructure design and construction (repetition of production), and/or collection of better data (recurring embodied energy). Many uncertainties will be difficult to quantify, but their existence should nonetheless be considered.

As infrastructure LCA becomes an increasingly influential tool in decision making about infrastructure funding, design and construction, uncertainty analysis must be standard practice, or we risk undermining the fundamental goal of reduced real-world negative environmental impacts.

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Data availability

Any data that support the findings of this study are included within the article and supporting information.

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