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People, planet and profit: Unintended consequences of legacy building materials

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Abstract

Although an explosion of new building materials are being introduced into today's market, adequate up-front research into their chemical and physical properties as well as their potential health and environmental consequences is lacking. History has provided us with several examples where building materials were broadly deployed into society only to find that health and environmental problems resulted in unintended sustainability consequences. In the following paper, we use lead and asbestos as legacy building materials to show their similar historical trends and sustainability consequences. Our research findings show unintended consequences such as: increased remediation and litigation costs; adverse health effects; offshoring of related industries; and impediments to urban revitalization. As numerous new building materials enter today's market, another building material may have already been deployed, representing the next "asbestos." This paper also proposes an alternative methodology that can be applied in a cost-effective way into existing and upcoming building materials, to minimize and prevent potential unintended consequences and create a pathway for sustainable communities. For instance, our findings show that this proposed methodology could have prevented the unintended incurred sustainability costs of approximately \$272-\$359 billion by investing roughly \$24 million in constant 2014 U.S. dollars on up-front research into lead and asbestos.

Keywords

Building materials; Triple bottom line; Sustainability consequences; Proactive research; Built environment

1. Introduction

Today's sustainability paradigm typically is conceptualized around the triple bottom line or the three pillars perspective. In 1994, John Elkington attributed the triple bottom line to the

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three Ps: people, profit and the planet, a sustainability term referred to as “P3” (EPA, 2015c, TheEconomist, 2009). From a sustainability perspective, the impact of our buildings and infrastructure (B&I) is stunning. B&I accounted for 16% of the gross domestic product (GDP) (USCB, 2007a). The production and manufacture of building components consumed 6 billion (10^9) tons of basic materials annually, or 40% of extracted materials in the United States (U.S.) (Yuan et al., 2012). Consumption and emissions are substantial when considering the total life cycle of commercial and residential buildings (Fig. 1): total energy use = 42% (EERE, 2012a); total electrical use = 74% (EERE, 2012b); total carbon dioxide (CO_2) emissions = 40% (EERE, 2012c); total freshwater withdrawals = 13% (Kenny et al., 2009) and non-industrial solid waste = 66% (EPA, 2009). It is also interesting to note that although we spend 90% of our time within buildings (EPA, 2015a), building research accounts for 0.2% of all federally funded research (USGBC, 2007).

In the built environment, history has provided us many examples of how changes to one of the sustainability pillars resulted in unintended consequences, both within the pillar and extending to the other pillars. As an example of unintended consequences occurring primarily within the planet pillar, methyl *tert*-butyl ether (MTBE) provides an interesting illustration. In removing lead from gasoline, MTBE was recommended by the US Environmental Protection Agency’s (EPA) reformulated gasoline program as one of several fuel additives that could boost octane content and oxygenate gasoline (Erdal and Goldstein, 2000), with the intended benefit of reducing air pollution. Unfortunately, MTBE’s high water solubility (~43,000 part per million (ppm)) (Sutherland et al., 2004) had the unintended consequence of vastly increasing the extent of soil/water contamination from leaking underground storage tanks, a concern previously expressed by EPA’s environmental scientists (EPA, 1992, Erdal and Goldstein, 2000). A review of 700 service station sites in the United States revealed that >80% of the active sites and 74% of the inactive sites had MTBE contamination (Hatzinger et al., 2001).

History has also provided us with many examples of how changes in one of the pillars resulted in unintended consequences in another pillar. An excellent example is “sick building syndrome” (SBS). In short, the energy crisis of the 1970’s significantly increased the cost of heating or cooling a building (profit). Building owners, faced with these increasing costs, tried to decrease their energy costs by increasing the building efficiency through insulation and decreasing the amount of fresh or makeup air to the building (profit). The unintended consequence was an increase in indoor air pollution that concurrently increased health complaints from the building occupants resulting in “sick building syndrome” (people). At the height of the crisis, the World Health Organization (WHO) estimated that up to 30% of the new and remodeled buildings may have been linked to “sick building syndrome” (EPA, 1991). Approximately 30–70 million workers in the U.S. were estimated to have exhibited SBS related symptoms (Mikatavage et al., 1995).

This paper will focus upon two legacy materials issues from a triple bottom line sustainability perspective as well as a current class of building materials centered on nanotechnology. This is quite important given that the number of unique substances available to create new materials and products has expanded at an exponential rate. As an example, the Chemical Abstracts Service (CAS) Registry for unique chemical substances

has seen a 730-fold increase from 1965 through 2014 as illustrated in Fig. 2. (e.g., alloys, coordination compounds, minerals, mixtures, polymers and salts, and sequences) (Binetti et al., 2008, CAS, 2008, CAS, 2011, CAS, 2014a, CAS, 2014b). The exponential equation of the trendline in Fig. 2 shows that the CAS substances increased at an annual rate of about 11.6%. This increase in the creation of new substances has coincided with an increase in the number of building materials available for use. Case in point, there are over 100 types of decking materials today (Colgan, 2009, Pepitone, 2009) compared to four wood types in the 1970s (StarCraft, 2014). Given the explosion of building materials in use today, we present an alternative, lower cost method that employs up-front, proactive research to prevent/attenuate future legacy issues. The proposed path is sustainable - pay a little now to understand a building material's potential health and environmental impact rather than paying dearly later when a building material is broadly deployed throughout society having unintended health and/or environmental consequences.

2. Materials and methods

Observing temporal and spatial patterns of legacy materials and its effect upon the three sustainability pillars is a critical part of this paper. In using statistical data and analysis, the sustainability aspects of building legacy materials were typically evaluated using time-series data plots with information obtained from reputable sources including government agencies and peer-review literature. Descriptive statistics are used to illustrate both the central tendencies (e.g., mean) and variability (e.g., range) where possible. All the data presented in this paper were publicly available with an attempt to qualify reliability, relevancy, and representativeness. Sparse data sets and/or potential bias were specifically called out within this article.

With regard to reliability, data were collected from sources considered recognized, credible and reputable. Data was typically ranked using the following order, with an assumed most to least reliable, understanding that each category has its potential for bias: peer-reviewed journals, governmental agencies, professional organizations, non-profit organizations, and industry organizations. With regard to data relevancy, we considered both temporal and spatial aspects of data. For example, national data sets that extend over a long time period would be considered more relevant compared to a short-term, local result. Additionally, it is worth noting that new scientific information may often challenge established dogma. Typically, established "scientific facts" have their own inertia before new knowledge is accepted in the scientific and public domains (Ross and Anderson, 1982). In this article, we attempt to point out both established dogma as well as the new scientific information.

We have also attempted to maximize the representativeness of data while avoiding biases resulting from selection bias. Identifying different opinions among groups and acknowledging their potential selection bias is crucial in sifting through and reporting representative legacy material data. Vetted (e.g., peer-review publication) data with fully elucidated methodologies (i.e., identifying both their respective pros and cons) were selected preferentially as representative data sets in the paper. To improve the data completeness, we synthesized data from different sources after confirming methodologies from each source. We attempted to produce complete datasets while minimizing systematic errors caused by

different methods and terminology. Acknowledgments within the text and figures were made to denote missing data for specific year(s). In addition, differences between data from data sources were acknowledged in the figure notes.

3. Results: business as usual

Several of today's legacy building materials have followed surprisingly similar historical trends:

1. *Broad societal adoption*: building materials, having remarkable chemical and/or material properties, become known and desired by the end user. Industries meet consumer demands by increasing output, often developing new building materials that take advantage of the material's chemical/material properties.
2. *Indications of health and/or environmental issues*: although industries typically have limited evidence suggesting potential health or environmental problems associated with the building material, these adverse effects become widely known by the public, often in a sensationalistic fashion. Public panic often ensues with calls for immediate government intervention.
3. *Government intervention and litigation*: using limited scientific research information, government implements guidance/regulations to safeguard the public. Costly litigation closely follows government intervention in an attempt to remedy the affected population and punish the responsible parties including building material manufacturers and building owners.
4. *Unintended consequences*: subsequent research provides additional information on health or environmental effects, sometimes running contrary to established policy. Unintended consequences result, often at odds to a sustainability paradigm. To illustrate this process, asbestos and lead will be used to illustrate the "business as usual" case for legacy building materials with known health effects.

Supporting information regarding this process is explored and expanded in the following sections.

3.1. Broad societal adoption

Due to factors such as costs, chemical and physical properties, a building material is introduced and broadly deployed throughout society. Lead was widely incorporated into a variety of building materials from paints to piping since early Roman times. In the twentieth century, its use significantly increased within the United States as the world's leading producer and consumer of lead at 1.3 million tons per year (Lewis, 1985).

Lead was predominantly used in paints for moisture resistance until mid-1950s, followed by its marked use in gasoline to boost octane content (Fig. 3). A U.S. Department of Housing and Urban Development (HUD) study found that 83 percent of privately-owned homes and 86 percent of public housing built before 1980 contained lead-based paints (HUD, 1995b). Approximately 0.75 million tons (25% of 3 million tons applied) of lead on painted walls

and structures of pre-1980 housing units was unsound and deteriorated (CDC, 1991), consisting of about 0.5 million tons from the exterior and 0.25 million tons from the interior (HUD, 1990, HUD, 1995b). In contrast, approximately 4–5 million tons of gasoline lead (75% of total 5.9 million tons of gasoline lead consumed) were deposited in the environment in soil and dust as a result of lead gasoline particulate deposition (Mielke, 1999). Therefore, the extensive use of lead in gasoline appears to be the major contributor soil contamination around buildings, particularly in cities (Laidlaw and Filippelli, 2008), with additional contribution from exterior paint falling from structures. With regard to lead use in water supply system, lead was adopted widely due to the excellent properties of corrosion resistance and ductility. In 1900 more than 70% of cities with populations greater than 30,000 used lead water lines. 73% of 153 municipalities surveyed by EPA in 1984 still had lead service lines (Rabin, 2008).

Evidence of asbestos use in building materials and cloths dates to early Greek and Roman times. The first century historian Pliny the Elder noted the early deaths of the asbestos miners and suggested the use of a respirator made of bladder skin to protect workers (Barbalace, 2004). Asbestos, a naturally occurring material, was widely incorporated into a wide variety of building materials (1920–1970s) for its ability to add strength to materials as well as its excellent thermal and chemical resistance properties. It can often be found in concrete, concrete tile products, and building insulation, of which about 3000 products may have contained up to 50% asbestos by weight (Radford-University, 2014). Approximately 30 million US homes are estimated to contain asbestos in roofs, attics, ceilings, floors, walls, ducts, and/or pipes (EIA, 1992, Kazan-Allen, 2007, OSHA, 2011, Testa et al., 2011). Based upon a 1984 national survey conducted by the EPA, approximately 2.2 million public and commercial buildings contained asbestos (EPA, 1984a, EPA, 1988). In the early 1970s, the annual asbestos consumption increased to about 800,000 tons (Fig. 4), continuously decreasing since the 1970s due to health concerns (Radford-University, 2014, Virta, 2006b).

3.2. Indications of health and/or environmental issues

Health effects associated with lead poisoning have been known since Roman times (Grout, 2011) and the term “crazy as a painter” referred to the demented behavior of lead-poisoned painters. In the U.S. occupational environment, significant poisoning events occurred through early 1990s. As an example, more than 61% of workers in the lead smelting industry were exposed to a 200 μg per cubic meter ($\mu\text{g}/\text{m}^3$) before mid-1970s which could cause blood lead levels (BLLs) above 80 $\mu\text{g}/\text{dL}$ (Bayer, 1986). Later in the late 1980s and early 1990s, construction workers at 8 different worksites in five states developed lead poisoning because the workers inhaled or ingested lead dust and fumes during abrasive blasting, sanding, cutting, welding of structures coated with lead-containing paints (NIOSH, 1992). The BLLs for these workers ranged from 51 to 160 μg per deciliter ($\mu\text{g}/\text{dL}$) compared to the mean BLL for the U.S. population of 13.9 $\mu\text{g}/\text{dL}$. Such high BLLs resulted in acute lead poisoning including damage to the nervous system, including wrist or foot drop, tremors, and convulsions or seizures (NIOSH, 1992).

Another example of exposure was lead poisoning in the general public attributed to the use of leaded paints and gasoline. In 1970 the estimated annual incidence of symptomatic and

asymptomatic lead poisoning was as high as 250,000 cases (Hernberg, 2000). Children within cities had much higher BLLs compared to rural areas from 1976 to 80 (20 vs. 13.9 $\mu\text{g/dL}$) (Mielke et al., 1984/85). As a specific example, 1600 children had BLLs over 30 $\mu\text{g/dL}$ in the city of Chicago during the mid-1980s (LaBelle, 1986). Such high BLLs of children resulted in damage of major organ functions as well as developmental and cognitive disorders (Bellinger and Bellinger, 2006, Hernberg, 2000).

With the Industrial Revolution, commercial use of asbestos increased steadily until the 1970s when its use markedly dropped over health concerns (Fig. 4). In the late 1950s and 1960s an association between asbestos exposure and health effects became known to the public (Virta, 2006b). In 1964, Dr. Irving Selikoff presented his landmark study about asbestos-mesothelioma/lung cancer link among asbestos insulation workers revealing approximately sevenfold higher deaths of the asbestos insulation workers than expected (45 vs. 6.6 deaths) (Breslow et al., 1977, ILO, 2011). Several factors limited the study including: exposure dose, smoking habits, personal history, and types of asbestos fibers. The study also showed an association to asbestos workers' family member exposures (Selikoff et al., 1964). In a similar time period, other studies discussed asbestos exposure limits and risks in various occupational environments (Williams et al., 2007).

3.3. Government intervention and litigation

Following documented cases of illness, disease and poisoning, federal intervention for both lead and asbestos occurred in the early 1970s. As documented by Fig. 3, Fig. 4, these materials had been widely adopted and used in our society until federal regulations were enacted. It should be noted that paint manufacturers voluntarily reduced lead in paints before federal regulations were adopted. Following the original regulations, amendments were made, primarily in the form of lower exposure levels. Lead based paint regulations focused upon children's lead poisoning while asbestos regulations targeted both occupational workers and school-aged children.

Focusing only upon federally assisted housing, the Lead Based Paint Poisoning Prevention Act of 1971 was amended in 1992 by the Residential Lead-Based Paint Hazard Reduction Act (RLPHRA) to include both remediation and disclosure of lead-based paint (LBP) (GAO, 1994, HUD, 2004b). Including deterioration, RLPHRA also included intact lead paint with friction, chewable, and impact surfaces, such as doors and windows. RLPHRA also added control of lead-contaminated dust or soil associated with the presence of LBP and clearance levels after control work. It required owners or landlords to disclose lead based paint hazards to buyers and tenants before the sale or lease of most housing built before 1978. HUD established the residential lead dust hazard standards of 0.43 milligrams per square meter (mg/m^2) for a floor and 2.7 mg/m^2 for an interior window sill in 1999 (HUD, 2004a). Another milestone lead regulation was EPA's gradual phase-out of maximum allowable lead levels of leaded gasoline from 1.7 g per gallon (g/gal) in 1975 to 0.1 g/gal in 1986 and to prohibited leaded gas use after 1995 (Bridbord and Hanson, 2009, EPA, 2000). In addition, the lead poisoning previously discussed, aided in reducing occupational exposure standards to the permissible exposure level (PEL) of 50 $\mu\text{g/m}^3$ by 1993 in an attempt to decrease worker BLLs to below 40 $\mu\text{g/dL}$ in all the industries (HUD, 1995a, OSHA, 1993). During

1960–1992, the CDC recommended limit for lead in children’s blood decreased from 60 to 10 µg/dL (ATSDR, 2007, Bellinger and Bellinger, 2006); it is also worth noting that the current CDC recommendation is 5 µg/dL (CDC, 2013).

With respect to asbestos regulations, the newly-formed Occupational Safety and Health Administration (OSHA) initially enacted a PEL of 12 fibers per cubic centimeter (f/cc) in 1971 (OSHA, 1994). In 1972, OSHA promulgated a new PEL of 5 f/cc (OSHA, 1994). This exposure limit was further decreased to 0.1 f/cc in 1994 (Brownson et al., 2012, University-of-Montana, 2014). Also, National Emissions Standards for Hazardous Air Pollutants (NESHAP) started regulating friable asbestos material in buildings by setting 1% asbestos content limit of asbestos containing materials by weight in 1970s and no visible emission of asbestos particulate material from the repair or demolition of buildings except for a single-family dwellings (EPA, 1973). Subsequently, the Asbestos Hazard Emergency Response Act (AHERA) of 1986 required the clearance level 0.01 f/cc and all school buildings to be inspected for asbestos-containing materials (EPA, 1987). The Asbestos School Hazard Abatement Reauthorization Act amended AHERA to require individuals performing asbestos inspections and abatement projects not only in school, but also in commercial and public buildings (EPA, 1994).

3.3.1. Benefits from regulations—Lead and asbestos regulations contributed to public health improvements attributable to human exposure reductions. National Health and Nutrition Examination Surveys (NHANES) from the period of 1976–1980 to 1991–1994 revealed that children with elevated BLLs (BLLs > 10 µg/dL) had decreased from 77.8% to 4.4% (CDC, 2005). Regulatory exposure limits combined with improved industrial hygiene practices in the early 1970s reduced both occupational and building fiber concentrations (e.g., building occupants, maintenance, insulation, boiler workers) (Williams et al., 2007). The occupational exposure to workers handling asbestos containing insulation (e.g., construction workers, asbestos containing product manufacturers) achieved approximately up to 5-fold reduction in average concentrations (Williams et al., 2007).

3.3.2. Costs of remediation and litigation—Total estimates of U.S. lead and asbestos abatement and litigation are expected to approach \$2.1 trillion in constant 2014 U.S. dollars with actual incurred costs of \$272–\$359 billion (Fig. 5) (BLS, 2015). The removal costs for approximately 60.8 million LBP containing homes are estimated as \$953 billion in the today’s value (HUD, 1990) with an actual incurred cost of \$44–87 billion (Levin, 2005, OTA, 1994, USCB, 2000, USCB, 2002, USCB, 2007b, USCB, 2012). \$24 billion is estimated for replacing lead service lines (Kirmeyer et al., 1994), and \$9 billion for the phase-out of lead from gasoline (EPA, 1985, Schwartz, 1994). The estimates of asbestos removal for approximately 2.2 million public and commercial buildings are as high as \$324 billion (EPA, 1988, Mossman et al., 1990). While no references were found to estimate the asbestos remediation costs associated with roughly 30 million homes (Kazan-Allen, 2007, OSHA, 2011, Testa et al., 2011), assuming an average cost of \$10,000 per home (DoItYourself, 2015, Walker, 2011a) places the total residential asbestos remediation bill as high as \$300 billion. This estimate is based on a conservative assumption where asbestos-containing attic insulations of 30 million homes (CARD, 2016, OSHA, 2011, Reuben, 2010)

can average the removal cost of around \$10,000 per home (Eakes, 2014), not counting additional costs of removing asbestos from other parts (e.g., roofs, ceilings, sidings, floors, walls, ducts, and/or pipes). To date, the actual incurred costs of buildings asbestos abatement range approximately \$131-\$175 billion (Levin, 2005, OSHA, 1995, OTA, 1994, USCB, 2000, USCB, 2002, USCB, 2007b, USCB, 2012).

Litigation associated with lead and asbestos has also resulted in unintended costs. About \$5 billion was incurred by lead paint litigation against landlords (Wriggins, 1997). Roughly 50 mass tort lawsuits, with estimated costs approaching \$134 billion (Richardson, 2005) have been unsuccessfully filed. One recent \$1 billion lawsuit is currently undergoing repeal (Rosenblatt, 2013). This is a relatively new phenomena compared to asbestos lawsuits. In contrast, 730,000 individuals filed claims for asbestos injuries through 2002 (White, 2004) with twelve large companies reporting 520,000 asbestos claims filed in 2000 alone (Carroll et al., 2002). As a result, the today's values of cumulatively unintended costs associated with litigation dramatically increased to \$92 billion with a predicted cost of \$349 billion (Carroll et al., 2002, White, 2004). It is noteworthy that typical plaintiff lawyer's fees average one third of the settlement amount by a contingency fee arrangement and defendant lawyer's fees are paid at an hourly rate (Boesch, 2015). In the asbestos case, approximately 59% of the total litigation costs were attributed to 29% for plaintiffs' legal fees and 30% for defense legal fees (White, 2004).

3.4. Unintended consequences

3.4.1. Unintended consequences of regulation—Scientific research continuously evolves and changes, such that common knowledge of the past can radically change with new information. Unfortunately laws and regulations initially promulgated to address societal or environmental issues do not tend to concurrently evolve. The result of this disconnect can create unintended consequences. In looking at legacy materials, such as lead and asbestos, several issues have resulted in unintended regulatory consequences including: 1) costly removal of materials not necessarily associated adverse health consequences, and 2) fundamental lack of understanding of the chemical/physical properties of the legacy materials leading to costly remediation.

While hundreds of billions of dollars were spent on remediating both lead and asbestos of buildings, the continued emphasis on the removal of intact lead paint and asbestos building materials has resulted in increased exposure levels and health risks to building occupants. Six of the 12 studies on effectiveness of lead paint removal in the U.S. (Battelle, 1998) showed the lead paint removal increased both airborne lead dust levels and human BLLs. Three studies—Baltimore Traditional/Modified Paint Abatement (Farfel and Chisolm, 1990), Boston Retrospective Paint Abatement (Amitai et al., 1991), Phase II of the Boston 3-City Soil Abatement (Aschengrau et al., 1997)—showed that the paint removal elevated children's BLLs by 1.0–6.8 µg/dL. Two other studies—Central Massachusetts Retrospective (Swindell et al., 1994) and the Baltimore Repair and Maintenance Paint Abatement (Battelle, 1998)—showed post lead abatement BLLs increases up to 2.5 µg/dL for young children when compared to with pre-abatement BLLs. Another study in Denver, the Comprehensive Abatement Performance (CAP), reported the abated homes' surface lead

load levels ($\mu\text{g}/\text{ft}^2$) were significantly higher than the unabated ones (e.g., 370% higher in air duct, 124% higher in exterior entryway, 84% higher in window sill, and 76% higher in the floor) (Battelle, 1995, Battelle, 1998). According to 23 projects that measured asbestos abatement effectiveness, asbestos airborne levels increased postabatement levels in 13 projects up to one order of magnitude when compared to pre-abatement levels (HEI-AR, 1991). As another example, indoor asbestos concentrations within asbestos-containing buildings can be up to one order of magnitude lower when compared to outdoor exposures in urban environments (HEI-AR, 1991).

In addition to the potential exposure from abatement, the crucial exposure route of lead has been historically attributed to lead paints rather than lead in soils resulting from the use of leaded gasoline. Scientific evidence has shown that continued emphasis on lead paint removal appears to be out of step with the prevention of children's lead exposure because lead contaminated soils appear to be the key source of exposure (Mielke and Reagan, 1998, Zahran et al., 2013). In addition to eating paint chips due to lead's sweetness, children are also exposed to leaded soils and dust that contaminate household surfaces. As shown previously, lead contamination of soils appears to be five to seven times higher from leaded gasoline than lead paint. Studies on soil lead contamination in Baltimore, MD, New Orleans, LA, urban areas in Illinois, the Twin Cities, MN, and other cities showed lead contaminated soils have been significantly associated with leaded gasoline (LaBelle, 1986, Laidlaw and Filippelli, 2008, Mielke, 1999, Mielke et al., 2011). The Twin Cities were 10 times (Mielke, 1999) and 60 times greater than levels found in adjacent suburbs and rural Minnesota, respectively with 95% of all the contamination being attributed to leaded gasoline (ATSDR, 2008).

The lack of understanding of the chemical/physical properties of asbestos provides another example of an unintended consequence. Asbestos regulations have treated all forms of asbestos in the same manner (Brownson et al., 2012, Langer, 2008) although there are significant material property differences between the various asbestos forms. For example, a serpentine (i.e., chrysotile) and amphiboles (e.g., amosite, crocidolite) in Fig. 6 have fundamental chemical and physical differences, leading to different toxicity within the lungs (HEI-AR, 1991, NRC, 1984). Chrysotile consists of thin, rolled magnesium and silicate sheets that are soluble in the lungs while amphiboles consist of double chains of silicate tetrahedral structures that are insoluble in the lungs (Bernstein et al., 2013). This fundamental structural/chemical difference makes amphibole fibers over 100 times more durable in the lungs when compared to chrysotile fibers (Bernstein and Hoskins, 2006).

The relative health risks of the amphiboles amosite and crocidolite are 100 and 500 times greater for mesothelioma, respectively, compared to chrysotile. In addition, amphibole lung cancer risk can be up to 50 times higher than that of chrysotile (Hodgson and Darnton, 2000, NIOSH, 2011). As such, cumulative exposures of 0.01 chrysotile f/cc-years are estimated to result in insignificant risk level (i.e., less than 1 deaths per 100,000 exposed to chrysotile) due to mesothelioma or lung cancer (Hodgson and Darnton, 2000). However, when comparing the asbestos types, over 95% asbestos used in building materials is chrysotile (Spengler et al., 1989). In asbestos containing buildings, occupant exposures are often one to two orders of magnitude lower than this cumulative exposure level making it highly unlikely

that building occupant exposures would result in asbestos related diseases (Spengler et al., 1989). Similarly, only 2% of the fibers were amphiboles in air samples from 315 different buildings nationwide (Lee et al., 1992), and lifetime asbestos cancer risks to building occupants were estimated to be 1.1–2.1 deaths per million exposed to asbestos fibers (Lee and Van Orden, 2008). Accordingly, the overestimation of building occupants' health risk may have resulted in costly and potentially unnecessary removal of intact asbestos building material composed of chrysotile fibers.

Health risks of asbestos overestimated by regulation (Camus, 2001) also appears to have promoted using asbestos substitutes that had poorly understood health effects and material properties (ICF, 1989, Krusell and Cogley, 1982). As an example, synthetic vitreous fibers (SVF) were used as an asbestos substitute. However, SVF is also biopersistent, a key health effect determinant (Hesterberg and Hart, 2001). As such, SVFs can be one order of magnitude higher in the lungs when compared to chrysotile asbestos fibers (Bernstein and Hoskins, 2006). Long-term inhalation exposure to SVFs also appears to have resulted in similar adverse health effects such as lung cancer or mesothelioma (ATSDR, 2004a, ATSDR, 2004b, Hesterberg and Hart, 2001).

Additionally, asbestos substitutes are not as materially sound and durable, lacking both fire resistance and dimensional stability (ICF, 1989) leading both to decreased service life and premature failure (Kim and Rigdon, 1998, Miller et al., 2015). For example, glass fiber, mineral wool, and organic synthetic materials are 1.5–8 times lower in thermal resistance; likewise, aramid fiber, glass fiber, and mineral wool are about twice lower in tensile strengths compared to chrysotile (Virta, 2002, Virta, 2006a). As such, shingles and corrugated sheets reinforced by fiberglass, cellulose, or polyvinyl chloride (PVC) typically require replacement twice as frequently as their asbestos counterparts (ICF, 1989) resulting in a significant increase in material consumption and labor costs. With respect to building's fire safety, premature failure of building structures such as ceilings and floors equipped glass-fiber or cellulose fiber was a key factor for the collapse of the MGM Grand Hotel building in 1980 and the Sight and Sound Theater building in 1997 (CCFD, 1980, FEMA, 1997). Therefore, asbestos substitutes having similar health effects and poor material properties and have resulted in several unintended sustainability consequences affecting people (similar health effects), profit (decreased service life, higher probability of traumatic building material failure), and the planet pillars (increased consumption of materials).

3.4.2. Shifting material production to less developed nations—Both regulation and litigation within the United States and other developed countries have shifted material production for both asbestos and lead to less developed countries. Several unintended consequences have resulted including: 1) dismantling the related material industries in developed countries (profit pillar), and 2) shifting the associated health/environmental consequences to less developed countries (people & planet pillars) (Harris and Kahwa, 2003, ILO, 1998, Tong et al., 2000).

Litigation and regulation in the United States has had the unintended consequence of losing every asbestos related industry as well as the last lead smelter. Approximately 350,000 tons of lead per year has been mined and exported from the United States since 2010, ranking

third in the world (USGS, 2013, USGS, 2015d). The processing of a portion of this lead had occurred until recently at Doe Run lead smelter in Herculaneum, Missouri (1892 until 2014) (USGS, 2015d). The consequence of removing these US industries is that these refined materials are still being imported to the United States—395,000 tons of lead per year since 2010 (USGS, 2015d) and 4230 tons of asbestos per year since 2000 (USGS, 2014). This shift (shipping out raw materials and shipping in finished products) resulted in domestic economic losses (profit pillar) as well adverse environmental factors such as air pollution from material transport (planet pillar).

As these materials continue to be used both in the US and in other countries, the production has shifted to less developed countries that do not prioritize human exposure or mitigate environmental damage. For global lead production, China, Mexico, India, Russia & Kazakhstan shared approximately 76% of the total in 2010 (USGS, 2012). As examples, over 51% of Chinese and Indian children had BLLs higher than the CDC's elevated blood lead level (EBLL) of 10 µg/dL in the mid and late 1990s (Shen et al., 1996, Tong et al., 2000). Comparatively, 4.4% for the U.S. children BLLs were above the EBLL (CDC, 2005). For global asbestos production, Russia, Kazakhstan, China, Brazil, Zimbabwe, and India shared over 95% of the total since 2005 (Fig. 7) (USGS, 2015a). Occupational asbestos exposure levels in China and India are similar to the U.S. occupational exposure levels before the early regulation era. Although engineering controls exist, their exposure levels were one to three orders of magnitude higher than the current U.S. OSHA PEL (Joshi et al., 2004, Luo et al., 2003, Ramanathan and Subramanian, 2001, Wang et al., 2013). Shifting material production simultaneously resulted in economic loss to developed countries and increased health/environmental consequences for less developed countries.

3.4.3. The consequence of high remediation costs—Remediation of lead and/or asbestos carries a significant financial burden to a building owner and the profit pillar in general. In some cases, high remediation costs associated with lead and asbestos renovation costs can actually exceed its estimated property value. Several unintended consequences have resulted including: (1) forcing building owners to neglect and abandon their buildings and (2) increasing impediments to community revitalization (NVPC, 2005). For 139-square-meter (= 1500-square-foot) home remediation, the costs can be as high as \$17,000 for lead paint (Walker, 2011b), \$5000 for replacing lead-bearing solder and pipes (Bousquin, 2010), and \$10,000 for asbestos (Walker, 2011a), a conservative low-to-average remediation assumption acknowledging that remediation costs could be significantly higher. Combined costs of remediation and other renovation efforts can exceed the average home value of approximately \$118,000 (BLS, 2015, USCB and HUD, 1973). Commercial building asbestos remediation can range from 21% to 32% of building value, representing both a financial and liability burden (Fisher et al., 1993). As a result, any planned renovations to increase the building value will be significantly dampened by the additional remediation costs (HUD, 2001). In many cases, building owners decide against renovations altogether, leading to increased vacant and abandoned structures, especially in cities (Mallach, 2010). Estimated housing stocks abandoned by owners in distressed cities ranged 4%–10% or more (Brachman, 2005), mostly associated with a renovation cost exceeding a value of the property (Brachman, 2005, NVPC, 2005, Reiss, 1996).

As vacant and abandoned buildings have been piled up in cities, public safety of abandoned properties, associated tax revenue losses and the decreasing value of neighboring properties have impeded city revitalization. Although the urban population has increased 160% since 1950 (USCB, 1995, USCB, 2015), the vacant and abandoned buildings in the U.S. urban area has disproportionately increased by approximately 510% (USCB, 1953, USCB, 2013). The maintenance costs and tax revenue losses resulting from the increased vacant and abandoned buildings can be tens of millions of dollars to a city. In addition, these buildings are linked into increased rates of community crime (e.g., arson and violence) (GAO, 2011, HUD, 2014). 91% cities surveyed by the United States Conference of Mayors (USCM) struggled with the lack of remediation funds to address such vacant or abandoned buildings (USCM, 1999).

The impediment to revitalization resulting from a myriad of abandoned buildings and costly demolition are particularly severe in older, industry-based cities facing population losses. Rust belt cities such as Baltimore, Buffalo, Cincinnati, Cleveland, Detroit, Newark, Philadelphia, Pittsburgh, and St. Louis have lost over one-third of their urban population in comparison to their 1950s population statistics (ACHP, 2014, Glaeser and Gyourko, 2005). A large number of pre-1980 built buildings with lead and/or asbestos containing materials have increased the number of vacant and abandoned buildings (HUD, 2014, Mallach, 2012). The average number of abandoned buildings in older industrial cities was significantly higher, up to about 14 times, compared to 70 cities surveyed nationwide (Pagano and Bowman, 2000). Eight Ohio cities have demolished about 50,000 housing units since 2010 with average demolition costs per unit of up to \$8000 (Mallach, 2012). The average costs of demolition per building in Baltimore, Philadelphia, New York City, Buffalo, Detroit, and in other older industrial cities can be up to \$40,000 (HUD, 2014, Mallach, 2012). In particular, about 94% of 365,058 homes in Detroit were built before 1980 (USCB, 2010). Approximately 67% are estimated to contain lead paint (HUD, 2011, USCB, 2010) and to a lesser extent asbestos (CPSC, 2015, DBRTF, 2014c). Approximately 27% of Detroit's 263,569 building structures are destined for demolition in 5 years (DBRTF, 2014a, DBRTF, 2014c). The total costs for Detroit's revitalization are estimated to range from \$1.4 billion to \$1.9 billion (DBRTF, 2014b), a significant financial impediment.

4. Discussion: proposed alternate methodology using proactive building material research

What might have happened if proactive R&D coupled with coordinated communications of findings to society had occurred before rather than after broad chemical/material adoption? This is an exceptionally daunting task as previously discussed due to the vast number of chemicals and materials that enter the market (Fig. 2). As an example, there are over 84,000 chemical substances (i.e., 62,000 grandfathered and 22,000 newly added after 1976) listed in EPA's Toxic Substances Control Act (TSCA) inventory (Schierow, 2009). A threshold production volume of new chemicals to be on the list is 10,000 kg (kg) per year at a single manufacturing site (EPA, 2011, EPA, 2015b). Approximately 82% of the TSCA substances have no health effects and/or environmental fate/effects testing (EPA, 2003, Schierow, 2009, Wilson and Schwarzman, 2009), a conservative assumption where all of the premanufacture

notices' substances having test data have been added into the TSCA inventory. It should also be noted that TSCA listed substances exclude a much larger number of low production substances. With the huge number of chemicals substances in the market today, it is interesting to note that EPA's Integrated Risk Information System (IRIS) Dataset has human health and/or environmental information on only 557 chemical substances (Gray and Cohen, 2012).

Given the consequences of legacy issues previously discussed, what chemicals and materials currently used by society represent the next "asbestos?" One potential example is engineered nanomaterials. Societal use of nanotechnology and related engineered nanomaterials has markedly increased. For example, nanotechnology articles have shown a quasi-exponential annual growth rate of 20.7% (1991–2004) (Li et al., 2008), which introduces a new dimension to the potential for human exposure and toxicological properties. One of the benefits of using nanomaterials is to enhance/modify their chemical (e.g., reactivity) and material (e.g., solubility) properties from traditional "bulk" behavior. Even with appropriate health and environmental fate/effects testing for a bulk chemical, will this be sufficient for engineered nanomaterials? As an illustrative example, bulk titanium dioxide typically is thought of as an unreactive white metal oxide while nano-scale titanium dioxide become transparent, conductive, and photoactive (Warheit, 2008). These property changes of nano TiO₂ have been broadly used—about 14-fold increase in nano-TiO₂ consumption during the 2000s (Robichaud et al., 2009) on consumer products, such as pigment, solar cells, self-cleaning windows, and cement (Lee et al., 2010). In contrast, safety data sheet information is often prepared from parent material and does not contain additional information regarding the changed chemical and/or material properties as well as its potential health/environmental effects through nano-scaling the material (Lee et al., 2010).

Adequate up-front research can attenuate and prevent future legacy issues by modifying and/or removing potential building legacy materials before broad deployment into society. Latex paint and poured gymnasium rubber flooring (i.e., Tartan flooring) are the illustrative examples. Both of these building materials were formulated with phenylmercuric acetate (PMA), a form of mercury. PMA was used in 25–30% of latex paint as a preservative to control bacteria, mildew and other fungi before it was banned in 1991 (Mielke and Gonzales, 2008). Also, PMA was added as a catalyst for polymerization in hundreds of poured gymnasium rubber floors (i.e., Tartan flooring brands) before its discontinuation in 1985 (NEWMOA, 2012, NPK & H, 2003). PMA was banned in both of these building materials because health research showed the adverse effects phenylmercuric compounds including kidney and liver toxicity, memory loss, and detriments to the central nervous system of infants, children, and pregnant women (EPA, 1984b). As a result, proactive research prevented the widespread societal adoption and use of PMA containing building materials, thus preventing the unintended sustainability consequences previously noted for asbestos and lead.

Although the PMA case provides a proactive example of banning its use before widescale societal adoption, a method needs to be developed to screen and target a chemical/material before their extensive society use. A potential method could involve initial screening followed, when warranted, by a detailed analysis. As an example, a screening method using

computational toxicology and/or rapid assays could flag a chemical/material with potential health or environmental problems (EPA, 2016). Using the potential for the material for broadscale societal deployment and the screening results, additional research could provide a more detailed understanding of factors such as chemical properties, exposure pathways, and potential health/environmental effects.

The proposed methodology can be remarkably cost effective and could guide material use improvements. For example, investing \$24 million dollars on lead and asbestos up-front research with this methodology could have prevented an actual incurred cost \$272-\$359 billion with an estimated \$2.1 trillion cost from ongoing remediation and litigation (Fig. 5). Computational assay costs about \$25,000-\$34,000, and additional research, if needed, costs range from few million dollars to \$10 million for companies and about a million dollars for the EPA to determine a new chemical safety (Perkel, 2012, Schmidt, 2009). As such, the up-front research cost for lead and asbestos was based upon the an upper bound estimate of \$24 million in the 2014 constant dollars (BLS, 2015). It should also be noted that economies of scale would likely result in a marked decrease in per chemical/material costs for toxicological testing. The actual incurred (\$272–359 billion) and estimated (\$2.1 trillion) costs for asbestos and lead was previously described (Fig. 5). Thus, paying for upfront for material research for both asbestos and lead could have resulted in an 11,000–92,500 fold reduction in remediation and litigation costs.

On top of the cost-effectiveness, this logical approach could be used to scope both appropriate application and limitations associated with using a specific material. As an example, the superior chemical and material properties of asbestos make its continued use essential for some applications today including chemical engineering applications requiring resistance to strong acids/bases. Nature has produced a material that has been very difficult find an equivalent and economic substitute. Additionally, lead is still in use today in a number of societal applications including batteries and radiation shielding. The key is to fundamentally understand the material properties as well as its potential health and environmental consequences before a material is widely deployed throughout society.

5. Conclusion

Using historical examples of legacy materials in our built environment, this paper has revealed the intended and unintended sustainability consequences of using building materials throughout our society and finding health and environmental consequences after widespread use. Given the exponential rise of building materials, proactive research into their potential health and environmental consequences before broad scale societal deployment potentially represents more cost effective approach.

In particular, our findings in “Government intervention and litigation” and “Unintended consequences” sections provided examples of two legacy materials that had been extensively deployed in our built environment, asbestos and lead. In these examples, preventing or attenuating the widespread application of these materials may have:

- Reduced remediation and litigation costs

- Decreased adverse health effects
- Prevented offshoring of the related industries
- Attenuated impediments to urban revitalization

The “Proposed alternate methodology” section provided two examples where proactive research prevented the broad scale deployment of phenylmercuric acetate in building materials, preventing the sustainability consequences previously noted for both asbestos and lead. To illustrate the potential for the next legacy building material, the widespread use of titanium dioxide nanomaterials was provided.

Although we spend 90% of our time in buildings, we dedicate 0.2% of our federal research budget on building research (USGBC, 2007). This research funding does not reflect the significant impact that the built environment has upon the three pillars of sustainability. Using the information provided by this paper, paying for upfront for material research for both asbestos and lead would have resulted in an 11,000–92,500 fold reduction in remediation and litigation costs alone.

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Fig. 1.

Buildings and infrastructure's (B&I) impacts. Data from 1. EERE (2012a), "Building energy data book, table 1.1.3 & 1.1.9" for energy use & electricity consumption, "table 2.4.1 & 3.4.1" for CO₂ emission, "table 8.1.1" for water consumption, and "table 1.4.14" for construction & demolition (C&D) materials; 2. EPA (2009) for municipal solid waste (MSW); 3. Kenny et al. (2009) for water consumption.

Fig. 2.

Growth trends in Chemical Abstracts Service (CAS) Registry chemicals (1965–2014). Data from 1. Binetti et al. (2008) for data from 1965 to 2007; 2. CAS (2008) for data year of 1965–2007; 3. CAS (2011) for data year of 2011; 4. CAS (2014a) for data year of 2014 (Not available years of data: 1977–79, 2008–10, 2012, & 2013).

Fig. 3.

Trends in lead consumption in paint and gasoline and significant federal regulations. Data from USGS (2015c) except for lead-in-gasoline data prior to 1940; Figure adapted from Laidlaw and Filippelli, 2008, Mielke, 1999, and Nriagu (1990) for lead in gasoline prior to 1940. (Note: Lead-Based Paint Poisoning Prevention Act (LBPPPA) of 1971 = the first federal housing lead paint regulation; Occupational Safety and Health Act (OSH Act) of 1970 = the first federal occupational lead exposure regulation; Residential paints made of white lead from Gooch (2002) and RSC (2007)).

Fig. 4.

Trends in U.S. asbestos consumption and significant federal regulations. Data from Virta (2006b) ("Building materials" consist of asbestos cement pipe and sheet, flooring, roofing, insulation, and paper. The category "Other" consists of coatings and compounds, friction products, packing and gaskets, plastics, textiles, and other nonspecific end-use categories. Also, data for the consumption of separate building materials and the category "Other" prior to 1965 are not available) (Note: Occupational Safety and Health Administration's (OSHA) Emergency Temporary Standard (ETS) of 1971 and EPA's National Emissions Standards for Hazardous Air Pollutants (NESHAP) of 1973 = the first federal regulatory invention in occupational and environmental areas; Asbestos Hazard Emergency Response Act (AHERA) = the first federal commercial and public buildings' asbestos abatement regulation).

Fig. 5.

Estimated (total \$2.1 trillion) and actual incurred (\$272–359 billion) costs of lead and asbestos remediation and litigation in the U.S. in constant 2014 U.S. dollars. Data from 1. HUD (1990) for lead paint abatement; 2. Kirmeyer et al. (1994) for replacement of the utility and residential portions of lead service lines; 3. EPA (1985) for leaded gasoline phaseout; 4. Mossman et al. (1990) for commercial and public buildings asbestos abatement; 5. Walker, 2011a, DoItYourself, 2015, Kazan-Allen, 2007, Testa et al., 2011, & OSHA (2011) for residential buildings asbestos abatement; 6. Levin, 2005, OSHA, 1995, OTA, 1994, USCB, 2000, USCB, 2002, USCB, 2007b, & USCB (2012) for actual incurred costs of remediation of lead paint and asbestos at annually \$1-\$2 billion of lead paint and \$3-\$4 billion of asbestos in current dollars during 1985–2014; 7. Wriggins (1997) for lead paint litigation costs spent; 8. Richardson (2005) for lead paint litigation costs anticipated; 9. Carroll et al. (2002) & White (2004) for asbestos litigation costs spent and estimated; 10. BLS (2015) for conversion into constant 2014 dollar using the Consumer Price Index for All Urban Consumers (Note: Actual incurred costs do not include the remediation costs incurred prior to 1985 and the litigation costs incurred after 2002 due to no reference found).

Fig. 6. Asbestos fibers in micrometers (μm). Reprinted from USGS (2015b), a) chrysotile, b) crocidolite, c) amosite.

Fig. 7.
Global trend of asbestos production by major producers. Data from 1. Virta (2006b) for asbestos production 1930 through 2000; 2. USGS (2015a) for 2005 and 2010.