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Patrick Ilg, Christoph Hoehne, Edeltraud Guenther

High-performance materials in infrastructure: a review of applied life cycle costing and its drivers – the case of fiber-reinforced composites

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Corresponding Author: Prof. Edeltraud M. Guenther, Prof. Dr.

Corresponding Author's Institution: Technische Universitaet Dresden

First Author: Patrick Ilg

Order of Authors: Patrick Ilg; Christoph Hoehne; Edeltraud M. Guenther, Prof. Dr.

Abstract: Over the last years, an investments bottleneck for public infrastructure has been built up in many industrial countries. Life cycle costing (LCC) is an appropriate management instrument for long-term and sustainable investment. This article addresses the evaluation of high performance materials (HPM), with LCC in order to reduce that investments bottleneck. Our research questions are, first, if and how LCC is applied to HPM, second, which drivers are influencing primarily the result of a LCC for HPM, and last, whether HPMs are suitable for infrastructure investments, in terms of economic, social and environmental criteria. We use a comprehensive literature review to analyze existing case studies applying LCC to HPM. Our review shows that LCC is applied to HPM for structural applications with different levels of detail and quality. At first sight total life cycle costs for HPM are on average 10% higher. We argue for a more holistic approach not ignoring sustainable criteria along the entire life cycle of HPM based on the identified drivers of LCC: external costs, an extended life cycle, discount rate and expected service life. Indeed, a screened subsample of eight cases is well competitive with average total life cycle costs for HPM 8.4% lower. We share the belief in a more eco-centric approach and, therefore, demand further research in a societal type of LCC, which improves the mechanical properties while not ignoring sustainable criteria for new product systems like HPM.

High performance materials in infrastructure: A review of applied life cycle costing and its drivers – the case of fiber reinforced composites

Authors: Ilg, Patrick; Hoehne, Christoph; Guenther, Edeltraud
Technische Universitaet Dresden, Faculty of Economics, Chair of Environmental Management and Accounting, Muenchner Platz 1/3, 01062 Dresden, Germany

Corresponding author: Chair of Environmental Management and Accounting, TU Dresden, 01062 Dresden, Germany. Tel.: +49 351 463 34313.
E-mail addresses: ema@mailbox.tu-dresden.de (E. Guenther).

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1 Introduction

Investment in public infrastructure is an important policy area for most of the developed and developing countries (Bhattacharya et al., 2012; Lin and Doemeland, 2012). In particular, repair and maintenance costs dominate the public discussion. In France, about 50% of more than 20,000 bridges located along 30,000 km of national roads require repairs (Radomski, 2002). A similar picture is seen all over Europe, where nearly 84,000 concrete bridges require maintenance, repair and strengthening with an annual budget of EUR 253 million, excluding external costs e.g. traffic management (Hollaway, 2003; Pantura, 2011). In the USA, a recent federal highway bill signed into law authorizes USD 25.2 billion for interstate maintenance and USD 21.6 billion for preventive maintenance or improvements on highway bridges through 2009 (Kendall et al., 2008). As a result, a bottleneck in infrastructure investments is evident. Infrastructure responsible for high material consumption and significant CO₂ emissions may require new materials that are more sustainable and resource efficient. Eco-innovations that provide long term solutions, i.e. low maintenance or high recyclability, exist and are well developed to enter a broad market to diminish the aforementioned bottleneck (Hofstra and Huisingsh, 2014).

Innovations in infrastructure are diverse and cover products, processes, and organizational areas. According to the Oslo Manual (OECD/Eurostat, 2005), a product innovation can be defined as the introduction of a new good or service that has significantly improved with respect to its characteristics. Regarding infrastructure, this includes new mobility technologies and innovative construction materials. Process innovations are defined as “the implementation of a new or significantly improved production or delivery method [...] significant changes in techniques, equipment and/or software.” (OECD/Eurostat 2005). An organizational innovation describes “the implementation of a new organizational method in the firm’s business practices, workplace organization or external relations” (OECD/Eurostat, 2005).

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4 That embraces concepts like “least cost planning” (Bracher et al., 2002). As Bender and
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6 Laestadius (2005) discuss, the Oslo manual is rather analytical. They argue that product and
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8 process innovations can highly depend on each other.
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12 One promising product innovation in infrastructure is the application of high performance
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14 materials (HPM). Among these construction materials, high performance concrete, engineered
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16 cementitious composites (ECC), fiber reinforced polymers (FRP), and fiber reinforced
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18 concrete (FRC) are seen as important, in particular for innovative repair and rehabilitation
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20 (Ehlen, 1997). For the latter, FRC, continuous fibers of carbon or glass are embedded in a
21
22 cement-based matrix. Filaments replace large single cracks with a dense system of
23
24 microcracks which are acceptable for both safety and durability (Brandt, 2008). FRC is
25
26 mainly used as a reinforcing material, applied e.g. in tunnel construction, structural ceilings,
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28 and wall cladding (Asokan et al., 2009). A similar product, although used differently, is FRP.
29
30 FRP is defined as “a combination of a polymer (plastic) matrix [...and] a reinforcing agent
31
32 such as glass, carbon, aramid or other reinforcing material” (Sahirman et al., 2003). In
33
34 contrast to FRP, ECC is an ultra-ductile short-fiber reinforced cementitious composite mixed
35
36 together with concrete on the construction side (Li, 1998; Lin et al., 1999). From hereon, for
37
38 linguistic convenience, the abbreviation HPM is used to express general characterization of
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40 fiber reinforcements for FRC, FRP, and ECC. Further differentiations of the three materials
41
42 follow in chapter 3.
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50 HPM were “not seen as a material likely to make an impact on general bridge engineering,
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52 until the last 10 years when the full implications of corrosion of steel in modern bridges and
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54 the specific weight of the material were appreciated.” (Hollaway, 2003). At the moment,
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56 manufacturing of HPM is often more expensive than conventional steel reinforced concrete
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58 (SRC). Initially high production costs, including what Ehlen (1999) calls “new-material
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60 introduction costs”, are typical for innovations. Thus, the potential of innovative materials
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4 becomes only visible if life cycle costs are considered and the planning horizon of
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6 investments is appropriate.
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11 Past reviews mainly concentrate on technical and materials science issues or a specific
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13 subfield of HPM, but less on (life cycle) costs. This is partly surprising, because only changes
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15 in the decision-making process, currently often based on financial and minimally on
16
17 sustainable criteria, will lead to changes in infrastructure investments. Only then would it help
18
19 to overcome the existing bottleneck. Two reviews by Keller (2001) and Burgoyne and Balafas
20
21 (2007) come close to what is attempted here. Our review assesses HPM for structural
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23 applications using life cycle costing (LCC) by means of a comprehensive literature review to
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25 investigate the aforementioned aspects and draw general conclusions. We direct our interest
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27 on the state of the art for LCC and similar cost estimation techniques in comparison with
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29 conventional materials. Drivers and stakeholders receive special attention during analysis.
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31 The latter share unequal levels of life cycle costs, though all participating in the dissemination
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33 of new products (Fassin, 2009; Mitchell et al., 1997). Both mentioned reviews do not cover
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35 the comprehensive scope of this study.
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43 To the best of our knowledge, this is the first review of that kind. The objectives of this study
44
45 are to:
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- 47 • investigate if and how LCC is applied to high performance materials and to compare the
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49 results of the LCC calculations while analyzing the level of details and quality (4.2),
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- 52 • identify drivers that influence primarily the result of LCC for HPM, its share and
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54 impacts on involved stakeholders (4.3),
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56
- 57 • discuss whether HPM are suitable, in terms of sustainable criteria, to solve the
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59 investment bottleneck in public infrastructure existing in industrialized countries and,
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61 eventually, draw general conclusions about innovations in HPM for infrastructure (4.4).
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6 The results of this study are helpful, in particular, for planners, users, and builders of public
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8 infrastructure who evaluate various material options and may justify or deny the feasibility of
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10 using HPM for construction projects. The identified drivers for a comprehensive LCC are
11
12 valuable for future calculations.
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17 After describing the material and methodology of the comprehensive literature review in the
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19 second chapter, the theory behind LCC, stakeholder approach, and high performance
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21 materials is discussed in chapter three. Following, the results of our review are presented in
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23 chapter four, answering the aforementioned research questions. In the last chapters, five and
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25 six, the findings of this comprehensive review are discussed, summarized, and conclusions are
26
27 drawn.
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30 31 32 33 **2 Material and Methodology** 34

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36 We use a comprehensive literature review to explore and synthesize relevant studies applying
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38 LCC to HPM for construction. According to Cooper (1982) a comprehensive literature review
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40 consists of five steps: problem formulation, data collection, data evaluation, analysis and
41
42 interpretation, and public presentation. Similar steps are suggested by Seuring and Müller
43
44 (2008), following an approach by Fink (2010) and Mayring (2003). A detailed description on
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46 how to review data for life cycle assessment (LCA) provides further inspiration (Zumsteg et
47
48 al., 2012). Combining all suggestions, we use four steps for our review: selection of research
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50 questions and bibliographic databases, practical screening, methodological screening, and,
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52 last, synthesis of results. Prior to the decision regarding search strategy and delimitation
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54 criteria, existing reviews (see Appendix B) are analyzed to identify the academic and
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56 practiced status quo, withdraw preliminary research questions, extract search words, and
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58 develop a set of categories used to code our final sample.
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6 In the first step, we select our research questions, the databases and websites, as well as the
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8 appropriate search terms. The cases are sourced via established bibliographic databases
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10 (EBSCOhost, Thomson Reuters' Web of Science, Fraunhofer IRB-DB, and IEEE Xplore) and
11
12 search engines of major publishers (Elsevier, Emerald, Springer, and Wiley). Google Scholar
13
14 is used to broaden the scope. We include only cases from peer-reviewed journals and
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16 conference proceedings. In a systematic search process, the keywords and expressions for
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18 cases ('case'), synonyms for LCC ('life cycle cost*' 'cost of ownership*' 'whole life cost*')
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20 and HPM ('fib* reforc*', 'textile reforc*', 'carbon fib*') are deployed and connected by
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22 Boolean operators. The search terms stem from the screening of existing reviews.
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29 In the second step, the practical screening, determined criteria for the inclusion or exclusion
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31 of the relevant literature in German and English are applied. The screening is performed by
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33 two authors and repeated once after the coding of all papers to assure all relevant articles are
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35 included. Using the approach of Becheikh et al. (2006), only title and abstract are examined to
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37 identify valuable articles during a first screening (see Figure 1). The authors agree upon
38
39 applying rather broad inclusion criteria (Nutley et al., 2000) owing to the innovative character
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41 of HPM and low amount of studies examining specifically LCC in this area. A peer review
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43 criteria is selected to satisfy minimum quality standards. A case criteria is applied to base the
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45 synthesis of our analysis upon empiric evidence (Hoon, 2013; Tranfield et al., 2003). We
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47 include only cases with concrete cost data of any life cycle stage. Moreover, the articles must
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49 relate to construction and any type of HPM using fiber reinforcements. Of the 1,098 studies
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51 initially identified by the search terms, 1,036 are excluded during this first screening, resulting
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53 in 56 studies (six studies are not available). Additionally, the concept of the "invisible
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55 college" by Cooper (1982) is applied during a doctoral workshop at the TU Dresden to
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57 broaden the search area and validate our methodology. Five more studies are added in this
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way or by means of cross references (snowball system). The low amount of additional papers indicates the validity of the research design.

[Figure 1]

In the third step, the methodological screening, we develop and apply criteria from the aforementioned reviews to form a coding scheme via feedback loops. The articles are analyzed and coded using Maxqda, a qualitative data analysis software. The coding is conducted by two authors. Intercoder reliability is addressed by doubling the coding, formulating a comprehensive review protocol, and – where necessary – discussing different judgments (Seuring and Müller, 2008). Uncertainty about the coding is resolved in various meetings via communicative validation (Kvale, 1995). The coding scheme takes into account the relevant information of the studies including elements for LCC and HPM. The scheme is discussed and validated by experts and PhD colleagues following (El-Diraby and Rasic, 2004). Rigor of research is accomplished by the systematic approach that ensures objectivity of the research process. Reliability is addressed by having all steps of the formal analysis conducted by two researchers. By comparing the codings, we observe a high intercoder reliability. We individually assess and resolve coding differences.

In the fourth step, syntheses of the findings are summarized and presented (see chapter 4). Prior to that, section three elaborates on necessary theory behind LCC, stakeholders, and HPM.

3 Theory

Tang and Podolny (1998) claim “that the space age technology that delivered the stealth aircraft can eliminate corrosion from our bridges”. Accordingly, high performance materials

are seen as functionally superior. Yet, the question remains as to if they are financially, environmentally, and socially viable.

These last aspects are of interest when assessing management instruments that adequately support decision-makers in the evaluation of infrastructure investments by comparing HPM to other technologies. Blake et al. (2009) call “for a multidisciplinary [design] optimization [...] not only examin[ing] performance but also incorporat[ing] financial modelling, such as life-cycle cost [...]”. Life cycle costs refer to all costs associated with the product or system as applied to a defined life cycle (IEC 60300-3-3:2005). Life cycle costing (LCC) is then the method of assessing life cycle costs or cashflows. Its concrete definition depends on a variety of factors, creating diverse phrasing in existing literature. In our sample, the following definitions for LCC or life cycle costs exist (Table 1).

[Table 1]

As displayed in Table 1, each case has a different understanding of LCC and its system boundaries. In fact, Simões et al. (2012) state that LCC “cannot be considered a uniform concept”. Table 1, however, depicts core elements such as economic technique, project-based, externalities, life cycle stages or principles, and minimum performance requirements.

LCC is hereby defined rather broadly as an economic method for project assessment and evaluation of all (direct, indirect, internal, and external) costs and revenues arising within a defined life cycle considered important to the investment decision (Fuller and Petersen, 1996, modified) while meeting a specific set of minimum performance criteria. Synonyms with minor differences e.g. total cost of ownership (TCO), whole life costing (WLC), and life cycle cost analysis (LCCA) are consistent with that wider definition. The defined life cycle shall account for the entire lifetime of the study object (Hoeft, 1992). It may cover four main life cycle stages (Song et al., 2009): manufacturing (including research and development, testing,

etc.), installation, use, and end-of-life (EoL). Raw material extraction (Simões et al., 2012) and transportation processes may be additionally included or explicitly modeled. Overall, LCC results in calculating a single aggregated monetary value, the total life cycle costs, to compare relevant design or investment options. Scholars often integrate LCC with other stand-alone techniques such as target costing, activity-based costing, or LCA for a differentiated display of its results (Hunkeler et al., 2008).

LCC also incorporates “non-price considerations” (Fabrycky and Blanchard, 1991; Maltz and Ellram, 1997). The SETAC working group differentiates three types: conventional, environmental, and societal LCC (Hunkeler et al., 2008). Life cycle sustainability assessment (LCSA) currently refers to societal LCC (Swarr et al., 2011; Valdivia et al., 2011). LCSA serves hereby as a prototype for extending conventional LCC by relevant externalities. Externalities “are defined as value changes caused by a business transaction that are not included in the price or are side effects of the economic activity” (Simões et al., 2012).

Conventional LCC is well established within the research fields of construction and bridges (Christensen et al., 2005; Ertekin, 2013; Frangopol and Liu, 2007; Zehbold, 1996).

Environmental LCC attracts widespread interest within this journal, too (Bierer et al., 2014; Carlsson Reich, 2005; Correia et al., 2011; Ribeiro et al., 2013; Utne, 2009). Some national and international standards establish a base for LCC (ASTM E 917:1994; IEC 60300-3-3:2005; ISO 15686-5:2008). The USA and Canada even offer federal guidelines for LCC applied to bridges (Hastak et al., 2004; Hawk, 2004; Ozbay et al., 2003).

Yet, adoption levels for LCC are low (Aouad et al., 2001; Lukka and Granlund, 1996; Sterner, 2000); so is the total number of HPM projects (Potyrala, 2011). According to Ozbay et al. (2003), only 12.5% of their surveyed studies apply any sort of LCC on bridges. And practices of LCC may not represent its state of the art (Hunkeler et al., 2008; Korpi and Ala-Risku, 2008; Simões et al., 2012). Indeed, the US Transportation Research Board (2012) is still seeking to fill that “gap between LCC[A] state of practice and state of the art”.

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6 Data quality and integrated uncertainty analyses are of great importance considering the data
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8 intensive nature of LCC (Cole and Sterner, 2000). As Roychoudhury and Creese (2001)
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10 claim, a “sensitivity analysis [...] for each alternative material, using different data inputs that
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12 are both relatively uncertain and significant, should be performed”. Many examples exist
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14 within the literature on LCC and construction (Farran and Zayed, 2012; Girmscheid and
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16 Kapp, 2005; Minne and Crittenden, 2014; Padgett et al., 2010; Van Noortwijk and Klatter,
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18 2004) or scenarios (Höjer et al., 2008). Although uncertainty may increase when integrating
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20 externalities, it is advisable to assess “all potential dimensions of a given product” using LCC
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22 (Simões et al., 2012).
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26 Data quality indicators (DQI) as suggested by Weidema and Wesnæs (1996) are modified and
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28 selectively applied to a case during analysis. DQI is part of a quantitative data quality
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30 approach adapted from LCA, the pedigree matrix. That concept is inspired by the NUSAP
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32 system (Funtowicz and Ravetz, 1990) and refers to two types of parameter uncertainty: data
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34 inaccuracy and lack of representative data for the context of use (Huijbregts et al., 2001).
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36 Research on DQI is still ongoing (Ciroth et al., 2013; Muller et al., 2014), though focused on
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38 LCA (de Saxcé et al., 2014; Henriksson et al., 2014).
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45 Reasoning for societal types of LCC, our research aims to differentiate stakeholders and their
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47 shared burden and benefits. Typical stakeholders of bridge construction encompass planners,
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49 owners (e.g. state agencies), investors, manufacturers, constructors, maintenance contractors,
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51 users (e.g. motorists, pedestrians), neighbors (e.g. residents close to the bridge) and society at
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53 large. The number of stakeholders is easily enlarged depending on the defined life cycle.
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55 Following Akadiri and Olomolaiye (2012), “cost effectiveness [...] is] of common interest to
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57 all stakeholders.” They continue that stakeholders could put “significant foci on the early
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59 identification of financial viability”, if they were able to “increase pressure” upon owners or
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4 planners. Lozano et al. (2014) recently discuss a newly developed “sustainability oriented
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6 theory of the firm” while visualizing that influence of stakeholders. We draw parallels
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8 assuming different levels of power and demands by stakeholders of bridge constructions.
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10 Some stakeholders may be ignored. Thoft-Christensen (2009) states “that user costs are
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12 usually not included [though they] ought to be included”. He argues that LCC practitioners
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14 underestimate significant parts of total life cycle costs, therefore not “considering the long-
15
16 term effects of the decision”. We assume that societal LCC (i.e. addressing all stakeholders)
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18 results in different total life cycle costs when used for comparison. In chapter four, we explore
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20 the understanding of pertinent stakeholders within our cases (Frangopol and Liu, 2007; Hu et
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22 al., 2013; Hunkeler et al., 2008).
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29 Innovative HPM are predestinated for that type of LCC. Concentrating on long lasting,
30
31 corrosion resistant fiber reinforced materials, our case research is delimited to FRP, FRC, and
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33 ECC. FRP is known to readers of this journal. Previous work on FRP has a focus on
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35 retrofitting of existing buildings (Cho, 2006) and recycling technologies (Asokan et al., 2009;
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37 Correia et al., 2011; Howarth et al., 2014; Meira Castro et al., 2014). FRC consists of a
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39 concrete matrix usually reinforced by carbon or glass fibers. In comparison, FRP has a
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41 polymer matrix, like vinylester, reinforced by carbon, glass, or aramid fibers. ECC, in
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43 contrast, embeds different types of short fibers in a concrete matrix using microstructure
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45 tailoring as well as material optimization (Li, 2003). Detailed research of reinforcements with
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47 natural fibers is rather new. Its lower environmental impacts and cheaper manufacturing has
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49 attracted popularity within the industry and academia (Al-Oqla and Sapuan, 2014; Eichhorn et
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51 al., 2010; Joshi et al., 2004; Kidalova et al., 2012). Nevertheless, we identify only one case
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53 study for natural fibers meeting our inclusion criteria; not even one on FRC. Materials such as
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55 pure high performance concrete (Brandt, 2008) are not included because fiber reinforcement
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is not applied. Acknowledging the vast literature on the many types of composites, this review concentrates on synthetic, inorganic fibers as classified in Figure 2.

[Figure 2]

To sift the existing literature on HPM, we browse relevant reviews in that research area. Similar databases are used as for the case search. However, the methodological criteria are less stringent. In total, we identify over 40 reviews looking at all kinds of fiber reinforced materials (see Appendix B). 19 of these reviews cover fibers in general, 13 natural fibers; seven focus on carbon fibers, in addition to three on glass fibers. More than half of the reviews (28) are directly related to construction. Then, bridges are the main application field. A review by Parvin and Brighton (2014) examining the use of FRP or carbon fiber reinforced polymers (CFRP) for column strengthening concludes that only one in seven compared cases considers costs.

Invented at the beginning of the 20th century, global fiber polymer production first started in the mid-20th century. Decreased material and production costs, new product categories, and improved manufacturing technologies allowed for an economical polymer production.

Innovative HPM provides a set of advantages in comparison to traditional SRC: “higher strength and stiffness [...]; higher fatigue strength and impact energy absorption capacity; better resistance to corrosion, [...] acids, and natural hazardous environments; longer service life [...]; non-conductivity and non-toxicity” (Dittenber and GangaRao, 2012). As an example, prestressing is a logical use of FRP given its advantages of high strength, strain capacity, and corrosion resistance (Burgoyne and Balafas, 2007). The reviews show that nearly 40% strength enhancement is possible for SRC beams using glass fiber reinforced polymers (GFRP) or even 200% with CFRP. Moreover, the shear strength of virgin beams can be increased by 60–120% using FRP sheets (Pendhari et al., 2008). Very thin layers of

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4 FRC are sufficient to yield strength and ductility improvements (Curbach and Scheerer, 2012)
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6 allowing for the reconstruction of heritage-protected buildings without changing the overall
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8 appearance.
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11 Apart from higher strength (Azwa et al., 2013), high stiffness (Duflou et al., 2012), high
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13 ductility (Hollaway, 2010), and low weight (Gholami et al., 2013), corrosion resistance is the
14
15 biggest advantage as it leads to low maintenance costs (Dittenber and GangaRao, 2012;
16
17 Karbhari, 2004). Corrosion leads to failing construction material, in particular steel, and
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19 occurs when exposed to moisture, alkalization, thermal effects, or ultraviolet radiation.
20
21 Consequently, (preventive) maintenance, repair, and rehabilitation (MR&R) as well as retrofit
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23 measures are necessary. Whereas MR&R focuses on the extension of the lifetime, retrofit also
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25 includes the improvement of functionality. The relation between life cycle performance and
26
27 MR&R is intensively studied by Richard et al. (2007).
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34 Shah (2013) reviews market shares and the global production of FRP. The global production
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36 raised from 5.9 million tons in 1999 to 8.7 million tons in 2011. Global sales of CFRP
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38 reached USD 16.1 billion in 2011, and are forecasted to reach USD 48.7 billion in 2020
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40 (Roberts, 2011). The overall amount is dominated by GFRP (85%), followed by CFRP and
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42 aramid polymers (2%), see Figure 3. The much cheaper production costs of GFRP matters
43
44 most. The booming natural fibers account for 13%.
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46

47 **[Figure 3]**

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51 Roberts (2011) estimates that, by 2020, the USA and Europe will produce 28% of the world's
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53 carbon fiber each, Japan 25%, and China 9%, respectively. Contrary to many traditional
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55 construction products, only a few suppliers of carbon fibers exist. For FRP bridges, only four
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57 suppliers served 82% of the deck panels in the USA in 2008 (O'Connor, 2008). Figure 4
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59 shows the market shares of textile fibers according to their industrial use. Around 6-8% of the
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global carbon fiber production is used in the construction industry (Schmohl et al., 2014; Shah, 2013) and 26% for FRP application (Duflou et al., 2012).

[Figure 4]

However, a discrepancy in the geographical distribution between market shares and existing FRP bridges is evident. Table 2 presents an overview of global bridges newly built or retrofitted by means of HPM. The USA dominates with a share of 55.3% followed by the Netherlands (13%), Korea (8.8%), and the UK (6.8%).

[Table 2]

Among the two reviews closest to our research objectives, Keller (2001) surveys FRP bridges and buildings constructed between 1997 and 2000. 36 bridges using FRP deck slabs are identified (30 road and 6 pedestrian bridges). In the conclusion, Keller identifies a gap in life cycle modeling for FRP structures. His review lacks a detailed analysis of different life cycle stages and the identification of cost drivers. Similarly, a review conducted by Burgoyne and Balafas (2007), focuses on the financial aspects of FRP constructions. The authors discuss the feasibility of FRP for different application fields. They conclude that only if LCC includes external costs, e.g. traffic delays, will FRP structures be economically viable for specific structural applications. Although this conclusion seems reasonable, both reviews lack the comprehensive scope of this article.

4 Results

We identify 25 cases eligible for the fourth step of the comprehensive review considering the delimitation criteria laid out in the methodology section (see all cases in Appendix A).

4.1 Bibliographic analysis

The following bibliographic analysis is mainly inspired by Seuring and Müller (2008) as well as Schaltegger et al. (2013). In 1975, the first pedestrian bridge made of FRP was built in Tel Aviv, Israel. In 1986, the first highway bridge using FRP tendons was installed in Germany followed, six years later, by a pedestrian bridge solely made of composites in Aberfeldy, Scotland (Sahirman et al., 2003). However, regarding our confined search, namely LCC applied to HPM, cases are only published starting from 1997 on (see Figure 5 below).

Overall, there is little published work. The number of publications per year ranges from zero to three. The total number remains almost negligibly small until the millennium, then it almost steadily grows, but with lower rates for the last 5 years. De Solla Price (1981) and Rider (1944) argue that a research area receiving scientific attention is characterized by a doubling of related publications within 10 to 20 years (Schaltegger et al., 2013). Looking at our sample of 18 years, we observe such a doubling: 11 publications in 2006, 25 in 2014. Considering the two years left until 2016, we predict a total of 29 cases in 2016. Therefore, we argue that LCC applied to HPM for construction is a niche, but a young and vivid field of scientific research.

[Figure 5]

In order to illustrate “geographic hotspots”, we “count the number of authors for each country in which the institutional affiliation of the researcher is located” (Schaltegger et al., 2013). On a single country base, the USA (40) is leading with a large gap of 31 to second placed Germany (9). If countries within the EU are accumulated (16), the gap still exists, though smaller (24). China, Hong Kong, as well as Japan also contribute to our research field (12). As illustrated in Table 1 in chapter three, existing bridges made of HPM strongly indicate a US dominance. That is not supported by previously depicted data on rather equally patterned market shares for global carbon fiber production between the USA, Europe, and Asia. In

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3
4 addition, Dutch, Korean, and British authors are underrepresented in our sample as compared
5
6 to Table 1. We will continue discussing that geographical bias in the coming chapters.
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10 The majority of articles are published by more than one author. Schaltegger et al. (2013) cites
11
12 two articles having observed average multiple authorship rates within social sciences between
13
14 43 and 45 percent. Our sample is way above that threshold (84%). One reason may be rooted
15
16 in the interdisciplinary approach of combining economics and engineering skills to assess
17
18 LCC for construction.
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22 Regarding the topics covered by journals publishing on LCC applied to HPM, we see a clear
23
24 focus on engineering. None of the journals relate to (policy) planning, accounting, or other
25
26 economic aspects. We conclude that, currently, our research area is driven by rather technical
27
28 issues. This is shown by the vast amount of literature on mechanical testing, but little on LCC.
29
30 Journals from the field of civil engineering and materials science dominate the literature (see
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32 Figure 6).
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35 **[Figure 6]**

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39 A group of seven journals marks the top of the list. The Journal of Composites for
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41 Construction outruns its successors with three cases. Of note is the fact that the International
42
43 Journal of Life Cycle Assessment, as an established conversant for LCC (especially related to
44
45 LCA or LCSA), provides two cases to our screened literature pool. The most cited article is a
46
47 case of an FRP bridge deck (BER06). After eight years, that publication attracts 76 citations.
48
49 With a shortfall, EHL97 (66), EHL99 (67), and NYS03 (63) follow. If appearance of authors
50
51 is ranked, R.C. Creese, A.C. Berg, D. Berger, C.A. Bernardo, M. Hastak, and S. Sahirman
52
53 lead the sample with 3 counts. Most of these authors publish in the USA.
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Summarizing the bibliographic insights, we display the regional origin of all study objects within the case pool in Figure 7. The x-axis divides the USA (below) and the rest of the world (above). Some landmark installations of bridges made of HPM are included, too.

[Figure 7]

4.2 Overall LCC results and data quality

Based on our cases, we hereby sum up insights concerning our first research question: investigate if and how LCC is applied to high performance materials and to compare the results of the LCC calculations while analyzing the level of detail and quality of the calculations.

There is little published work on LCC. That is surprising when reconsidering statements of previous reviews that economic viability is a major argument for, or against HPM in comparison to conventional materials. Moreover, if LCC is applied throughout the literature, it is for FRP but not FRC. Applications for ECC are also underrepresented with three cases (GEN13; KEN08a; KEN08b). FRP covers GFRP in vinylester resin (majority), CFRP or hybrid composites such as one combining steel, glass, carbon, and twaron fibers (CUI08). Looking at fibers, EHL99 solely examines partly a type of natural fibers, namely a bamboo wood core, whereas all others rely on synthetic fibers. Thereof, five cases (20%) deploy carbon fibers or hybrids such as CUI08, the majority (19 cases) use leastwise partly glass fibers (76%). And then, FRP is often examined as the preferred material for bridges, specifically bridge deck panels. The latter explains well the dominating GFRP: it is currently (and was) the cheapest industrial composite for that purpose. Only three cases examine different study objects. CUI08 studies reinforcement bars universally applicable for bridges and building superstructures, GEN13 only the latter, and SIM12 street column lighting systems. That limited application area was initially not expected by the authors, but well

supports the initial discussion on the existing investment bottleneck for public infrastructure. As comparing alternative materials, various types of SRC or steel are chosen. Sometimes, refinements to reduce corrosion such as epoxy-coating is explicitly mentioned and applied. Regarding the “geographic hotspots” discussed in previous chapter 4.1, the location of study objects follow mostly their authors’ origins. That results in a dominating two-thirds within the USA (64%), two cases (8%) each in Germany, the Netherlands, and Japan, and one case in Israel, Australia, and Sweden, respectively. Again, the UK and Korea are missed entirely. All European countries add to five cases (20%). Not displayed in the succeeding Table 3, we examined what type of renewal – retrofit/ repair or new construction – is chosen for each case. Both types are almost equally presented with an 8% lead for retrofit/ repair. Likewise not illustrated, only one case is structured as a stand-alone analysis (HON07a). All others compare study objects made of HPM with conventional materials. Beyond, HPM and non-HPM materials are often mixed within one project. For example, a retrofit may be characterized by keeping an existing superstructure made of steel while replacing an old concrete deck with lighter FRP e.g. KEN08b.

[Table 3]

Resulting total life cycle costs are mixed (see Table 4). The second column illustrates the difference between HPM and a conventional alternative in percent. The third column displays the absolute values. All currencies presented are converted into USD as of Oct 31, 2014 using appropriate exchange rates and consumer price indices. Where necessary, values are converted from square foot into square meter. HPM as well as non-HPM gain first and second places. Eleven cases suggest favoring HPM; twelve do so for conventional materials. However, the relative advantage of HPM as expressed in percentage is steadily smaller as compared to the calculated monetized disadvantage. Alone five cases suggest a difference of

greater than 100% not in favor of HPM. Overall, HPM is characterized by higher total life cycle costs with a median average of +10% within our sample.

[Table 4]

LCC application level varies a lot. Although well-explained examples (EHL97; EHL99) exists, we do not see a growing set of equally or more comprehensive (related to life cycle stages, external costs, metadata, uncertainty treatments) LCC cases after the year 1999.

Conventional LCC practice is the standard, but environmental or societal types of LCC are highlighted (see Figure 8). Almost 44% calculates only internalized costs, whereas 56% extends the scope to external costs. Within the societal LCC, we mark all cases integrating “user costs” as suggested by EHL97 as “sLCC*”. Only two cases (KUH07; SIM12) can be accounted for as a LCSA (Valdivia et al., 2011).

The type of LCC, as explained in Hunkeler et al. (2008), is reflected in many other choices that authors of each case have made. For the defined life cycle, roughly 60% consider impacts within the manufacturing or EoL stage as important to be monetized. That neither means EoL scenarios are well explained nor is manufacturing data always sourced directly from producers with real data sets. The lowest response rate is illustrated by “transportation/distribution” (32%), a rather intermediary activity between the other life cycle stages. That is surprising when acknowledging the weight advantage of HPM and the consequential lower LCC results for any transportation activity.

[Figure 8]

The next table (Table 5) provides an idea to what extent main assumptions for each LCC vary. Discount rates, ideally real discount rates, are chosen between 0-5% with a median of 3.3%. The level of chosen discount rate influences future costs significantly, especially in case of

long study periods. Expectations about the latter, especially service life, is a key LCC driver, too (see next chapter 4.3). Therefore, that choice must be well explained. The table shows expected service life for HPM and the comparable non-HPM as well as a calculated delta. Roughly a third use service life for HPM below 50 years, at least as baseline scenarios. Over 90% apply those 50 years up to a maximum of 153 years (KEN08b). The delta as compared to non-HPM materials is on average +50%. That means non-HPM need to be replaced on average entirely within one lifetime of HPM. As a new material, the lifespan of HPM is difficult to predict. A practitioner of LCC must run sensitivity analysis on this key parameter. A good example for explaining that decisive choice is SHA97: they provide a bundle of published articles reasoning for their chosen value. Another crucial system boundary is related to external costs (the three last columns). We assume that any inclusion of external costs is rather positive for HPM as compared to conventional materials. About half of the cases (partially) calculates external costs or quantifies non-monetary impacts (as LCA). User or third party costs are explicitly mentioned cost categories suggested by EHL97 that are adopted in LCC by only a minority (40% state user costs, respectively 16% third party costs). Some data rows, specifically seven cases, offer no or little data for these categories.

[Table 5]

As reviews suggested, components made of HPM are eventually lighter because of their better weight-strength ratio. For bridges, this could be reflected in using smaller superstructures or enlarged bridge deck panels extending the available space for bridge users (MAR14). It could also result in shorter installation times due to easier handling, less heavy machine equipment, or more precision of prefabricated components (instead of cast-on-site) (BER06). Table 6 illustrates some given data points for our sample. Unfortunately, this is little or only qualitatively reported within the cases with no specifications on reduced kilograms or hours.

[Table 6]

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6 Data quality and uncertainty is a highly relevant topic for innovative HPM. EHL97 argues
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8 that “the costs and technical performance of new materials are intrinsically uncertain”. Many
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10 studies conduct sensitivity analyses (60%) or Monte Carlo simulations (24%) to show effects
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12 of changes in parameter values and identify hotspots in the calculation (GEN13; HON07b;
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14 MEI02) or use “estimates [...] based on composite material properties and the data available
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16 for conventional material at a component or system level” (HAS00). However, these
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18 approaches do not assess data quality or eligibility of data values per se. We attempt to assess
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20 data quality, in particular of identified LCC drivers (next chapter), using a modified pedigree
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22 matrix as suggested by Weidema and Wesnæs (1996) including data dimensions of reliability,
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24 completeness, temporal, geographical as well as technological correlation referred to as
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26 metadata. Each dimension is evaluated with scores of 1, 3, and 5 indicating a specified level
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28 of data quality (Table 7) forming a 5-digit data quality indicator (DQI).
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33 **[Table 7]**

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38 The pedigree matrix shall easily survey the data quality, show improvements, and indicate
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40 sources of uncertainty. In many cases, data sources are often not replicable, are based on
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42 personal communication or are not mentioned at all. As an example, EAM12 states that
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44 “mean material costs such as concrete, steel reinforcement, and CFRP are based on 2009
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46 estimates from MDOT and CFRP producers”. For the comparing non-HPM alternative, e.g.
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48 steel prices, sources are reported in an even less transparent manner. As a consequence, we
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50 can neither realize a full pedigree matrix nor for the entire sample of cases due to missing
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52 metadata. It is unclear if metadata gaps exist because of data unavailability or publishing
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54 behavior. The former is rather difficult to overcome. The latter means authors could increase
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56 data quality when explicitly describing metadata within their articles or supplements.
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As a showcase, SIM12 is analyzed (Table 8 and Appendix C). Note that we are forced to limit our analysis to an aggregated cost data such as “environmental costs” instead of e.g. the carbon price per kilowatt hour electricity consumed. For cost aggregates like “conventional costs”, no appropriate DQI can be allocated (“na”). On the base of DQI, Weidema and Wesnæs (1996) then calculate a “modified uncertainty”, namely coefficient of variation, per data aggregate. We are not able to retrieve such metric values for SIM12, but rather suggest using the DQI to screen for LCC drivers. This means all low scoring DQI shall be scrutinized with means of sensitivity analysis to assess the data parameters influence on total life cycle costs. For SIM12, we suggest screening data for manufacturing, service life, and conventional costs.

[Table 8]

We believe that a sound DQI extends LCC practitioners’ and readers’ understanding of total life cycle costs. It allows a review of the data sets and assumptions in a metric manner which, therefore, more easily indicates sources of uncertainty. This holds foremost true for parameters within each LCC that drive the total result (see next chapter).

4.3 LCC drivers and their impact on stakeholders

We move on to our second research question: identify drivers that influence primarily the result of an LCC for HPM, their share and impacts on involved stakeholders.

Reconsidering the overall LCC results from the previous chapter, we cannot find any other significant pattern resulting in LCC advantages for HPM versus conventional materials than including external costs (e.g. user costs). EHL97 states that “costs and technical performance of new materials are intrinsically uncertain; the method must address this uncertainty.” As laid out in chapter 3, practitioners of LCC may analyze and assess uncertainty with methods like sensitivity analysis, scenarios, simulation techniques, or probability modeling. We expect

that all relevant LCC drivers are scrutinized by any of these methods within each case. This chapter analyzes major factors influencing the total life cycle costs. At first, we display what LCC drivers are discussed within the cases. Thereafter, a subsample within our sample presents effects on the total life cycle costs.

Table 9 provides an overview of potential LCC drivers and total life cycle costs. Note that columns starting with “Δ” use a computed delta between the concrete value per case and the median average of the total sample. For example, EAM12 using a discount rate of 3% is displayed as -0.3% (3 minus the median average of 3.3%).

[Table 9]

The discount rate is often discussed as an LCC driver within our cases. The lower the rate, the greater the weight of future costs within the total life cycle costs. For example, maintenance costs fall to roughly 35% after 10 years and 0.5% after 50 years when using a discount rate of 10%. The median average within our sample is 3.3%, resulting in 71.5% and 18.7%, respectively. Discount rates shall reflect real interest rates, but also long-term considerations. A good example is KEN08b, who argues for a falling discount rate with progressing time citing Weitzmann (2001): “the near term, to the medium term, and to the distant future [...] 4, 3 and 2% respectively”.

The choice of expected service life is closely related to the effect of the chosen discount rate and the study period. We see three effects: the longer the period, the smaller the discounted values. On the other hand, the longer the period, the greater the likelihood of repair measures. Eventually, the longer the period, the larger uncertainties regarding all parameters. A fundamental question for our research area is the assumed difference of service life between HPM and conventional materials. The average of 60 years seems appropriate when reflecting all reviews and cases.

We additionally examine how many life cycle stages each case considers. As previously shown in chapter 3, four main stages, namely manufacturing, installation, use, and EoL, are feasible. Transportation processes within or across these stages can be modeled, too. The seventh column displays a value between 0 and 100% (each stage shares 25%). On average, 75% is covered, i.e. three stages. However, completeness is only a rough indicator for the overall quality or the total result of the LCC. Seven cases consider transportation, but on different scales. For IBB14, shipping represents 9% of material costs; SIM12 includes all intermediate transportation processes, but does not explicitly specify these costs. SIM12 is also the only case computing the life cycle stage “raw material production”. That stage represents a significant share (41.51%) in total life cycle costs within their comparison. External costs are of even greater importance. Externalities are not priced within the market and different approaches exist to estimate their levels (SIM12). Burgoyne and Balafas (2007) argue that if user costs were included, then HPM would most likely be financially viable. The underlying traffic volume is their greatest LCC driver.

Our presented choice of LCC drivers is supported by the authors within the cases. We display in Table 10 all explicitly mentioned LCC drivers, often evaluated by means of sensitivity analyses.

[Table 10]

To show impacts of LCC drivers, we have selected a subsample within the sample using following criteria: external costs are included, share in the main four LCC stages is greater than 50%, and all columns must contain data values (Table 11). Within that selected sample of eight cases, two cases show a disadvantage based on calculated LCC for HPM (EHL97; SAH03b), but six with an advantage as compared to traditional non-HPM (second column). Overall, median average for that advantage is -8.4%, i.e. HPM has lower life cycle costs. If

we look closer at each data row, we observe controversies we cannot fully explain. Discount rates are almost similar. Assumed service life, however, varies significantly. A few cases (EHL97; EHL99; partly SIM12) assume conventional materials lasting as equally long as HPM. Other cases estimate a significant advantage for HPM of +100% (KUH07; MAR14; SAH09; partly SIM12). The decision to monetize transportation/ distribution processes within the LCC calculation indicates no clear overall outcome (SAH03b; SAH09; SIM12), although the lower weight of HPM is assumed to give HPM a financial advantage here if external effects of that transportation is calculated.

[Table 11]

We sum up that external costs, expected service life, used discount rate, and system boundaries such as life cycle stages account for the most influential LCC drivers. A question now is, who bears the life cycle costs? And are all stakeholders equally represented within current decision-making on public infrastructure? Only some cases integrate external costs (48%). These cases then often follow EHL97 and differentiate agency, user, and third party costs (EHL99; KEN08a; KEN08b; SAH09). However, only KEN08a, KEN08b, SIM12, and MAR14 set concrete values for third party costs – though in two cases mixed with user costs – referring to the society at large.

Figure 9 visualizes effects of system boundary extension and external costs on total life cycle costs for typical stakeholders. All underlying monetary values within that figure are fictional. The selected stakeholders are interpreted as initiators and/or bearers of given life cycle costs. The figure displays a scenario where a societal type of LCC is applied to a bridge construction throughout five relevant life cycle stages: raw material extraction, manufacturing, installation, use, and EoL. Once the system boundaries for LCC are extended by that more eco-centric view, the picture changes greatly compared to conventional LCC. Stakeholders such as

traveling users, neighbors, and society at large bear the burden associated with traffic user delays, increased car accidental rates, higher fuel consumption, greenhouse gas emissions, noise and dust emissions, etc. External costs either increase the overall sum of total life cycle costs or serve as tighter budget constraints regarding the installing bridge dimensions. In short, decision-makers face the choice to either pay more or get a smaller bridge for the same lump sum. If a virtual budget of 1 million currency units existed, it would require virtually shifting money flows (life cycle costs) between relevant stakeholders. That could result in having less money to be dedicated to manufacturers (purchase price of raw products to build the bridge) and constructors (purchase price for installation services). In the end, the bridge could end up being smaller than expected not serving the same functionality (e.g. a specific load capacity of the bridge). We believe that visualizing these effects gives valuable information to decision-makers interested in meeting all stakeholders' demands while applying LCC to HPM for bridge construction as well as structural applications in general.

[Figure 9]

4.4 HPM suitability to resolving the investment bottleneck

In this chapter, we evaluate whether HPM is suitable, in terms of sustainable criteria, to resolve the investment bottleneck in infrastructure which exists in most (Western) countries. After the advantages and disadvantages are presented, further research needs in the field of HPM are highlighted.

The comprehensive review shows that there is an increasing number of projects solely or partly made of HPM; however, the total amount of empirical evidence is still comparably low. In combination with the high strength and ductility, HPM is a promising technology that is suitable for certain structures. If tailored applications, i.e. retrofitting and reconstruction of bridges, are considered, HPM is already superior to conventional materials based on

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4 conventional LCC. For these circumstances, the new materials are able to strengthen existing
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6 structures and increase load capacity while inhering long lifetimes and guaranteeing a fast
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8 construction process due to its lower specific weight. This results in advantages for all
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10 stakeholders, in particular traffic users.
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15 Nevertheless, the full life cycle benefits become visible only if external costs are included. As
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17 a screened subsample illustrates (see Table 11), HPM outperforms conventional structures
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19 with lower average total life cycle costs. Currently, user costs are barely included e.g.
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21 EAM12; KEN08a; MAR14. However, third-party environmental costs are not. EHL97 classes
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23 two different third-party costs: “"downstream" environmental costs such as pollution of
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25 wetlands caused by toxic runoff from a specific project, but also "upstream" environmental
26
27 costs such as pollution resulting from the mining, fabrication, and transport of the
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29 construction material.”
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36 Regarding the fact that more than 180,000 bridges in the USA are considered deficient
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38 (31.4%) (Alampalli, et al. 2002), continuous retrofitting is neither socially desirable nor
39
40 economically feasible. In the long run, investment bottlenecks, which exist in most
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42 industrialized countries, can be solved by HPM although initial investment might be more
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44 expensive in the coming years. Keeping this argument in mind, our statement is that net
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46 present value of HPM is positive, if LCC is applied with an eco-centric view. To fully
47
48 incorporate the new technology in the construction market some organizational barriers have
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50 to be overcome. First, ignorance among some practitioners has to be overcome by
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52 conversations and awareness raising with colleagues experienced with HPM. Second, CAD
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54 software has to be extended by HPM elements to make it applicable to a broad range of
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56 designers and engineers. Third, new standards and guidelines have to be developed to avoid
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58 special authorization on an individual project base. And last, political support is essential to
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bring HPM structures to the broad market. The large amount of bridges in the USA numbered in Table 1 shows the importance of political backing. After the advantages of HPM became obvious, a lot of US transport and infrastructure agencies on federal (American Concrete Institute, Federal Highway Administration, National Concrete Bridge Council) and state levels (Missouri Department of Transportation, Wisconsin Department of Transportation) published guidelines and requirements for fiber reinforced products. These obstacles could also be found in strengths and weaknesses mentioned in the investigated case studies. Figure 10 shows both aspects in a net diagram.

[Figure 10]

Similar aspects have also been raised by the authors of the case studies with respect to future research areas (see Figure 11). Dividing the nine areas into three research groups: social, technical, and environmental, an utmost need for further research has been identified in durability characteristics and long-term monitoring (22 times). Moreover, minimum material performance specifications, design guidelines, and analysis methods (15) have been mentioned by the authors. Regarding life cycle and environmental concerns, the development of LCC models (15) for FRP bridge deck panels has been mentioned most. Interestingly, most of the weaknesses discussed in the part above were also mentioned for further research. This implies that current weaknesses need further research to improve the performance of the entire technology.

[Figure 11]

5 Discussion

This section highlights findings and points out directions for future research. The comprehensive review of cases on LCC applied to HPM using fiber reinforcements is seen as major contribution of this paper. So far, we can summarize that if LCC is applied as a societal

type, overall results will likely favor HPM as compared to non-HPM for structural applications. This proposition is limited to our sample's scope of street lighting columns, building superstructures, and bridges as well as a thoroughly defined set of minimum performance requirements such as meeting AASHTO load capacities. Hereafter, we reflect on the eligibility of our methodology and LCC as a technique for our research questions.

A comprehensive literature review may be perceived as partly subjective as the construing and coding of the cases is conducted by the authors. With respect to reliability, research consistency is improved by predefined selection criteria (Becheikh et al., 2006), strict application of the search terms, using a well-documented review protocol, and double coding by two authors enhancing intercoder reliability. Validity is addressed by following the guidelines of Zumsteg et al. (2012) and incorporating discussions with other scholars.

Considering our own professional experience at a large German multinational, we are aware that the amount of published scientific work is only a small part of the main population of projects applying LCC to HPM. We follow Baitz et al. (2012) by assuming a larger pool of industrial but inaccessible LCC applications. Regarding the availability of reviewed cases, there are two pertinent issues. First, the majority of cases focus on bridges. Second, although searching for the generic string "fib* reinforc*", we identify almost exclusively structural applications of FRP (22) and ECC (3). It seems that, currently, cost objectives for FRC are off the record. However, the application of LCC for FRC is a highly important topic of further research. One long-term research project on FRC known to the authors is jointly conducted by TU Dresden and over 70 industry as well as research partners investigating the entire life cycle of FRC in order to design optimized structural applications (Schladitz, 2014). Within our review, we can carefully generalize for HPM concerning technological characteristics similar between FRC, FRP, and ECC. Thus, conclusions drawn from FRP may be assigned to FRC and ECC depending on the material composition, structural design, and cost structure.

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4 Second, a discrepancy between actual market share and geographical application within our
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6 sample is noticeable (Table 2, Figure 7). The USA dominates the number of constructive
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8 examples as compared to all other countries. We screen for English publications within well-
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10 known databases to avoid a language bias. A literature search in other languages may result in
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12 different geographical distribution patterns. We tested with German publications, but could
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14 not find more or different insights. The current lead of US originated research could be a
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16 result of existing structured guidelines by federal authorities alike the Federal Highway
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18 Administration. Push and pull factors for the introduction of HPM in the broad market is still
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20 an area of further research.
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27 We continue by scrutinizing the eligibility of LCC. As previously shown, societal LCC can
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29 properly incorporate and monetize all relevant internal and external effects for long-term
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31 projects. Alternative techniques like real option analysis, full cost accounting, or least cost
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33 planning may serve our research objectives, too. Yet, LCC is preferred because its word stem
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35 “life cycle” already captures our targeted holistic mindset. Three issues are noteworthy. First,
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37 the case studies show that HPM perform on average better than conventional materials, if
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39 screened for incorporating external effects. This may imply, in cases where SRC performs
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41 better, an incomplete LCC, e.g. social costs, specifically user costs, are missing in BER06 or
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43 CUI08. Infrastructure is one of the areas where externalities play an important role due to the
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45 participation of a large variety of stakeholders (Thoft-Christensen, 2009). Positive
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47 externalities of bridges are seen rather as a result: an improved traffic flow or less congestion
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49 after its construction. However, monetizing externalities is by far not only an issue for the
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51 construction industry (Simões et al., 2012). KPMG (2014) recently published a methodology
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53 on how to “combine financial earnings data with monetized externality data and quantify the
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55 likelihood and potential impact of the latter [...]”
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Second, the application of LCC in the context of HPM requires diligent investigations along the entire life cycle. As shown in chapter 4.3, raw material extraction is rarely considered. In addition, even though life cycle costs for the EoL stage are more often provided (14 cases), its values are confusing: for some cases HPM has lower EoL life cycle costs (EAM12; EHL97; EHL99; MAR14; NYS03; SAH09), for others non-HPM (KUH07, SIM12). Others even assume zero costs (EAM12 for FRP; HON07a; NIS06). Except of the reviews by Pimenta and Pinho (2011) and Correia et al. (2011), no article explicitly discussed the cost of disposal or recycling alternatives. Acknowledging the existing difficulties of recycling HPM like FRC, we fully support the findings of Hofstra and Huisingh (2014) that early stages of their life cycle need to address these issues in order to tap the full potential of eco-effectiveness.

Third, we identify data quality and uncertainty treatment as crucial for our derived insights. As outlined in chapter 4.2, studies conduct sensitivity analyses or Monte Carlo simulations to showcase impacts of data variations, but rarely discuss fitness of deployed data per se. In the identified cases, data sources are often not replicable. The low level of provided metadata makes comparisons rather difficult for techniques like the pedigree matrix. We see leeway for improved descriptions of underlying assumptions and a more stringent documentation of the metadata as a stimulus for further practitioners in the area of LCC calculation.

Summarizing, we may conclude that a comprehensive literature review of the application of LCC in HPM is a valuable method. Our sample is partly biased or incomplete, but it may represent the best possible fit. Acknowledging the aforementioned limitations, the results need to be interpreted with caution but no less thrust: HPM could be environmentally, socially, and financially viable. Still, the manufacturing process of HPM is too expensive, and the early and late life cycle stages still lack proper in-depth examination. Thus, future research shall focus on commercialization, its efficient manufacturing, and sustainable assessments of raw material extraction as well as EoL stages. By now, we can state that product innovation in

materials science for construction should not only be explored by feasibility studies for the sake of new structural application. Rather, we share the belief in “a more eco-centric approach” of “eco-effectiveness for the short and long-term welfare of society and nature” (Hofstra and Huisingsh, 2014).

6 Conclusion

Investments in public infrastructure were initially identified as an important policy area for the 21st century (Lin and Doemeland, 2012). Over the last years, a backlog of investments has been built up in almost all industrial countries (Hollaway, 2003; Pantura, 2011). Eligible management instruments for decision makers to cope with the investment bottleneck are rare. We believe that life cycle costing (LCC) provides a sound base for better long-term and sustainable investment decisions if applied appropriately. This article addresses the evaluation of innovative products and processes, e.g. high performance materials (HPM), with LCC as a way to solve that infrastructure holdup. Our research questions are, first, if and how LCC is applied to HPM, second, which drivers primarily influence the result of a LCC for HPM, and last, whether HPM are suitable for infrastructure investments, in terms of economic, social and environmental criteria. We use a comprehensive literature review to analyze existing case studies applying LCC to HPM.

Our research indicates that LCC is applied to HPM for structural applications with different levels of detail and quality. Most published work concentrates on a specific construction area, namely bridge decks, and are located in the USA. For our sample, total life cycle costs for HPM are on average 10% higher. However, frequently, external costs and stakeholders are not comprehensively assessed as suggested by Simões et al. (2012), Fassin (2009), and Mitchell et al. (1997), resulting in narrow LCC calculations. Identifying external costs, an extended life cycle, discount rate, and expected service life as main drivers of LCC, we argue

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4 for a more holistic approach to improve mechanical properties of HPM while not ignoring
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6 sustainable criteria along the entire life cycle. Including these drivers in an LCC results in
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8 total life cycle costs that are 8.4% lower. Therefore, we believe LCC is a valuable method to
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10 assess the suitability of HPM to solve the investment bottleneck in infrastructure.
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15 Product innovation in materials science for construction, such as HPM, should not only be
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17 explored by feasibility studies. Sustainable development demands an approach which
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19 improves the mechanical properties while not ignoring sustainable criteria for new product
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21 systems (Klemeš et al., 2012). To fully incorporate new technologies in the construction
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23 market some organizational barriers have to be overcome: awareness raising with respect to
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25 engineers and practitioners, the incorporation of the new technology in software and working
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27 processes, and the development of federal standards and guidelines. Push and pull factors for
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29 the introduction of HPM in the broad market is still an area of further research.
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Glossary

ASTM	American Society for Testing and Materials
CAD	computer-aided design
CFRP	carbon fiber reinforced polymers
DQI	data quality indicators
ECC	engineered cementitious composite(s)
EOl	end-of-life
FRC	fiber reinforced concrete
FRP	fiber reinforced polymer(s)
GFRP	glass fiber reinforced polymers
HPM	high performance material(s)
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LCA	life cycle assessment
LCC	life cycle costing
LCCA	life cycle cost analysis
LCSA	life cycle sustainability assessment
MDOT	Michigan Department of Transportation
MR&R	maintenance, repair and rehabilitation
non-HPM	non-high performance material(s) (~ conventional material(s))
SETAC	Society of Environmental Toxicology and Chemistry
SRC	steel reinforced concrete
TCO	total cost of ownership
WLC	whole life costing

Figure captions

Title	Description
Figure 1: Comprehensive review screening process	Overview of review process
Figure 2: Classification of natural and synthetic fibers for reinforcement (based on Jawaid and Khalil, 2011)	Overview of existing fibers
Figure 3: Market share of reinforced composites in 2011 (based on Shah, 2013)	Visualization of reinforced composites
Figure 4: Market share of textile fibers and composite types (based on Duflou et al., 2012)	Visualization of textile fibers and composite types
Figure 5: Historic development and geographical authorship	Overview of the historic development of published research articles dealing with high performance material
Figure 6: Most published journals and topics	Overview of the published journals and topics
Figure 7: Geographic distribution of high-performance materials constructions	Visualization of already existing high performance structures
Figure 8: Types of LCC and considered life cycle stages	Overview of applied life cycle stages in the selected case studies
Figure 9: Total life cycle costs assorted by stakeholders' impacts	Visualization of a three dimensional stakeholder model, in which life cycle stages and cost are included
Figure 10: Identified strength and weaknesses in the case studies	Overview of identified strength and weaknesses of the selected case studies
Figure 11: Further research identified in the case studies	Overview of further research areas of the selected case studies

Figure 1

Figure 1: Color

Figure 1: Black & white

Figure 2
Figure 2: Color

Figure 2: Black & white

Figure 3

Figure 3: Color

Figure 3: Black & white

Figure 4

Figure 4: Color

Figure 4: Black & white

Figure 5

Figure 5: Color

* all EU countries combined

Figure 5: Black & white

* all EU countries combined

Figure 6

Figure 6: Color

Figure 6: Black & white

Figure 7
Figure 7: Color

Figure 7: Black & white

Figure 8

Figure 8: Color

^a types integrating user and third party costs

^a following “raw material production” in SIM12

^b “transportation/distribution” may also be included within all other life cycle stages

Figure 8: Black & white

^a types integrating user and third party costs

^b following "raw material production" in SIM12

^c "transportation/distribution" may also be included within all other life cycle stages

Figure 9

Figure 9: Color

Figure 9: Black & white

Figure 10

Figure 10: Color

Figure 10: Black & white

Figure 11

Figure 12: Color

Figure 12: Black & white

Table captions

Title	Description
Table 1: Selected definitions of LCC	Overview of different LCC definitions
Table 2: Existing bridges made of HPM, respectively FRP worldwide	Overview of existing bridges made of high performance materials
Table 3: Study objects of the cases – details and chosen scenarios for comparison	Overview of the selected case studies
Table 4: Overall LCC results – HPM vs. conventional materials	Overview of the LCC results, comparing high performance materials and conventional materials
Table 5: System boundaries – from discount rates to external costs	Comparison of system boundaries
Table 6: Overall LCC results – non-monetary advantages of HPM	Comparison of the non-monetary LCC results
Table 7: A modified Pedigree matrix for data quality assessment	Assessment of the data quality via Pedigree matrix
Table 8: An example for data quality indicators	Overview data quality indicators
Table 9: Overall LCC results – deviation from median average values	Comparison of the median values of the identified drivers
Table 10: LCC drivers – tested by sensitivity analyses or explicitly discussed	Comparison of the drivers for a selected sample
Table 11: Selected cases – deviation from median average values	Comparison of the median values of the identified drivers for a selected sample

Table 1

Case	Definition
MEI02b	“Life-cycle cost (LCC) usually consists of an initial construction cost and maintenance cost.”
EHL97	“The new material life-cycle cost method [...] is a ‘project-based’ approach [...] allows the designer to choose any construction material that satisfies the project’s performance requirements [...] includes a cost classification scheme which allows the bridge planner to compare the intrinsic life cycle cost advantages and disadvantages [...]”
EHL99	“Using a LCC method consistent with ASTM E 917 for measuring LCCs [...]”
KEN08b	“LCCA calculates agency, user, and environmental damage costs over the entire lifetime of the infrastructure application. In general, user and environmental costs are not reflected in conventional costing methods.”
KEN08a	“LCCA is a total cost accounting technique and a complementary methodology to LCA. It uses life cycle principles to augment conventional cost analyses by estimating not just initial costs, but also use and disposal costs.”
SIM12	“LCC is a means to show that, by reducing use, maintenance or disposal costs, a financial compensation can ensue”
SIM12	“[...] there are three different types of LCC [...]: conventional, environmental and societal. [...] Environmental LCC summarizes all costs associated to a product LC that are directly covered by one, or more, of the actors involved in its LC (supplier, producer, user or costumer and/or final disposer). It includes the externalities that are anticipated to be internalized in the decision-relevant future. Societal LCC uses an expanded macro-economic system and incorporates a larger set of costs.”
MAR14	“LCC analysis takes account of construction costs, operation/maintenance/repair costs, end-of-life costs, social costs and environmental costs. Social costs comprise user delay costs, vehicle operation costs and accident costs.”

Table 2

Country	Number of bridges		Total	Share
	Pedestrian	Vehicular		
Australia	0	1	1	0.2%
Austria	0	1	1	0.2%
Barbados	1	0	1	0.2%
Bulgaria	0	1	1	0.2%
Canada	1	13	14	3.0%
China	12	1	13	2.8%
Denmark	2	1	3	0.6%
France	1	0	1	0.2%
Germany	3	7	10	2.1%
Italy	1	0	1	0.2%
Japan	8	11	19	4.1%
Korea	25	16	41	8.8%
Russia	0	1	1	0.2%
Spain	1	4	5	1.1%
Surinam	0	1	1	0.2%
Switzerland	1	2	3	0.6%
The Netherlands	42	19	61	13.0%
UK	13	19	32	6.8%
USA	123	136	259	55.3%

Source: ACMA (2003a and 2003b); Keller (2001); Lee and Hong (2009); Canning and Luke (2010); Fiber Core Europe (2015)

Table 3

	Study object	Length	Area	Country	HPM details	non-HPM details	Chosen scenarios
ALA02	bridge superstructure	7.807m	39.31m ²	USA	GFRP in vinylester resin; tensile strength 310 MPa	SRC, existing deteriorated reinforced concrete slab bridge	-
BER06	bridge deck	32.7m	12.75m	USA	GFRP in vinylester resin, not for overhangs, parapet walls	SRC, epoxycoated steel rebars	-
CUI08	bridge/building superstructure	na	na	USA	hybrid composite reinforcement bar (steel, glass, carbon, twaron fibers)	steel reinforcement bar	-
DAN10	full bridge	13.5m	21.6m ²	NL	GFRP in polyester resin, pultruded profiles	structural steel	3 other material options neglected
EAM12	bridge superstructure	18.7m	254.32m ²	USA	CFRP	epoxycoated steel	high average daily traffic, box beam
EHL97	bridge deck	71.6m	1,203m ²	USA	GFRP with bamboo core sandwich	SRC	2 FRP alternatives neglected
EHL99	bridge deck	71.6m	1,203m ²	USA	GFRP with bamboo core sandwich	SRC	2 FRP alternatives neglected
GEN13	building superstructure	na	na	USA	ECC only	SRC only	high cost bridge design
HAS00	bridge substructure	na	na	USA	carbon-composite column wrap	steel jackets	-
HON07a	bridge deck	na	na	USA	GFRP, not specified	zero-maintenance scenario for GFRP	median of 3 bridges
HON07b	bridge deck	69m	675m ²	USA	GFRP, not specified	precast concrete	-
IBB14	bridge superstructure	6,098m	na	AU	GFRP, pultruded profiles	stainless steel (40% recycled)	-
KEN08a	bridge deck	160m	na	USA	ECC link slab deck design	SRC deck with expansion joints	ECC vs. SRC
KEN08b	bridge deck	160m	na	USA	ECC link slab deck design	SRC deck with expansion joints	ECC mixes; best (D-5) vs. worst (D-13)
KN110	bridge deck	27m	135m ²	DE	GFRP, hollow-section pultruded profiles	Concrete	-
KUH07	full bridge	35-45m	528m ²	DE	steel-GFRP hybrid	precast concrete	"fly-over" bridge
MAR14	full bridge	12m	72-84m ²	SE	GFRP bridge deck (alternative 2)	precast concrete	-
MEI02a	bridge superstructure	800m	24000m ²	JP	CFRP/GFRP hybrid; GFRP for wheel guards etc.	steel	"future prices" neglected
NIS06	full bridge	37.8m	162.5m ²	JP	GFRP in vinylester resin (CASE-5)	prestressed concrete, epoxycoated steel (CASE-2)	only 2 out of 5 cases
NYS03	full bridge	<10m	<100m ²	USA	CFRP and GFRP in vinylester resin tubes	SRC	St. James bridge only
SAH03b	bridge deck	na	1715m ²	USA	GFRP, not specified	cast-in-place SRC	lowest LCC for WV/ NY
SAH04	bridge deck	na	1715m ²	USA	GFRP, not specified	cast-in-place SRC	median of all bridges
SAH09	bridge deck	27.83m	121.34m ²	USA	GFRP, not specified	cast-in-place SRC	Katy Truss bridge only
SHA97	bridge superstructure	3m	na	IL	GFRP in polyester resin, pultruded profiles, "off-the-shell"	SRC (beam 4)	median of 3 beams
SIM12	lighting column	8m	na	NL	GFRP in polyester resin	steel (+zinc)	aluminum option neglected

Table 4

	Δ Total life cycle costs (HPM vs. non-HPM)	Total life cycle costs (HPM)	Unit ^a
ALA02	-73%	527.849	USD
BER06	62%	745.076	USD
CUI08	222%	+222%	-
DAN10	55%	124.407	USD
EAM12	-60%	2.305.758	USD
EHL97	19%	606.442	USD
EHL99	-9%	1.269.946	USD
GEN13	-10%	14.488	USD
HAS00	20%	413.589	USD
HON07a		1.091	USD/m ²
HON07b	25%	85.977	USD
IBB14	10%	+10%	-
KEN08a	-14%	24.514.130	USD
KEN08b	-23%	25.495.986	USD
KNI10		786.482	USD
KUH07	-6%	42.062.693	USD
MAR14	-31%	18.081	USD
MEI02a	290%	1.285.132.141	USD
NIS06	-11%	755.529	USD
NYS03	164%	993	USD/m ²
SAH03b	39%	1.066	USD/m ²
SAH04	165%	2.029	USD/m ²
SAH09	-7%	112.928	USD
SHA97	547%	172	USD
SIM12	-40%	537	USD

^a USD in values for Oct 31, 2014.

Table 5

	Discount rate	expected Service life (HPM)	expected Service life (non-HPM)	Δ Service life (HPM/ non-HPM)	LCC study period	External costs included?	User costs included?	Third party costs included?
ALA02	na	na	na	na	na			
BER06	na	na	na	na	na			
CUI08	na	na	na	na	na			
DAN10	na	50	35	+43%	50	(LCA only)		
EAM12	3.0%	100	65	+54%	100	Y	Y	
EHL97	4.0%	40	40	0%	40	Y	Y	
EHL99	4.0%	40	40	0%	40	Y	Y	Y
GEN13	1.0%	100	30	+233%	50		Y	
HAS00	na	na	na	na	na		Y	
HON07a	4.0%	85	85	0%	85			
HON07b	na	na	na	na	Na			
IBB14	na	na	na	na	na	(LCA only)		
KEN08a	3.0%	60	30	+100%	60	Y	Y	Y
KEN08b	3.0%	7-153 ^a	30	-76-410%*	60	Y	Y	Y
KNI10	na	na	na	na	na			
KUH07	3.0%	100-120	50-60	+100%	100-120	Y		
MAR14	4.0%	80	40	+100%	80	Y	Y	
MEI02a	2.9%	100	100	0%	100			
NIS06	0.0%	50-100	50-100	0%	50-100			
NYS03	4.0%	60	40	+50%	120			
SAH03b	4.0%	60	40	+50%	75	Y		
SAH04	na	60	40	+50%	75	Y		
SAH09	2.8%	60-70	30	+100-133%	60	Y	Y	Y
SHA97	5.0%	50	50	0%	50			
SIM12	3.5%	30-60	30	0-100%	30-60	Y		
median	3.3%	60	40	+50%	60	N (= 56%)	N (= 60%)	N (= 84%)
min-max	0-5%	30-120	30-100	0-233%	30-120	Y (= 44%)	Y (= 40%)	Y (= 16%)

^a related to mixes of ECC; excluded from median/ min-max

Table 6

Relative advantage (HPM vs. non-HPM)		Weight reduction	Installation time
ALA02	-75%	na	-75%
BER06	-47%	na	-47%
HON07b	-64%	na	-64%
KNI10	0%	na	~ 9 days
KUH07	-7%	na	-7%
SHA97	-64,2%	-64%	na
SIM12	-45,0%	-45%	na

Table 7

Indicator	1	3	5
Reliability	Measured data, verified	Non-verified or verified data partly based on assumptions	Non-qualified or qualified estimate
Completeness	Representative from a sufficient sample and adequate periods	Representative from a sufficient sample but shorter periods or smaller sample but adequate periods	Unknown or incomplete or smaller sample and shorter periods
Temporal correlation	Less than 3 years to year of study	Less than 6 years	Unknown or older
Geographical correlation	Data from area under study	Data from area with similar production conditions or from larger area	Unknown or with slightly similar or of different production conditions

Source: based on Weidema and Wesnæs (1996).

Table 8

LCC component	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation	Overall DQI
Discount rate	1	1	3	3	1	1/1/3/3/1
Service life HPM	3	na	1	1	1	3/na/1/1/1
Service life non-HPM	3	na	1	1	1	3/na/1/1/1
Conventional costs	na	na	na	na	na	na
Environmental costs, CO2	3	3	1	3	1	1/1/1/1/1
Social costs, fine particles, NOX, SO2	3	3	1	3	1	3/3/1/1/1
Social costs, safety features	3	3	1	3	1	3/3/1/1/1
General estimates for all costs	3	3	1	3	3	3/3/1/3/3

Table 9

	Δ Total life cycle costs (HPM vs. non-HPM) ^a	Δ Discount rate ^a	Δ expected Service life (HPM) ^a	Δ Service life (HPM vs. non-HPM) ^a	External costs included?	All 4 life cycle stages included? ^b	Transportation /distribution included?
ALA02	-75%	na	na	na		50%	
BER06	59%	na	na	na		50%	
CUI08	220%	na	na	na		25%	
DAN10	53%	na	-10	-7%	(LCA only)	75%	
EAM12	-63%	-0.3%	+40	+4%	Y	75%	
EHL97	17%	+0.8%	-20	-50%	Y	100%	
EHL99	-12%	+0.8%	-20	-50%	Y	100%	
GEN13	-12%	-2.3%	+40	+183%		50%	
HAS00	18%	na	na	na		75%	
HON07a	na	+0.8%	+25	-50%		75%	
HON07b	23%	na	na	na		50%	
IBB14	8%	na	na	na	(LCA only)	25%	Y
KEN08a	-16%	-0.3%	0	+50%	Y	25%	
KEN08b	-25%	-0.3%	-53-93	-126-360%	Y	75%	
KN110	na	na	na	na		25%	Y
KUH07	-8%	-0.3%	+50-60	+50%	Y	100%	
MAR14	-33%	+0.8%	+20	+50%	Y	100%	
MEI02a	0%	-0.4%	+40	-50%		75%	Y
NIS06	-13%	-3.3%	-10-40	-50%		100%	
NYS03	162%	+0.8%	0	0%		100%	Y
SAH03b	37%	+0.8%	0	0%	Y	100%	Y
SAH04	162%	na	0	0%	Y	100%	Y
SAH09	-10%	-0.5%	0-10	+50-83%	Y	100%	Y
SHA97	544%	+1.8%	-10	-50%		25%	
SIM12	-42%	+0.3%	-30-0	-50-50%	Y	100%	Y
median	10%	3.3%	60	+50%	-	75%	-

^a Δ relates to actual value of the case vs. median average value (***) of total sample.

^b relates to manufacturing, installation, use, and end-of-life.

Table 10

	External costs	User costs (traffic conditions)	Maintenance (amount & frequency)	Service life	Discount rate	On-site environment (e.g. sea salt)
ALA02	Y	Y				
DAN10			Y	Y		Y
EAM12	Y	Y				
EHL99	Y	Y			Y	
IBB14	Y					
KEN08a	Y	Y	Y	Y	Y	
KEN08b	Y	Y	Y	Y		Y
MAR14		Y				
MEI02a					Y	
NIS06	Y					
SAH03b		Y	Y		Y	
SAH04			Y			
SAH09	Y	Y	Y	Y		
SHA97				Y	Y	
SIM12				Y	Y	

Note: not listed cases do not report

Table 11

	Δ Total life cycle costs (HPM vs. non-HPM) ^a	Δ Discount rate ^a	Δ expected Service life (HPM) ^a	Δ Service life (HPM vs. non-HPM) ^a	External costs included?	All 4 life cycle stages included? ^b	Transportation/distribution included?
EAM12	-70%	-0.3%	+40	+4%	Y	75%	
EHL97	+9%	0.8%	-20	-50%	Y	100%	
EHL99	-19%	0.8%	-20	-50%	Y	100%	
KUH07	-16%	-0.3%	+50-60	+50%	Y	100%	
MAR14	-41%	0.8%	+20	+50%	Y	100%	
SAH03b	+49%	0.8%	0	0%	Y	100%	Y
SAH09	-17%	-0.5%	0-10	+50-83%	Y	100%	Y
SIM12	-50%	0.3%	-30-0	-50-50%	Y	100%	Y
median	-8.4%	3.8%	60	+52%	Y	100%	N

^a Δ relates to actual value of the case vs. median average value (Table 9) of total sample.

^b relates to manufacturing, installation, use, and end-of-life.

Appendix A

[Click here to download Supplemental Bibliography: Appendix A_list of cases.docx](#)

Appendix B

[Click here to download Supplemental Bibliography: Appendix B_list of reviews.docx](#)

Appendix C

[Click here to download Supplemental Bibliography: Appendix C_DQI example SIM12_citation.docx](#)