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1   **Uncertainties in Whole-building Life Cycle Assessment: A Systematic Review**

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16

17   **Abstract**

18   Environmental impacts (EIs) of building stocks have been receiving significant attention in recent

19   decades as they consume more than 40% of the world's energy, release one third of total

20   greenhouse gas emissions, and account for 30% of global landfill waste. Prior efforts have focused

21   on mitigating EIs during the operation stage of buildings, while the environmental performance of

22   other stages is relatively overlooked. Addressing this, whole-building life cycle assessment

23   (WBLCA) has gained prominence from a life-cycle perspective to ensure the best environmental

24   performance. However, there is an array of factors that can affect WBLCA results, and such

25   uncertainties render decisions made for sustainable development untenable. Aiming to understand

26   the comprehensive uncertain sources of WBLCA (*what*) and their corresponding solutions (*how*),

27   this paper systematically reviews existing publications on WBLCA, presents its status and

28   challenges, and analyses the taxonomy of uncertainties and eight uncertainty methods and variants

29   thereof. Accordingly, a framework is developed that enables LCA practitioners to readily

30 understand the correlation between WBLCA uncertainties and solutions, and conveniently locate

31 and appraise them throughout the WBLCA process. Upon answering the *known-what* and *known-*

32 *how* questions, this study contributes to the body of knowledge of LCA by providing a

33 comprehensive and systematic methodology to evaluate the EIs of buildings.

34 ***Keywords:*** Whole-building life cycle assessment, Uncertainty, Environmental impact, Solution,

35 Building performance

36

37 **1 Introduction**

38 Confronted with the pressing challenge on climate change, governments around the globe are

39 prioritising environmental consideration on their agenda. For example, the United Kingdom (UK)

40 became the first major economy to commit to achieving net zero greenhouse gas (GHG) emissions

41 by 2050 [1]. Among the various GHG emitters, the building sector instigates a massive impact on

42 the environment due to its intensive resource depletion and energy consumption [2,3]. However,

43 such a striking phenomenon will not disappear imminently due to the population growth, longer

44 time spent inside buildings (e.g., over 20 hours due to Covid-19 restriction rules), and demands

45 for better building services and comfort (e.g., 300,000 new homes per year by the mid-2020s in

46 England) [4]. Therefore, concepts such as green buildings, sustainable buildings and net-zero

47 energy buildings [5], and different types of building rating systems, including Building Research

48 Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and

49 Environmental Design (LEED), and Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) [6]

50 have been developed and adopted by countries to optimise building design and reduce energy

51 consumption and emissions. To name a few, a net-zero building requires that the energy use of a

52 building equals to its energy generation [7], and the LEED rating system requires a building to

53 earn credits in six categories, covering location and site selection, water and energy efficiency,

54   materials, and resources [8]. Nevertheless, endeavours of this kind only consider one or a few

55   aspects of building performance, failing to capture buildings' full inventory and variations over

56   time. Given that the ultimate goal is to deliver overall sustainable buildings throughout their life

57   cycle [9,10], there is a need to develop a more comprehensive method to evaluate the 'cradle to

58   grave' EIs of a building.

59

60   To do so, whole-building life cycle assessment (WBLCA) has pervaded the analysis of the overall

61   building performance [11,12] by monitoring and assessing buildings' life-cycle EIs (e.g.,

62   production, construction, operation and maintenance, and decommission phases) [13]. According

63   to [14], WBLCA can avoid passing the environmental load from one life cycle phase to another in

64   the decision making process. However, it should be noted that buildings' lifecycle is relatively

65   long (e.g., 50 to 70 years), contains complex structures, and necessitates a great number of

66   materials [13]. This may explain the copious LCA studies that have focused on materials. For

67   example, Lan *et al*. [15] emphasied the integration of system-level management (e.g., forest

68   management) into harnessing the benefits of cross-laminated timber in GHG emission. Hollberg

69   *et al*. [16] argued that the building information modelling (BIM)-LCA appraoch (using BIM to

70   automatocally take bill of quantities of materials) could be misleading due to the use of placeholder

71   materials. However, a BIM-based life cycle sustainability assessment (covering wider aspects than

72   LCA) helped Patel and Ruparathna [17] confirm geomembrane can be a sustainable material of

73   roads. As an important material in construction, Zhang *et al*. [18]investigated how LCA should be

74   properly applied to evaluate the application of recycled aggregate concrete. Despite these

75   promising efforts, their findings have not been widely adopted in the building sector, and more

76   importantly, Nwodo and Anumba [10] contend that the lack of uncertainty analysis strikes as a

77   major challenge in building LCA. Failure to do so, as argued by Igos *et al*. [19], would decrease

78   the reliability and credibility of LCA results.

79

80   Faced with the uncertainties casued by these 'dynamics' and the subsequent inconsistent and

81   perhaps unreliable final WBLCA results [20,21], several uncertainty analyses have been conducted

82   to improve the WBLCA results and facilitate decision making. For example, Robati *et al*. [22]

83   applied Monte Carlo simulation (MCS) to examine the uncertainty in materials. Harter *et al*. [23]

84   proposed the variance-based method to understand uncertainties in design parameters at different

85   building development levels. For uncertainty emanated from the LCA method itself, Buyle *et al*.

86   [24] promoted consequential LCA to identify marginal suppliers, market boundaries and market

87   volume trends as the attributional LCA has only a single set of model assumptions. Nevertheless,

88   these studies have a tendency to: (1) select specific methods (e.g., MCS) or a mixture of them (e.g.,

89   MCS and sensitivity analysis) to address specific uncertainties (e.g., materials and parameters)

90   (i.e., they appear in a sporadic manner); and (2) use uncertainty analysis as a 'procedure' in the

91   paper without providing how it was conducted and associated implications [25,26]. In other words,

92   a thorough investigation of the complete uncertainty sources, solutions and practical guidance is

93   currently not available in the literature. Without such a line of inquiry, the capability to further

94   minimise the uncertainties of WBLCA results is hindered. More importantly, identifying the roots

95   that cause the uncertainties of WBLCA results and illuminating the possible solutions are of the

96   uttmost concern of decision makers to realise sustainable building developments. Therefore, this

97   present study aims to critically review the current status of WBLCA, the uncertainties of WBLCA

98   results, and the latent methods to reduce the uncertainties, as well as propose a conceptual

99   framework to assist LCA practitioners in understanding and curbing the uncertainties of WBLCA.

100   Unlike previous examples, this study provides an aggregated view of the uncertainties of WBLCA,

101   their solutions and a practical pathway. Acknowledging the proliferating signifance of WBLCA in

102   improving building performance, this timely inquiry also paves an avenue for future headways to

103   be made.

104

105   The remainder of this paper is structured as follows: Section 2 explains the systematic method

106   followed throughout. Section 3 and Section 4 critically review the state-of-the-art WBLCA and

107   the factors/ sources that lead to its uncertainties, respectively. Section 5 details the existing

108   methods to quantify uncertainties of WBLCA. Building on the uncertainties and their solutions,

109   Section 6 proposes a conceptual framework to facilitate LCA practitioners' decision making. This

110   paper finishes by summarising its conclusions and channelling future work.

111   **2   Methodology**

112   To fulfill the research aim identified above, a systematic literature review was conducted to

113   identify, evaluate and interpret the current status of WBLCA, the uncertainties of WBLCA results,

114   their solutions, and the prospect of a framework in mitigating the uncertainties of WBLCA results.

115   Literature review, as a research methodology, is robust in synthesising research findings and

116   facilitating new knowledge production [27]. On the other hand, an unthorough, unsystematic and

117   selective literature review will result in flaws in the target research [27]. Hence, a step-by-step (i.e.,

118   systematic) searching and sifting process similar to Feng *et al*. [14] was implemented to eschew

119   authors' bias in selection (i.e., thorough and impartial). Figure 1 outlines the research flow of this

120   study, comprising: (1) database and sequential search; (2) screening and sifting; and (3) evaluation

121   and interpretation.
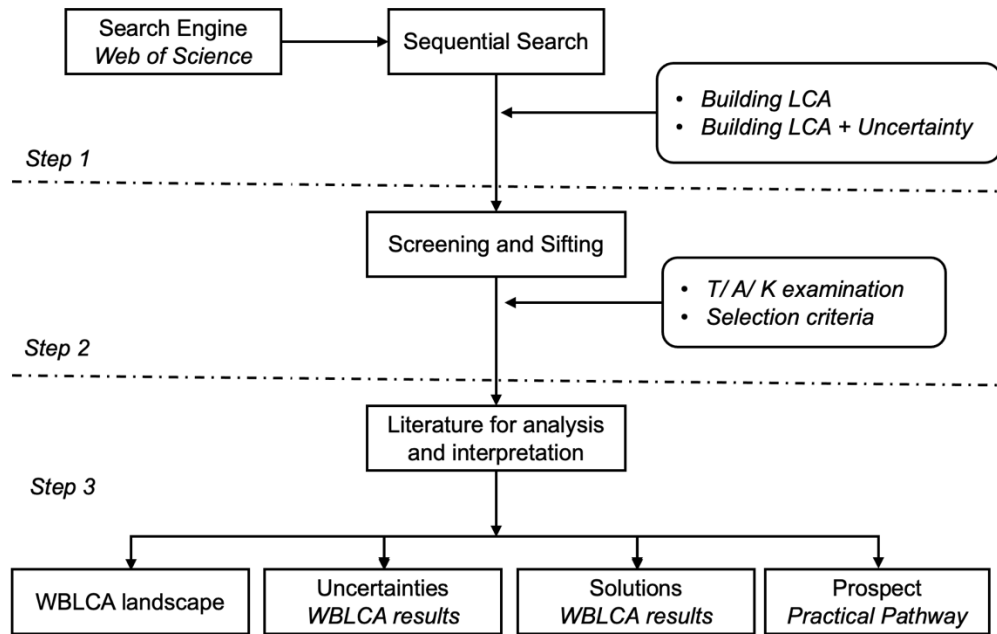
Figure 1. Research flow

2.1 Database and Sequential Search

To serve our research aim, the search engine Web of Science (WoS) was selected to conduct the literature search. WoS is a well-recognized database for academic articles and publications, which allows users to retrieve pertinent research with the function of advanced search [28]. In order to focus on the most valuable studies in the database and minimise authors' bias in selecting publications [27], titles, abstracts and keywords (T/A/K) were manually examined at each sequence. Moreover, four criteria were established and maintained to mitigate subjectivity throughout the screening and sifting process: (1) Year: 2000 to 2020 (both sides inclusive); (2) Type: peer-reviewed journals; (3) Language: English; and (4) Relevance: T/A/K related to search strings. In other words, only journal articles which are from 2000 to 2020, written in English, and focussed on building LCA were initially included. For instance, although Dai *et al*. [29] proposed a multilevel modelling approach to quantify uncertainties in terms of missing data, and temporal

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137 and geographical characteristics in the life cycle inventory (LCI) databases, this article was

138 excluded as it applies to the agriculture sector (i.e., nitrogen fertilizer application for corn

139 production).

140

141 The keyword "building LCA" was first used to identify the related literature. Consequently, a total

142 of 5890 results were generated to analyse the status of WBLCA. Then, the keyword "uncertainty"

143 was added to the previous search output, providing 426 results to have an in-depth view of the

144 uncertainty related to building LCA. Furthermore, among the 426 articles, those that not only

145 mention 'uncertainty' but also present a 'solution' were shortlisted (i.e., 43 publications) to

146 examine the existing solutions to WBLCA. This sequential literature identification process

147 provides a staged and comprehensive view of each aspect (Table 1) studied in this research. It also

148 shows the priorities and negligences of existing studies, for example, only 43 out of 426 articles

149 have performed an uncertainty analysis. A similar procedure has been followed in Feng *et al*. [14]

150 and Muazu *et al*. [30].

151 Table 1. Number of papers used for each stage of the review

Review objective	Number of papers for review
Status of WBLCA (Section 3)	5890
Uncertainties of WBLCA (Section 4)	426
Solutions to WBLCA uncertainties (Section 5)	43

152

153 *2.2 Evaluation and Interpretation*

154 Bibliometric analysis and content analysis were applied to evaluate and interpret the selected

155 literature (Table 1) [31,32]. Specifically, VOSViewer was adopted to facilitate the bibliometric

156 analysis to provide a visualised view of the *status quo* of WBLCA in the existing literature, viz.

157 development trend (i.e., publication yearly distribution), publication sources (i.e., density

158   visualisation), and research hotspots (i.e., keywords occurrence). VOSViewer is a computer

159   program that is capable of creating maps of scientific journals, researchers, keywords, etc. based

160   on co-occurrence, bibliographic coupling or co-citation networks extracted from literature

161   database [33]. Content analysis, on the other hand, was performed to deepen our understanding of

162   the uncertainties associated with the WBLCA and the current methods proposed to increase the

163   accuracy of WBLCA results. By synthesising the findings from the review, new knowledge on

164   how practitioners can better conduct a full WBLCA, treat WBLCA uncertainties, and make

165   informed building performance decisions were acquired.

166   **3   Status of Whole-building LCA**

167   Figure 2 displays the distribution of the 5890 papers over the period under investigation, which is

168   consistent with the statement that the topic of building LCA is becoming increasingly popular.

169
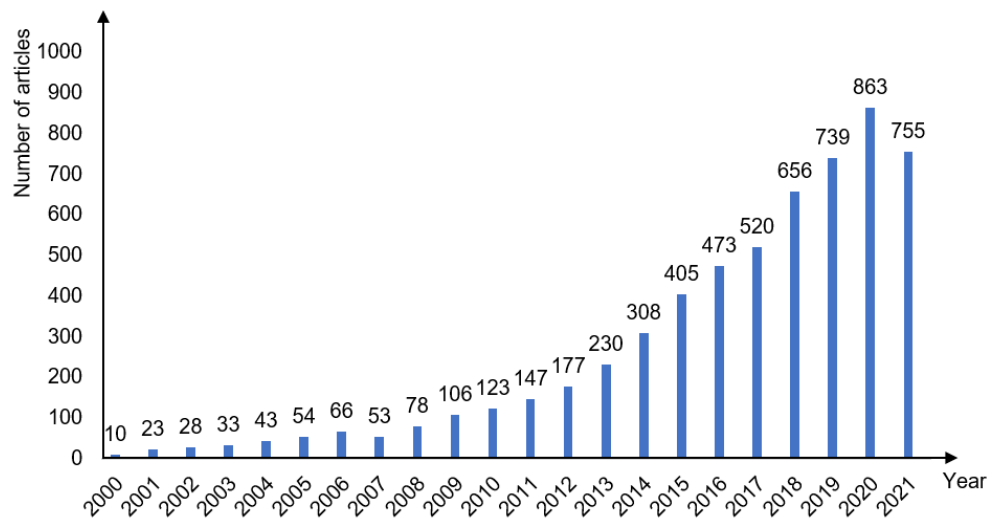
170   Figure 2. Distribution of source documents by publication year (search conducted in August 2021)

171

172   Among the 5890 papers published, *Journal of Cleaner Production* and *International Journal of*

173   *Life Cycle Assessment* were found two be the top two journals that have the most journal papers

174   published in this topic, which accounted for 26% in total. *Energy and Building* and *Building and*

8

175 *Environment* are the second top group that contributed a total of 13%. *Sustainability*, *Journal of*

176 *Industrial Ecology* and *Renewable & Sustainable Energy Reviews* are the third top group that

177 shared 10% of the selected journals. Among the bulky portions of journals that sometimes

178 overwhelm academics and practitioners [34], the resultant publication names can be readily used

179 by them to search and publish studies relating to building LCA. We now commence with the

180 analysis of the status of WBLCA.

181

182 Using the function of keywords occurrence VOSViewer, 'LCA' and 'building' were shown to be

183 the most occurred keywords, and "LCA" has different kinds of notation styles. 'Energy',

184 'embodied energy', 'impact(s)', and 'environmental impact(s)' were the second most occurred

185 keywords. Based on the keywords occurrence density, current studies on building LCAs mainly

186 focused on energy or environmental performance. While the embodied energy/carbon were

187 highlighted as the most occurred keywords, the operational energy/carbon emission haven't been

188 paid enough attention. However, studies show that the operational energy/carbon emission is as

189 important as the embodied energy/carbon emission [35,36]. Furthermore, these two aspects are

190 intertwined and need to be considered together. Table 2 lists the relationships between the

191 operational and embodied carbon emissions compiled by different researchers for different

192 buildings. It shows that a comprehensive analysis of building emissions requires the consideration

193 of embodied emissions in material production stage and the emissions in the operation stage, since

194 the emission percentage from other building life-cycle stages would increase when operational

195 energy consumption reduces. Based on the keyword occurrence density, it is suggested that more

196 studies should be conducted to analyse the operational energy/carbon emissions.

197

198   Table 2. Percentage of embodied and operational carbon emissions in different buildings

Building type	Building location	Building lifespan (years)	Embodied carbon emission (%)	Operational carbon emission (%)	References
Four student apartments	Israel	50	60	40	[36]
Low energy house	Sweden	50	40-60	40-60	[37]
New-built house	UK	25	20	80	[38]
20 apartments	Sweden	50	40	60	[39]
Energy efficient homes	Dutch	50	36-46	54-64	[40]
97 apartment buildings	Portugal	50	20.2	79.8	[41]
4-bedroom house	UK	60	20-26	74-80	[42]
95 residential buildings	worldwide	50	9-80	20-91	[43]
17-story resident building	China	50	17	83	[44]
Low energy buildings	worldwide	50	26-57	43-74	[45]
Low energy buildings	worldwide	50	9-46	54-91	[46]
Residential and office buildings	worldwide	50	10-20	80-90	[47]

199

200   'Design' and 'construction' were the other highlighted keywords in building LCA; however, there

201   are other life cycle stages (e.g., the maintenance and repair stage and disposal stage) that have not

202   been highlighted. However, [48,49] have shown that the percentage of emissions from

203   maintenance and repair stages increases with a corresponding significant reduction in operational

204   emissions. By only focusing on the design and construction stages, it is unlikely that designers can

205   garner a complete understanding of the building energy/environmental performance. In turn,

206   according to [22,50], this creates difficulties for designers to make the best decisions on the overall

207   building environmental performance. Therefore, the next step is to focus on the building over its

208   whole life cycle from the building material manufacturing stage, construction stage, to operation

209   and maintenance stage, and disposal stage. By following the EN15978 standard, WBLCA is a

210 comprehensive method that measures the building performance at all the life cycle stages, which

211 allows the designers to work out the optimal solution to improve building performance [51,52].

212

213 'Residential buildings' is another keyword that occurs frrequently in the building LCA keyword

214 search output, which demonstrates a number of research have been conducted on residential

215 buildings. For example, Kylili *et al*. [51] conducted a WBLCA for a passive house located in

216 Cyprus to assess the environmental performance. In Norway, Kristjansdottir *et al*. [53] performed

217 a LCA for eight different single-family houses, and the results illustrated the relationships between

218 the operational and the embodied environmental impacts. Atmaca and Atmaca [54] analysed the

219 life cycle carbon and energy emissions of two residential buildings from the construction phase to

220 the demolition phase. Evangelista [55] presented a "cradle to grave" LCA analysis for four typical

221 Brazilian residential buildings under eight impact categories. However, WBLCA has not been

222 widely used in other building types, such as commercial and industrial buildings. One of the

223 reasons could be the relatively simple structures of residential building, which makes it possible

224 to conduct the comprehensive WBLCA. Therefore, more attention should be paid to apply

225 WBLCA to other building types besides residential buildings.

226

227 WBLCAs are becoming increasingly popular in building construction-related decision making due

228 to the comprehensive and systematic approach of LCA to environmental evaluation [56,57]. Green

229 building rating systems worldwide also start to assign credits to WBLCA. Table 3 outlines a few

230 popular building rating schemes around the world that adopt WBLCA into the assessment criteria.

231 Most of these rating schemes analyse all the materials that form the building structure and

232 enclosure, and a whole-building life cycle is included from material production, building

233 construction, to building operation and demolition. Since no keywords related to building rating

234 systems were highlighted, future research could focus on analysing the impacts after applying

235 WBLCA into the green building rating systems.

236   Table 3. WBLCA methods applied in green building certification schemes.

Certification	Boundary	Details
BREEAM	Cradle to grave	All building materials used in construction included in the LCA, BREEAM LCA tools and benchmark established for credit calculation, and EcoPoints indicator introduced.
DGNB	Cradle to grave	Building elements clearly described with exclusions, environmental values of the reference building established for credit calculation, and five impact factors included.
LEED v4	Cradle to grave	Materials of building's structure and enclosure included in LCA, design building should achieve min. 10% reduction from reference building, and six impact factors included.
Green Globes	Cradle to grave	Building elements clearly described with exclusions, building final design achieves 10-20% reductions for different indicators in comparison with the reference buildings, and six impact indicators included.
CASBEE	Cradle to grave	Building elements defined, building final design reaches different level based on the reference building which is developed from historical data, life cycle CO_2 calculated.
Green Star	Cradle to grave	Building elements clearly defined, building final design achieves points by comparing with reference building (two options), and seven impact indicators included.

237

238 WBLCA is a valuable tool to help the public understand the life cycle impacts of buildings on

239 energy/carbon emissions. It also helps the government to fulfil the legislative requirement and

240 achieve the environmental targets. However, due to the uncertainties related to modelling, material

241 choices, data variability, and source parameters throughout the LCA process, ensuring the

242 reliability of WBCLA results is always a challenge [58,59]. Therefore, it is significant to elucidate

243 all the factors that might create uncertainties on WBLCA results and summarise all the possible

244 methods in the literature that could help reduce the uncertainties of WBLCA.

4 Sources of Uncertainties on WBLCA Results

The uncertainties of WBLCA results are mainly because of the complication of LCA development processes and the complexity of building structures [60,61]. For example, due to the data availability in LCA, the system boundary might not be complete which leads to uncertainty in results. Citherlet and Defaux (2007) [62] conducted a WBLCA for three home designs in Switzerland. However, the system boundary of this study was not complete and additional material losses were considered in the LCA. Due to the variety of LCA methods and databases, the LCA results could also be significantly different with uncertainties. One study indicates that the embodied CO_2e results could be over 50% different between Ecoinvent database and ICE database for different building designs [63].

On the other hand, the variances in building materials and cut-off rules could lead to LCA result uncertainty, and the reference service life of the building could also result in a variation of WBLCA results. For example, studies have indicated that the annual energy demand could decrease approximately 14% when the building service life changes from 50 years to 75 years [43,64]. Silvestre *et al*. [65] further argue that the prediction of construction materials' service life is subjected to methodological uncertainty (i.e., the deterministic approach and the stochastic approach) that can impact LCA decisions at the design stage. Moreover, Su *et al*. [66] reveal that the parameter identification of building insulation materials, and in particular, physical parameters (e.g., thermal conductivity) of glass wool are a significant source of the uncertainty of its life cycle energy consumption.

Furthermore, the variances on construction practices and design parameter selection could also lead to LCA results uncertainties. For example, Hong *et al*. [67] stated that the inherent uncertainty

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269   during building construction phase could result in a coefficient of variation of 18% in uncertainty

270   analysis. The major uncertainty sources during building construction, such as transport

271   measurement method and geographic representativeness, were identified in this study. Escamilla

272   and Habert [68] also indicated that the use of proper construction practices could build high

273   technical performance building with low LCA impacts using geographic information system (GIS).

274   In terms of design, Vuarnoz *et al*. [69] stated that the adoption of reality-based input parameters at

275   the building design stage, such as occupancy rate, appliance usage, and energy conversation factor,

276   would substantially impact LCA results. Therefore, the selection of construction practice and

277   design parameters are also sources of uncertainties on WBLCA results.

278

279   Huijbregts [70] listed the types of uncertainty that are related to LCA development phases, which

280   could be at the goal and scope definition phase, inventory analysis phase, as well as life cycle

281   impact assessment phase including life cycle inventory analysis (LCIA) method and database

282   (choice of impact categories, classification, characterisation and weighting methods). The source

283   of uncertainty could be parameter uncertainty, model uncertainty, and uncertainty due to choices

284   [59][70]. Elsewhere in the existing literature, Hong *et al*. [71] summarised those uncertain sources

285   could result from data availability and quality [72], technical performance, emission factors and

286   the functional unit [73] and cut-off, aggregation, temporal and geographic considerations [74]. To

287   encapsulate the sources, Huijbregts *et al*. and Lloyd and Ries concluded that they can be

288   categorised as parameter uncertainty, scenario uncertainty, and model uncertainty [75,76]. Favi *et*

289   *al*. [95] further cited Der Kiureghian and Ditlevsen [77] and classified them into epistemic

290   uncertainty, which can be mitigated by collecting more data and/ or optimising models, and

291   uncertainty in aleatory, which exists in the natural randomness in a process and thus is unavoidable.

292   Here, Table 4 identifies the most notable factors from the 426 papers that create uncertainties on

293   WBLCA results, namely system boundary (including service life), different building components/

294   elements, LCI, databases and methods used. In addition, Table 4 summarises the most relevant

295   WBLCA development details to facilitate a better understanding of the uncertain sources of

296   WBLCA results. The results show that the current WBLCA development methods are inconsistent

297   in different LCA phases, and the WBLCA results are presented with uncertainties, which point out

298   the necessity of proposing solutions to address them.

Table 4. The inconsistency of WBLCA methods in different case studies

Refer ence	Type	Goal and scope			LCI	LCIA
		Boundary	Building elements	Life (yr.)	Scenario development	Database/Method
[51]	Passive house	Cradle to site	Ground and first floor bill of quantity	50	External drainage, sewage, excavation not included	EcoHestia/ CML2001
[78]	Net-zero energy building	Product stage	Major components from structure to interior as well as ductwork, PV panel	50	Landscaping, interior finishes not included	Franklin USA98/ CED
[54]	Resident building	Cradle to gate	Major building structures, material replacement factors considered	50	Energy consumption and CO_2 emission in different stages accumulated	ICE database
[79]	Resident houses	Cradle to grave	BoQ from construction guides and material specifications	50	Energy and water in usage stage assumed	Econinvent/Gabi V4.3
[80]	Three types of buildings	Cradle to grave	Envelope and equipment system classified based on UNI 8290	50	Transport distance assumed, MC4 software for usage stage	Ecoindicator 99, IPCC 2007, CED
[81]	Passive house	Cradle to grave	Ground and first floor, entrance ramp and two exterior stairs, detailed end-of-life recycling stage	70	Life cycle improvement stage included, construction waste considered	Ecoinvent/ EPD 2007 Ecoindicator 99
[82]	Three hypothetical buildings	Cradle to gate	Building components built in Revit, VIP insulation material studied	50	Material transport not included	International, German and Norwegian EPD system
[83]	Three residential buildings	End-of-life stage not included	Seven building elements info obtained from original drawings.	75	Retrofit phase included, Only energy and GHG impact considered	ICE 2.0
[84]	10 case studies	Product stage	Material quantities from standard BoQ in public works department	n/a	Only embodied energy and carbon calculated	ICE 2.0/I-O LCA
[85]	26 buildings	Cradle to grave	BoQ not clearly presented, building floor area included	50	Life cycle CO_2 calculated only, retrofit phase not included	BELES database
[86]	Heritage theatre	Cradle to grave	Five main materials analysed	n/a	Usage stage excluded, only GWP and CED calculated	Ecoinvent 2.0
[87]	Industrial building	Cradle to grave	Equipment not analysed, electrical & mechanical components included	20	Designer builder applied in usage stage, Retrofit not studied	Ecoinvent 3.0 & ESUCO
[88]	Apartment building	Cradle to grave	Major renovation materials exterior walls, doors, windows, balcony	30	Retrofit not considered	Ecoinvent 3.1/ReCiPe
[55]	Four Brazilian dwellings	Cradle to grave	BoQ of main construction materials listed	50	water, energy use, waste during construction considered	Ecoinvent 3.01/CED 1.08 & ILCD 2011

301 **5   Solutions to Reduce the Uncertainties**

302 Through the literature review, it is revealed that while most of the studies (i.e., 426 publications)

303 acknowledge the existence of uncertainties of WBLCA results, less than 1/4 of them (i.e., 43

304 publications) attempt to resolve the problem. This finding concurs with Blengini and Carlo (2010)

305 and Rodrigues *et al*. (2018) arguing that existing LCA approaches generally do not address

306 uncertainty [89,90]. During the third round of literature retrieval, a total of eight potential solutions,

307 namely, MCS, sensitivity analysis, pedigree matrix and data quality indicators (DQI), fuzzy related

308 method, Taylor series expansion and analysis of variance (ANOVA), decision support diagram,

309 structured under-specification, and variants thereof (e.g., MCS mixed with pedigree matrix) have

310 been identified. Notably, MCS is the most popular method (25 times) adopted to understand the

311 uncertainties of WBLCA results, followed by sensitivity analysis (19 times), pedigree matrix and

312 DQI (12 times), and fuzzy methods (3 times). Those mentioned only one time are categorised as

313 'other miscellaneous methods' hereinafter. The total number of times appeared is over 43 as some

314 studies deployed more than one solution in a single study.

315 *5.1 Monte Carlo Simulation*

316 Compared with a single value assigned to each parameter (i.e., deterministic approach) [76], MCS

317 is a tool through which uncertainty can be quantified (i.e., probability distribution of output

318 parameters) by using random values of input parameters [22,91]. Within the identified WBLCA

319 studies, it has been applied to different parts (e.g., brick/ fired-clay walls, insulation, flooring, etc.),

320 phases (i.e., different system boundaries) and types (e.g., commercial and residential, traditional

321 and contemporary) of buildings in different regions (e.g., Canada, Australia, Belgium) to address

322 the result uncertainty caused by a variety of factors (e.g., materials, data, and model parameters).

323 For example, MCS is employed by Rodrigues *et al*. (2018) and Rezaei *et al*. (2019) to compensate

324 information shortage on materials at the early design stage of residential buildings in the South

325 European Climate and Canada, respectively [90,92]. In this sense, designers can become aware of

326 the EIs of their design and select materials that are environmental-friendly. Using MCS, Burek

327 and Nutter [93] analysed the LCIA uncertainties of Walmart's distribution centres and confirmed

328 electricity generation to be the biggest source of uncertainty. However, they consider only the

329 uncertainties resulted from LCI input data while overlook the characterisation factors. The LCI

330 data uncertainty was also examined by Hasik *et al*. [91] via MCS in three types of water systems

331 of buildings and they attributed the uncertainties to a low number or large variability of samples

332 and spatial and temporal scales. In addition, this uncertainty relates to how data are distributed (i.e.,

333 normally and uniformly). However, Pomponi *et al*. [94] argued that this relevance disappears in

334 the MCS result after 104 random samplings from within the data variation range. There are other

335 uncertain sources, such as material composition, transportation, energy usage, and service life

336 prediction methods of materials that have been measured by MCS [65,95]. For instance, Robati *et*

337 *al*. [22] predicted the EIs of each of 19 building materials for a 50-year building lifespan by

338 considering uncertain variables such as materials' lifetime, CO_{2e} and transport distance.

339 *5.2 Sensitivity Analysis*

340 While there are solutions (e.g., MCS) aiming to understand the uncertainty of the LCA result,

341 sensitivity analysis is commonly used to understand what parameters impact the result most [94].

342 Notably, a comprehensive list of the uncertainty types and their classification within the selected

343 studies is presented in Section 4. This scenario-based approach is considered to be complementary

344 to uncertainty analysis (sometimes even treated as the same, e.g., Walker *et al*. [96]) and a

345 combination of them facilitates better decision-making (Roder *et al*., [97]). In the selected studies,

346 we identify the most prevalent practice is a mixture of sensitivity analysis and MCS to target

347   uncertainties in design features and background LCI data (Eckelman *et al.*, [98]), foreground and

348   background LCI data and transport (distance and types of vehicles) (Cuenca-Moyano *et al.*, [99]),

349   materials (Favi *et al.*, [100]), commodity prices (Teh *et al.*, [101]), key performance indicators

350   (Walker *et al.*, [96]), etc. An example is Ross and Cheah [102] adopted MCS to study LCA

351   uncertainty of buildings' air conditioning systems resulted from different user behaviours and a

352   subsequent sensitivity analysis identified system cooling and unoccupied room to be the highest

353   influential factors. Similarly, maintenance frequency (frequent or periodic) and types (vacuum,

354   sweep, or mop) can contribute to different LCA results of different floors. However, the sensitivity

355   analysis in Minne and Crittenden [103] confirmed vacuuming's significant role in EIs. Aktas and

356   Bilec [104] addressed the different lifetime of residential buildings in affecting their interior

357   renovation energy consumption using MCS. Compared with the lifetime of carpet, ceramic, paint

358   and Vinyl, residential building lifetime was found to be most significant using a sensitivity analysis.

359   Different from the 'normal' procedure, Benetto *et al.* [105] firstly conducted a sensitivity analysis

360   and then an uncertainty analysis through MCS. However, they only considered limited parameters

361   in the sensitivity analysis and overlooked the uncertainties resulted from data recordings and data

362   collection, which in turn jeopardise the accuracy of the final result. By contrast, the normal

363   procedure followed in Su *et al.* [66] was able to examine all uncertain sources in the MCS and

364   uncovered that physical parameters (i.e., conductivity and density) affect the LCA of building

365   insulation materials most (i.e., 47% and 66.9%). Nevertheless, the use of hypothesis or empirical

366   information in MCS can lead to this big uncertainty of physical parameters. In addition, Teh *et al.*

367   [101] stated that the economy-wide system boundary embedded with the methodology resulted in

368   higher GHG emissions. Obviously, these point out the importance of selecting appropriate

369   uncertainty analysis methods *per se* and the awareness of their inherent uncertainty.

370

Sometimes (e.g., Cellura *et al*. [106], Walker *et al*. [96]), it is noted that sensitivity analysis is treated as the same as uncertainty analysis. This way, they tend to identify several variables that may be of high impact on the result and calculate their 'uncertainties' under a certain range (e.g., ±10%) or different scenarios (e.g., different impact assessment methods). For example, Cellura *et al*. [106] constructed different scenarios to study the uncertainties arisen from the secondary input data (i.e., transportation, electricity, and baking step) and methods (i.e., CML 2 baseline 2000, Ecoindicator 95, EDIP/ UMIP 97, IPCC 2007 and Impact 2002+) for roof tiles. However, problems can include: (1) it is not clear how these critical variables are identified; and (2) result shows the variables may not be critical, impeding a better understanding of the uncertainty. A case is, in Lu *et al*.'s study [107], three variables (change between -10% to +10) were presumably selected to check their uncertainties, and emissions from transportation processes was tested to be insensitive. In comparison, a hotspot analysis was undertaken by Wang *et al*. [108] to search the significant variables (i.e., transportation) and then calculated its variability. Therefore, it signifies not only the awareness of variances between uncertainty methods as mentioned above but also the careful selection of a single method with different types. As stated in Pannier *et al*. [109], different types of sensitivity analysis, such as screening and global ones, can present different relative influences of uncertain factors.

5.3 Pedigree Matrix and Data Quality Indicators

Pedigree matrix is introduced to ensure the reliability and applicability of LCA results by managing data quality. It encompasses five indicators, such as reliability, completeness, temporal correlation, geographical correlation, and further technological correlation, which have a score of 1 to 5, to adapt the actual data to a specific data quality goal [72]. In the target literature, we have

393   witnessed the synergies of pedigree matrix, MCS and sensitivity analysis to estimate uncertainty

394   and almost a half of them in CO_2 emission and embodied energy. Zhang *et al*. [110] used DQI and

395   MCS to cope with parameter uncertainty followed by a scenario analysis to treat scenario

396   uncertainty (e.g., different system boundaries and energy efficiency) and model uncertainty (e.g.,

397   different transformational relationships and distribution selection) for building life cycle carbon

398   emission. The identical approach was applied in Zhang *et al*. [110] but for carbon emission during

399   building construction. Similarly, the GHG emission during the construction was computed in Hong

400   *et al*. [71] by combining MCS and DQI to ascertain input data that were deemed highly uncertain.

401   The addition of MCS to DQI can mitigate the subjective evaluation and lower the calculation cost.

402   However, compared with statistical methods, the result is not accurate. Therefore, a hybrid MCS-

403   DQI-statistical method was proposed by Wang and Shen [111] for whole building embodied

404   energy analysis and more accurate result and cheaper cost were observed than pure DQI and

405   statistical methods, respectively. Moreover, recognising DQIs do not always contribute equally, a

406   weighting mechanism is considered in the sole use of the pedigree matrix. For example, the

407   analytical hierarchy process was employed by Wang *et al* [112] to determine the weighting of each

408   DQI and estimate better probabilistic values of embodied energy intensity for concrete, steel and

409   glass. Similarly, Taborianski and Prado [113] and Henriksson *et al*. [114] considered the weighting

410   level of each life cycle stage and data's central value when multiple reported values are available,

411   respectively.

412

413   In addition to the MCS and DQI to address absolute accuracy of the final LCA result, it is common

414   to compare the uncertainty between scenarios, such as different earth-retaining walls [115], fired-

415   clay bricks produced by different manufacturers [116], contemporary and traditional housing [117]

21

416 and country-wide clay hollow brick walls [58]. According to Piroozfar *et al*. [117], the pedigree

417 matrix showed that uncertainty for traditional houses is higher than contemporary houses, but the

418 LCA results stimulated by MCS presented better EIs in the traditional houses. On the one hand, it

419 challenges the environmental-friendly materials (e.g., limestone and lime mortar) as touted in the

420 contemporary houses. On the other, it reinforces the importance of recording real data relating to

421 building materials and methods that would otherwise generate uncertainties. This meaningful

422 comparison perhaps corroborates Blengini and Carlo's [89] statement on the relatively more

423 accurate comparative LCAs due to a higher correlation within scenarios' uncertainty.

424 *5.4 Fuzzy-related Methods*

425 Fuzzy-related methods (e.g., fuzzy rough sets, fuzzy variables, fuzzy logic approach and

426 intuitionistic fuzzy sets) have been performed to counter the uncertainties in variables/ parameters

427 and input data of LCA. For example, Li *et al*. [118] applied fuzzy rough sets to study the LCA

428 uncertainty of a distributed renewable energy system derived from its power plant capacity, annual

429 operation hours, and upstream Technosphere performance. Due to the different results from a

430 sensitivity analysis, they believed that fuzzy rough sets are a new way of addressing uncertainties.

431 However, how the different results impact decision-making should have been made clear. In the

432 wind energy sector, intuitionistic fuzzy sets have been adopted by Gumus *et al*. [119] to examine

433 uncertainties in indicators and lifecycle span of energy planning alternatives. In essence, a survey

434 conducted by Lloyd and Ries [76] indicated that fuzzy data sets are ranked as the third most

435 commonly used uncertainty method in addition to stochastic modelling (e.g., MCS) and scenarios.

436 However, this does not appear to hold in the context of WBLCA in this research because there

437 were only two articles that were qualified for review. Nevertheless, their applications in other areas

438 shed light on how the fuzzy concept can potentially be mobilised in WBLCA.

439

440   Using linguistic rules, fuzzy set theory assumes the elements of a set following a membership

441   function with the value ranging from 0 to 1 rather than binary terms [120]. This can solve the

442   problem where an arbitrary number is assigned to a variable or where precise values are not

443   available in WBLCA. As such, Ardente *et al*. [121] proposed a software based on fuzzy logic to

444   define uncertain data on their age, underlying technology, statistical and geographic

445   representativeness. In the case of plaster materials, it allowed WBLCA practitioners to view the

446   whole calculation process and describe the sensitivities of each solution. More recently, Kaziolas

447   *et al*. [122] chose two most uncertain variables, namely the end transport and recycling rate as

448   fuzzy variables to calculate the EIs of a timber residential building and a steel building,

449   respectively. A common feature of these two studies is that the fuzzy application to WBLCA

450   requires expert knowledge and judgement, indicating the importance of experienced experts.

451   *5.5 Other Methods*

452   Through the literature review, a variety of 'non-mainstream' methods have been identified, which

453   however, have provided a new stream of solutions to tackle uncertainties of LCA. For example,

454   Hoxha *et al*. [123] adapted the Taylor series expansion and ANOVA to depict uncertainties

455   (represented by mean value and the variance) in impact coefficient, density, mass and service life

456   of building materials (see Hoxha *et al*. [124] p. 56 and Scherre [125], p. 534 for equations of the

457   two methods). One benefit of this mixed method lies in that the Taylor series method can only

458   calculate the mean value and the variance of continuous variables while ANOVA complements

459   this by serving the discrete variables (e.g., the number of uses of material). Targeting at the specific

460   spatial dimension to reduce geographic uncertainty at every LCA stage, Patouillard *et al*. [126]

461   developed an iterative decision-support diagram to guide the inventory regionalisation and

462   inventory spatialisation process by considering existing approaches (e.g., GIS) in the literature.

463   While this provides a portable tool for practitioners to minimise spatial uncertainty without having

464   to develop new instruments, it is suggested that uncertainty contribution analysis (i.e., determine

465   if the uncertainty comes from inventory data or spatial variability of characterisation factors)

466   should be developed in the long-term. Standing at the early design stage when detailed information

467   on the system under investigation is unavailable, Tecchio *et al*. [127] proposed the structured

468   under-specification where a hierarchical data structure is established to classify building materials

469   and assemblies with different levels of specificity. Harter *et al*. [23], on the other hand, shifted the

470   specificity to different building development levels and used the variance-based method to

471   quantity uncertain design parameters, such as geometry, technology, operational design and

472   system efficiency. Primarily, they focused on decomposing the model output variance and

473   calculating the first-order effect and total effect to indicate the importance and effects of a

474   parameter on uncertainty. In this sense, it can be regarded as a form of sensitivity analysis.

475

476   There are some other advanced uncertainty calculation methods that can be considered in WBLCA.

477   A germane example is the Polynomial Chaos (PC) expansion where Sepahvand *et al*. [128]

478   demonstrated the use of orthogonal polynomials as the expansion base in various random variables

479   to compute the parameter uncertainty. Compared with the sampling method (e.g., MCS), PC

480   expansion represents the uncertain quantities as an expansion in a non-sampling and surrogate way,

481   and proves to be more accurate and time efficient. In fact, it has been pioneered by Galimshina *et*

482   *al*. [129] to understand the uncertainty value in LCA and life cycle cost of residential building

483   renovation in Switzerland. In addition, Latin hypercube sampling and quasi-MCS, which employ

484   the stratified sampling approach (i.e., the input parameters are more uniformly distributed) and

485   quasi-random numbers, respectively, have been identified by Groen *et al*. [130] to be more

486   accurate in calculating the sample mean than MCS in LCA. Bayesian approach is another

487   parameter uncertainty quantification method applied in Liang *et al*. [131]. It features a posterior

488   probability distribution of the parameter by combining prior information (i.e., existing knowledge)

489   and the likelihood information (i.e., the proximity of simulated and observed data). While these

490   methods may not be readily available in WBLCA, it explicitly implicates that WBLCA researchers

491   and practitioners need to learn from other areas and adapt the methods to their own needs.

492   **6   A Conceptual Framework**

493   The WBLCA community is in urgent need of a clear understanding of uncertainties associated

494   with WBLCA to underpin decisions for sustainable development [110,122]. However, despite the

495   sporadic efforts as we have uncovered, a comprehensive taxonomy of WBLCA uncertain sources

496   and corresponding solutions are far from being at the fingertips. Having in place a typology of

497   uncertainties and promising solutions, therefore, is important as this proposed pathway (Figure 3):

498   (1) configures life-cycle stages and function units to achieve true WBLCA; (2) considers an

499   exhaustive list of uncertainties and categorises them based on different LCA stages; and (3)

500   provides pinpoint solutions to treat each uncertainty. To better employ the framework, the

501   practitioners first need to decide on whether a true WBLCA or a 'fitness for purpose' LCA (e.g.,

502   not all life-cycle stages and function units are assessed) is needed. With the determined goal in

503   mind, they then need to understand the life-cycle stages, function unit and their corresponding

504   uncertainty taxonomy and solutions as depicted in Figure 3. For example, if the 'fitness for purpose'

505   scenario selects the 'production to demolition' stage for external walls, Figure 3 then makes it

506   clear to the practitioners that there will be five categories of uncertainties along the assessment

507   process that should be noticed and provides corresponding solutions to measure them.
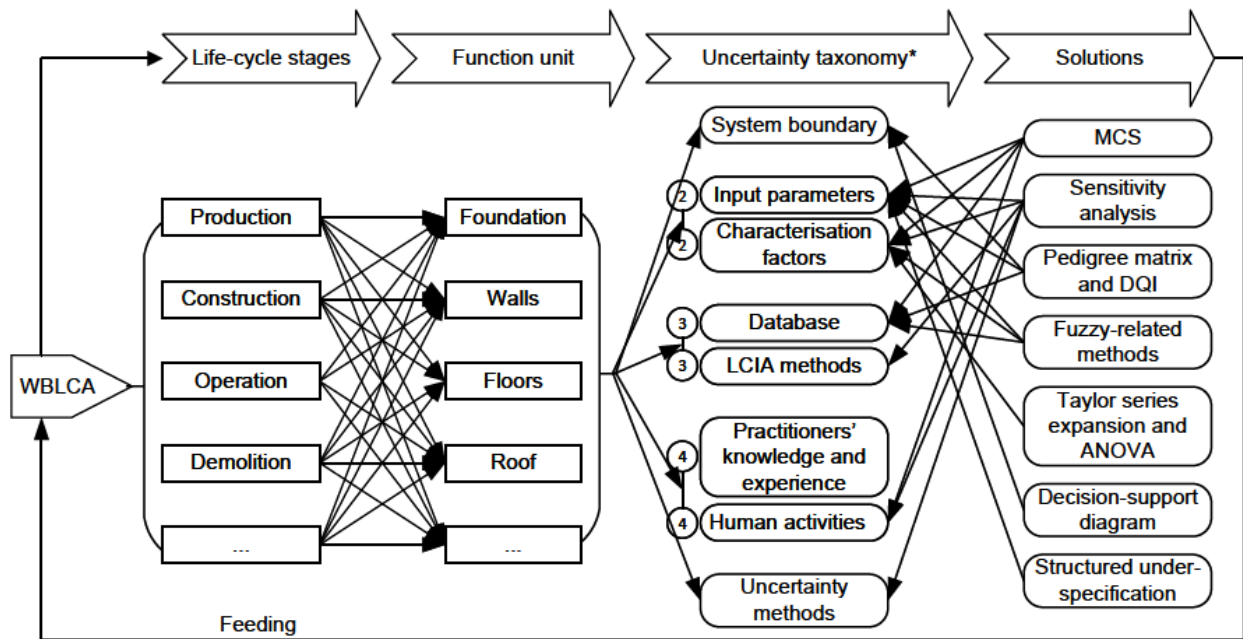
508
509   Figure 3. Conceptual framework for solutions to address WBLCA uncertainties

510

511   Current research tends to frame WBLCA into different stages, such as the construction stage [71]

512   and the replacement stage [58], and specific parts and materials, such as walls [115], floors [108]

513   and concrete and cement [101], rendering a somewhat 'quasi-WBLCA'. While it is difficult to

514   obtain a complete LCI and best guess values have to be used, it is possible to create a 'true'

515   WBLCA by integrating life-cycle stages and function units. For example, Hoxha *et al*. [123]

516   calculated the EIs of a building by calculating the cumulative sum of materials' (or components')

517   EI and energy's EI. Put simply, the WBLCA should consider every material and component and

518   their associated impact over the life cycle. In a 'fitness for purpose' scenario, where true WBLCA

519   is costly and time-consuming, the framework can be adapted to target components (e.g., materials

520   and embodied energy) that may be of high impact. However, these components should be

521   determined scientifically (e.g., a contribution analysis) as subjective choices can be

522   counterintuitive [117]. To realise the true WBLCA or fitness-for-purpose, we underlie a feeding

523   mechanism where information can flow and be recorded throughout the assessment of the present

524   project and lessons can be transposed to future projects. Another element relies on the

525   understanding of the uncertainties as part of the WBLAC process.

526

527   There are studies that have outlined the sources of uncertainties [71,76]. However, a degree of

528   ambiguity resides with the taxonomy of uncertainties and the correlation between each uncertainty

529   and each solution. Building on the LCA stages and the factors we identified from the review, the

530   goal and scope definition stage can contain such uncertainties as system boundary and function

531   unit and the inventory analysis stage can include parameter uncertainty. For the impact assessment

532   stage, database and the LCIA methods are the main uncertain sources while human related factors

533   (e.g., knowledge and experience) are evident at the interpretation stage. This classification allows

534   LCA practitioners to be aware of the uncertainties and conveniently locate them throughout the

535   assessment. More importantly, our framework suggests that the inventory stage and assessment

536   stage are more uncertain than other stages with parameter uncertainty and database uncertainty

537   being the prominent factors. To solve them, MCS, sensitivity analysis, DQIs and fuzzy related

538   methods can be useful and MCS and sensitivity analysis are able to address a broader range of

539   uncertainties. However, we argue these different solutions themselves can embed uncertainties

540   (i.e., uncertainty methods). Similarly, Cellura *et al*. [106] contend that the EIs are different using

541   different LCIA methodologies. This, again points out the importance of: (1) LCA practitioners'

542   capability to select an appropriate LCIA method and uncertainty quantification method to

543   minimise uncertainties; (2) using a mixture of uncertainty methods and developing new and

544   effective tools; and (3) an accurate way of recording data in industry and academia as they are

545   often the data source or benchmark of the LCA ('Three principles'). Hoxha *et al*. [123] and Feng

546 *et al.* [14] have reported that environmental product declarations (EPD) is a good example of

547 reliable material information as EPD records data directly from manufacturers and companies, and

548 is developed strictly following ISO 21931 and EN 15643 at the building level. Equally, this

549 conceptual framework demonstrates a pathway for a suitable uncertainty method to be chosen and

550 new ones to be developed for LCA practitioners.

551

552 Nevertheless, we are cognisant of the harsh reality that sometimes research findings are not applied

553 to practice and *vice versa* [132]. In our case, the solutions identified in Section 5 may not be easily

554 implemented by 'new' researchers and practitioners in the LCA field. This could be because some

555 studies (e.g., Morales *et al.*, [58], Teh *et al.*, [101], Su *et al.*, [66]) only mentioned, for example,

556 that MCS is employed to quantify uncertainties without detailing the procedure. To facilitate the

557 convergence of knowledge (i.e., understanding WBLCA uncertainties) between two communities,

558 we summarised in Table 5 some promising tools emerged from the review process to bridge this

559 gap. Taking the SimaPro software as an example, Silvestre *et al.* [65] elaborate five steps (see

560 Heijungs *et al.* [133]) to be taken when using MCS to incorporate the parameter uncertainty. With

561 these tools, the problem becomes 'how to use them and how to interpret the results after clicking

562 buttons'.

563

564 Table 5. Available tools to facilitate the application of uncertainty solutions/ methods

Tools	References
Microsoft Excel (generating a random sampling for input parameters)	Robati *et al.* [22]
SimaPro (different versions such as 8.4 and 8.0.2)	Burek and Nutter, [93], Cuenca-Moyano *et al.* [99], Almutairi *et al.* [95], Silvestre *et al.* [65], Minne and Crittenden [103], Piroozfar *et al.* [117], Mohajerani *et al.* [116], and Blengini and Carlo [89]

Open LCA software	Rezaei *et al*. [92] and Pons *et al*. [115]
Sobol's method	Favi *et al*. [100]
One Click LCA software	Petrovic *et al*. [134]
Discernibility analysis and independent sampling	Eckelman *et al*. 2018 [98]
@RISK package	Ross and Cheah [102], Aktas and Bilec [104], and Tushar *et al*. [135]
MATLAB R2015b (8.6.0) and Python 3.5	Pomponi *et al*. [94], Zhang and Wang [44], Zhang *et al*. [18], and Wang *et al*. [112]
Umberto 5.0	Benetto *et al*. [105]
Tally	Tushar *et al*. [135]
Hotspot analysis	Wang *et al*. [108]
Minimum-maximum sensitivity analysis, Morris screening, and Plackett and Burman design of experiment	Pannier *et al*. [109]
Sensitivity coefficient (the percentage change of emissions divided by the percentage change of each factor)	Lu *et al*. [107]
Crystal Ball software	Hong *et al*. [71]
Expert judgement	Hong *et al*. [71] and Piroozfar *et al*. [117]
Beta function	Wang and Shen [111]
Membership functions	Li *et al*. [118] and Kaziolas *et al*. [122]
F.A.L.C.A.D.E. software	Ardente *et al*. [121]
One at a time approach	Li *et al*. [118]
ImpactWorld+	Patouillard *et al*. [126]
MasterFormat structure	Tecchio *et al*. [127]

565 Note: Different from the uncertainty tools in Table 5, Al-Ghamdi and Bilec [56] provided a comparative
566 review of existing WBLCA tools. Notably, some WBLCA tools (e.g., SimaPro and OpenLCA) are embbed
567 with a function to perform an uncertainty analysis. A more recent review of the tools for visualising LCA
568 results can be found in Hollberg *et al*. [136].

569
570 It has been noted by Blengini and Carlo [89] the existing tools have their respective characteristics

571 that may (dis)encourage LCA researchers and practitioners from adopting them. For instance,

572 generic tools (e.g., SimaPro) are considered to be flexible by modelling different kinds of systems

573 and having access to powerful databases. They, however, may not be attractive to users who prefer

574 less complex analysis and friendly operation interface as in some building-specific tools (e.g.,

575 ATHENA system). Similarly, Meex *et al*. [137] suggest that current LCA-based EI assessment

576 tools have complex methodologies and cannot be easily adapted, which hamper their adoption in

577 the early design stage by architects. Therefore, it is important for researchers and practitioners to

578 learn and grasp skills (e.g., software operation) to undertake WBLCA. Alternatively, we concur

579 with Güereca *et al*. [138] that proper guidance and training should be provided to ensure the quality

580 of LCA. Akin to the feeding mechanism in Figure 3, the payoff for such investment will not be

581 one-off as the knowledge can be passed down internally. Another benefit is that the increasing

582 proficiency of LCA practitioners can counter the uncertainty caused by the users themselves as

583 stated in Henriksson *et al*. [114]. In tandem, we need to reiterate that the solutions and relevant

584 tools exist to help understand and reduce WBLCA uncertainties so that cautious decisions can be

585 made. It would not be ideal to completely rely on the tools to extirpate the uncertainties as some

586 of them cannot be reduced due to the natural randomness (see, Favi *et al*. [95]). In addition, the

587 tools may embed shortcomings as Burek and Nutter [87] state that SimaPro 8.4 software cannot

588 quantify the uncertainty of characterisation factors. This reinforces the awareness of the 'three

589 principles' as we proposed above. What is more, the review results can shed light on further

590 collaboration between policy-makers, researchers and practitioners into making sense of WBLCA

591 uncertainties by demonstrating their sources, solutions, tools and pathways.

592 **7   Conclusions**

593 WBLCA results can be unreliable, and further undermine decisions made for sustainable building

594 development due to the fragmented nature of the construction sector and the complexity of LCA.

595 To address the paucity of research that investigates the comprehensive uncertain sources of

596 WBLCA and their corresponding solutions, this study conducted a systematic review of WBLCA,

597 its uncertainties and solutions and proposed a conceptual framework that depicts their typology

598 for LCA practitioners. Our review on the *status quo* of WBLCA supports this research by

599 suggesting that WBLCA is experiencing a bottleneck period due to the variety of LCA methods

600 and the complexity of building structures, and thus more studies are needed to better understand

601 its results. This study also indicates that while the importance of uncertainty is recognised, research

602 does not follow the need for addressing or mitigating the uncertainty of WBLCA results.

603

604 Among the selected publications, we have identified that life-cycle stages, function unit, system

605 boundary, input parameters, characterisation factors, databases, LCIA methods, practitioners'

606 knowledge and experience, human activities and uncertainty methods can all be sources of the

607 WBLCA uncertainties. Accordingly, there are a total of eight solutions and variants thereof that

608 have been proposed with MCS and sensitivity analysis being the most common. Unlike previous

609 examples, details on how they were employed to estimate uncertainties were analysed. Aiming to

610 facilitate a true WBLCA and establish the correlation between uncertainties and their solutions, a

611 conceptual framework juxtaposed with a feeding mechanism was developed. Its novel way of

612 classifying a comprehensive list of uncertainties and solutions based on LCA stages allows LCA

613 practitioners to be aware of the uncertainties and conveniently locate and appraise them throughout

614 the WBLCA. Therefore, by answering the *known-what* (i.e., *status quo* of WBLCA and the

615 uncertain factors) and *known-how* (i.e., uncertainty methods) questions, this paper sheds light on

616 the WBLCA literature, in particular, provides a practical pathway for WBLCA practitioners to

617 conduct uncertainty analysis.

618

619 There are limitations of this research, which could form the basis for future work. First, if a

620 WBLCA is costly and time-consuming, a robust method should be developed to help select the

621 components that may have high EIs rather than arbitrary judgement. Second, a case study can be

31

conducted to demonstrate the application of the solutions identified in Section 5 (especially for the

ones that have not been widely implemented in WBLCA), which adheres to the idea that guidance

and trainings are important to demystify the 'black box'. Finally, the framework calls for an

empirical comparison of the uncertainty methods *per se* and the development of new effective

methods to evade the uncertainty resulted from the methods (i.e., solutions).

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