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SeeCarbon: a review of digital approaches for revealing and reducing infrastructure, building and City's carbon footprint

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Abstract: Dealing with climate change and its consequences on the environment have been one of the biggest challenges nowadays, where reducing the carbon footprint has been the focus of most sustainable strategies. The infrastructure is the dominant sector responsible for the total carbon footprint, accounting for approximately 70% of global carbon emissions. This study aims to illustrate the state-of-the-art of digital development and transformation of revealing and reducing carbon footprint in the Architecture, Engineering, Construction and Facility Management (AEC/FM) sectors. The digital tools for revealing and reducing infrastructure's carbon footprint would be summarized and also compared with other sectors, namely the tools for building and city. Current challenges and future development are also included.

Keywords: Infrastructure; carbon footprint, carbon accounting, digital tools

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC)'s 2014 Synthesis Report, 41-72% of the global emissions must be reduced to limit global warming to 2°C between 2000 and 2050 (Pachauri et al., 2014). The even urgent climate emergency pressed by the 2021 United Nations Climate Change Conference (COP26) requires all industries to step further beyond the current set of policy measures, which demands all industries to provide even "smarter" and "clear" metrics that are equitable to meet the earth's ecological limits (Saheb, 2021). The construction industry is certainly not an exception. Research conducted by (Müller et al., 2013) suggests that the western infrastructure stock using the existing technologies could cause about 350 Gt CO2 only from the construction material production, which corresponds to 35-60% of the remaining carbon budget given the 2 °C limits until the year 2050. With the tide of industry 4.0 and the introduction of more and more cyber concepts like the digital twin, it is suggested that these digital tools can also be utilized to counter global warming.

Although to promote sustainable building materials and reduce the construction project's whole life-cycle cost, methods like environmental product declarations (EPD) (Solís-Guzmán et al., 2018) and life-cycle assessment (LCA) (Passer et al., 2012) have been implemented in both the building and infrastructure projects. It is suggested their existing methodologies have not been actively linked with the existing building environment's digitalization progress, and most of these research works have not been tested in the real industry's working scenario. Therefore, it is suggested that there is a lack of review of the current sector adopted tools for the calculating and management of the project-based carbon footprint, not even to mention its connection with the other off-shelf building digitalization technologies (i.e., BIM, web-based deployment, IoTs) to achieve better sustainable compliance and better visualization for the multiple stakeholders. Furthermore, in order to validate the possibility of these carbon footprint estimation tools' connection capability to the existing building digital environment, a review needs to be conducted to find out the current standard coverage, operating environment (e.g., web-based or standalone), public availability and other features of these commercialized sustainable tools. As a result, both academia and the industry need a review of the existing carbon estimation and management digital tools for the existing working practice. A critical evaluation is also needed to compare different tools' functionalities in detail.

To address the research gaps, this paper presents a review of the digital tools that provide carbon footprint calculations in the AEC/FM industry, especially targeting infrastructure and building categories. The following of this paper is going to (1) introduce the review approach in this study; (2) illustrate the results of the review, and (3) provide a general analysis based on the significance of data attributes and a discussion of the potential developing trend from a digitalization perspective.

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2. REVIEW APPROACH

2.1 Review method and data sources

This study intends to review current digital tools that provide carbon footprint calculation functions in the AEC/FM industry. The review method contains four steps as follows.

The first step is to identify the review scopes and data sources. Considering features of assets in the AEC/FM industry (e.g., the complexity of building elements, operation synergies), the digital tools collected for reviewing are divided into two types, which are (1) infrastructure-oriented tools and (2) buildings-, city-level- and landscape-oriented tools. This study values the level of development and practicality for real-world scenarios. Thus, commercial digital tools (i.e., products) are chosen as the main research targets. As for the data sources, the Google search engine is chosen as the primary data source, alongside Web of Science and Google Scholar for supplementary information.

The second step is to specify the selected searching keywords. There are two types of keywords aligning with the review scopes. For the infrastructure-oriented type, the keywords were "carbon footprint tool + infrastructure", "carbon footprint tool + railway", "carbon footprint calculation + infrastructure", and "digital carbon footprint + infrastructure". For buildings-, city-level- and landscape-oriented type, the search terms are "carbon footprint tool + buildings", "carbon footprint digital tool/method + city-level", "carbon footprint calculation + buildings", and "digital carbon footprint + buildings/cities".

The third step is to select, screen and preliminarily document the tools. By searching the keywords selected in step two, the relevant digital tools or products that have comprehensive descriptions with attributes of descriptions including "Name", "Organization", "Introduction", "Main features", "Methods used" and "Limitations" are documented. Moreover, in this step, the authors attempted to test and validate the tools to confirm if demos or full versions of the tools are available from the providers in this step. If neither a full description nor a try-on demo is provided, the searched tool is excluded in this study.

The fourth step is to analyze the selected tools with the preliminary documentation generated from step 3. The analysis method is illustrated in Section 2.2.

2.2 Data analysis

Based on the documentation from step 3, the authors develop summarized tables that can easily compare the tools for each review scope with multiple standardized attributes and the information gathered from step 3. In total, there are three types of attributes groups (11 attributes in total) presented for each digital carbon footprint calculation tool.

- Type 1- basic information: it describes the information of each tool's developing origin and status. Specific attributes include "Name", "Developer Organization", "Industry", "Tool Type", "Current Availability".
- Type 2 - analytical information: this attributes group indicates how each digital tool measures the carbon footprint's environmental impact and the scopes of covered emissions. Specific attributes include "Standard Coverage", "Analysis Strategy", "Inclusion of Embodied Emissions", and "Inclusion of Operational Emissions".
- Type 3 - digitalization information: this attributes group is about how the tool has been connected to the development of updated technology applications. One of the most important considerations for this attributes group is whether the tool has been potentially designed to adopt building information modelling, a widely accepted digital twin approach in the AEC/FM industry. The specified attribute indicators are "BIM Integration", "Release form (Web-based/Standalone/Excel-based)", and "User Interface and Visualization Level".

Moreover, in this study, the attributes of the two different management target categories (i.e., infrastructure-oriented, and buildings-, city-level- and landscape-oriented) are summarized in the same format. Therefore, a comparison can be made between the two categories. The development trends and gaps of the digital tools of these two categories are identified in the following sections.

3. RESULTS

3.1 Review infrastructure-oriented carbon footprint calculation tools

In general, the number of available digital tools were limited in the infrastructure sector by the time authors conducted this review. In this category, a total number of 6 digital tools were documented through the review in Table 1, which summarizes the information of each tool with attributes discussed in Section 2.2.

Among the tools, 3 out of 6 provide very comprehensive introductions and are currently accessible by the public. Among the three available tools, Rail Carbon Tool (RCT) developed by Rail Safety and Standards Board (RSSB) and powered by Atkins for the UK rail industry is a web-based digital tool that can be accessed for free if the user works in the rail industry in the UK (RSSB, 2021). It provides a thorough whole-life carbon analysis, including both embodied emissions (i.e., greenhouse gas emissions from the creation of construction materials and products) and operational emissions (i.e., greenhouse gas emissions related to activities of operating, maintaining, and servicing business after construction). RCT adopts the standard of PAS 2080 by BSI, which is one of the lasted standards that provides a common framework exclusively for carbon management in infrastructure. Besides, the tool specifies Scope 1, 2 and 3 in the Greenhouse Gas (GHG) Protocol in the railway carbon scenario. The major aims of RCT are to provide quantified carbon emission calculation and comparisons of alternative design options that can assist decision-making during the whole life cycle of railway projects regarding to the environmental impacts. Except for RCT, the other two digital tools in the infrastructure category that are still in operation are National Highway Carbon Tool (NHCT) developed by UK

National Highways and asPECT developed by TRL from UK (NH, 2021). NHCT is a spreadsheet-based tool via Microsoft Excel that can be accessed for free, while asPECT is a standalone software that can be downloaded online for free. They both align with the schemes of PAS 2050, which is designed for the assessment of the life cycle carbon emissions of goods and services. However, the major difference between these two tools is the carbon emissions each tool includes. NHCT adopts carbon life cycle assessment (LCA) that includes both embodied emissions and a few parts of operational emissions. While, asPECT provides analysis only for embodied emissions. The abovementioned digital tools are all targeting the 2050 Net Zero mission in the UK proposed by environmental organizations. Moreover, the tools are supported with free guidance and training that address the GHG issue and promote the user experiences.

Except from the commercial tools, there were also some tools developed from an academic perspective like Carbon Footprint Estimation Tool (CFET) for transportation infrastructure in 2012 (Melanta et al., 2013) and a Carbon calculator design tool for bridges in 2015 (Smith et al., 2015). Besides, The digital platform or tools could also be included as a part of consulting services in consulting-services-based companies like Carbon Accounting Management Platform from CarbonStop, China (Carbonstop, 2021).

3.2 Review of building, city-level, landscape-oriented carbon footprint calculation tools

In this category, a total number of 13 tools are documented through the review (Table 2a and Table 2b). a total number of 13 tools are documented through the review landscape carbon emissions. Besides, 10 of 13 tools are available commercially (including both profitable and non-profitable tools).

Table 1. A summary of digital tools in the infrastructure-oriented scope.

Attribute	Tool Name \ Attributes	Rail Carbon Tool (RCT)	The Highways Agency Carbon Calculator for Construction	asPECT	Carbon calculator design tool for bridges	Carbon Footprint Estimation Tool (CFET)	Carbon Accounting Management Platform
Type 1	**Affiliation**	RSSB (Powered with Atkins)	National Highway	TRL	BCSA, Tata Steel and Atkin	Environmental Inc.; Unv. Of Maryland	CarbonStop
	Industry	Railway	Transportation (Highway)	asphalt used on highways	steel-concrete composite typical bridge	Railway	Multiple
	Tool Type	Commercial/ non-profit	Commercial/ non-profit	Commercial/ non-profit	Academic	Academic	Commercial
	Current Availability	Yes	Yes	Yes	N/A	No	Yes
Type 2	**Standard Coverage**	PAS 2080 GHG Protocol Scope 1,2,3	PAS 2050 GHG Protocol Scope 1,2,3	PAS 2050	ISO 14040	IPCC Guidelines GHG reduction policies	ISO 14064
	Analysis Strategy	Whole-life Carbon	LCA	Embodied emissions only	LCA	Construction phase analysis	LCA
	Embodied Emissions	Yes	Yes	Yes	Yes	Yes	Yes
	Operational Emissions	Yes	Yes (but limited)	No	Yes	Yes (but limited)	Yes
Type 3	**BIM integration**	N/A	No	No	No	N/A	N/A
	Web-based/ Stand-alone	Web-based	Excel-based	Standalone	Standalone	Standalone	Standalone
	User Interface/ Visualization	Well-designed No 3D	Well-designed spreadsheet	2D report analysis	2D report analysis	N/A	Well-designed No 3D
	Reference	(RSSB, 2021)	(NH, 2021)	(TRL, 2020)	(Smith et al., 2015)	(Melanta et al., 2013)	(Carbonstop, 2021)

Through the review, it has been found that there is a group of mainstream tools that dominate the market of carbon footprint calculation in the building sector. For instance, a digital tool called One-Click LCA is a global leading software kit that provides life cycle assessment for not only buildings but also infrastructures like airports, bridges, transmission systems, roads, flood alleviation schemes etc. (OneClickLCA, 2021). For buildings sector, it aligns with standards including ISO series and European series like EN 15978; for infrastructure sector, it complies with PAS 2080 for infrastructure carbon management. Moreover, One-click LCA is capable of integrating with BIM and energy simulation platforms like Microsoft Excel, Autodesk Revit, IES etc. Other nominated digital tools like the non-profitable Athena Impact Estimator for Buildings and Athena EcoCalculator for Assemblies by ATHENA Sustainable Material Institute, which are designed targeting the whole building LCA and simplified pre-design option respectively; and eToolLCD developed by eTool in UK (ASMI, 2021). These mature digital tools can also help clients to obatin environmental impacts certifications like LEED, BREEAM, CEEQUAL etc.

In the building scope, the requirements for integration with BIM are important Several digital tools designed especially for BIM as Revit add-ins, which are Tally by Building Transparency and IMPACT by BRE (Tally, 2021). Besides, companies like One-Click LCA and eToolLCD have developed the add-on version for Revit as well (OneClickLCA, 2021) (eTool, 2021). With the assistance of BIM data integration and visualization, the carbon footprint calculation can be integrated better in the early stage of building or infrastructure projects. Other tools that have been documented in Table 2a and Table 2b are developed with different characteristics that stand out for certain types of users and functions.

4. ANALYSIS AND DISCUSSION

4.1 Carbon footprint calculation strategy

Carbon footprint measurement strategy is one of the most important attributes that differentiates the digital approaches against each other. LCA has been defined in ISO 14040:2009 as a cradle-to-grave analysis approach of the inputs, outputs and the potential environmental impacts for products and services, consisting of calculation results of both embodied and operational emissions. While in the infrastructure and building sector, since embodied emissions account for a large part of the total emissions (e.g., operational emissions in the rail industry only accounts for about 3% of its GHG emissions), the tools designed for embodied emissions calculation are adequate for general usage purpose. Out of 19 tools collected in Table 1, Table 2a and Table 2b, there are 12 tools which are capable of LCA/WBLCA analysis and 3 tools which can only conduct embodied carbon emissions analysis only.

4.2 Digitalization approaches

The attributes related to the technology applications are worth focusing on considering the digitalization transformation trend in the whole AEC/FM industry. As for the capability of BIM integration, it has not been taken into consideration for all the tools in the infrastructure scope. In the building scope, the step has been made further. There are five tools that provide integration with BIM software like Revit as one of their main features. Tools like Tally and IMPACT are developed deliberately as add-ons for Revit to amend the integration gap between carbon management and BIM. Practitioners benefit their projects from earlier integrating the process of carbon management into a project's life cycle phase with other disciplines. As a result, better sustainable performance is reached. Besides, information from BIM like material inventories and the 3D visualization of the project can assist the understanding of carbon analysis results.

The attribute of the "Release Form" is also an indicator worth mentioning. From the review of the collected tools, there are four types of release forms: web-based (9/19), Excel-based (2/19), Standalone (7/19), add-in (3/19) and others (1/19) (form overlapping is allowed). It is observed that there is a trend to develop web-based digital tools.

Table 2a. A summary of digital tools in the building-, city-, landscape scope.

Attribute	**Tool Name \ Attributes**	**Athena Impact Estimator for Buildings**	**Athena EcoCalculator for Assemblies**	**One-Click LCA**	**Tally**	**Embodied Carbon in Construction Calculator (EC3)**	**IMPACT**	**Embodied Carbon and Energy Efficiency Tool**
Type 1	**Affiliation**	ATHENA Sustainable Material Institute	ATHENA Sustainable Material Institute	One Click LCA	Tally (stewarded by Building Transparency)	Building Transparency	BRE	Thornton Tomasetti and Unv. Of Bath
	Industry	Building	Building	Building/Infra-structure	Building	Building materials	Building	Building
	Tool Type	Commercial/ non-profit	Commercial/ non-profit	Commercial	Commercial	Commercial/ non-profit	Commercia l	Academic
	Current Availability	Yes	Yes (but no longer maintained)	Yes	Yes	Yes	Yes	No
Type 2	**Standard Coverage**	ISO 14040 and 14044 series	ISO 14040 and 14044 series	EN 15978, EN 15804, EN 15942, ISO 21931-1, ISO 21929-1, ISO 21930	EN 15643, EN 15978, ISO 14040 and 14044	Sorting and visualization of EPDs	EN 15804	N/A
	Analysis Strategy	WBLCA	LCA	WBLCA	WBLCA	comprehensive product database	LCA/LCC	N/A
	Embodied Emissions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Operational Emissions	Yes	Yes	Yes	Yes	No	No	No
Type 3	**BIM integration**	No	No	Yes	Yes	has API	Yes	N/A
	Web-based/ Stand-alone	Standalone	Excel-based	Add-in/Standalone	Add-in	Web-based	Web-based/ Add-in	Rhino-supported
	User Interface/ Visualizatio n	Well-designed 2D, No 3D	N/A	3D modelling from Revit, 2D report analysis	3D modelling from Revit, 2D report analysis	N/A	3D modelling from Revit, 2D report analysis	3D, parameter design
	Reference	(ASMI, 2021)	(ASMI, 2021)	(OneClickLCA, 2021)	(Tally, 2021)	(BuildingTransp arency, 2021)	(BRE, 2021)	(ThorntonTo masetti, 2014)

Moreover, the ways of user interface design and infrastructure and building elements are visualized make a significant impact over users' experiences and understanding of the carbon emission analysis. However, except from the add-in tools for Revit that absorb the visualization benefit of BIM and a tool that works with Rhino, none of the tools is capable of 3D visualization or simulation. Most of the tool generate analysis report with 2D diagrams. Besides, out of the selected poll, the user interface design of the tools is rarely taken care of well.

4.3 Future development trend

Based on the review of the digital tools and the analysis of data attributes, there are several findings can be summarized by authors as the potential trend towards the carbon footprint issue in AEC/FM sector, especially from the digitalization perspective.

First, the development of the digital tools for carbon emission calculation or analysis is not at a very blooming stage at present in AEC/FM sector despite of the overwhelming carbon emissions that infrastructure and building industry account for. In the infrastructure category, there is only one tool available (RCT) that provides railway specified LCA analysis of carbon footprint. Another tool documented in the building category (One-click LCA) has been claimed to have the capability of infrastructure LCA analysis as well. But, in general, the choices are limited for the public in this category. In the building and other category, the gap seems to be addressed by the mainstream group of digital tools. However, the step has not been moved very far from the infrastructure category. The limitations are obvious considering the project type, functions, fees of charge etc. And there is even no developed tool at all for city-level building carbon emission calculation.

Thus, more infrastructure targeted matured digital tools for carbon management should be encouraged in the following years.

Second, the analysis of infrastructure and building carbon footprint or carbon management should have been integrated into the whole life cycle of project better. It can be told from the review of study that the data integration and multi-disciplinary collaboration have not been addressed very well currently. Most of the digital tools are not open enough to talk with other platforms or systems. And the authors noticed during this review that a great part of the carbon management activities was only addressed via consulting services, which are more project-based and customized. An open and common environment might be helpful to tackle the urgent environmental issues in AEC/FM industry.

Last but not least, since the digitalization transformation has been emphasized in recent years, corresponding research and development should be focused on environmental realm as to achieve the goal of creating a more intelligent and smarter city as a whole. Technology applications including IoT, Big Data, blockchain and digital twin are not strangers to the AEC/FM industry. However, the commercial technology applications in carbon management related topics are still in the infant stage based the review of this study. The applying of spreadsheet-based tools or report-based analysis do help a lot for certain problems, but it is not sustainable enough as almost all subjects getting involved undergo a digitalization transformation. Therefore, further efforts are needed to bridge this gap.

Table 2b. A summary of digital tools in the building-, city-, landscape scope.

Attribute	Tool Name \ Attributes	CFCCP	Build Carbon Neutral	eToolLCD	OERCO2	The Structural Carbon Tool	i-Tree Planting Calculator	Pathfinder
Type 1	**Affiliation**	American University of Beirut, Lebanon	University of Texas at Austin, University of Washington	eTool	Erasmus+	The Institute of Structural Engineers	USDA Forest Service	Climate positive design
	Industry	Construction project	Building	building, infrastructure	Building	Building	landscape	City/ landscape
	Tool Type	Academic	Academic	Commercial	Academic	Commercial/ non-profit	Commercia l	Commercial
	Current Availability	NO	Yes	Yes	Yes	Yes	Yes	Yes
Type 2	**Standard Coverage**	Renewable Energy Laboratory (NREL)	Inventory of Carbon & Energy (ICE)	EN 15978 and ISO 14044	IPCC 100a methodology	BS EN 15978, BS EN 15804	N/A	Based on ATHENA
	Analysis Strategy	Embodied emissions only	Embodied emissions only	LCA	LCA	LCA	N/A	WBLCA
	Embodied Emissions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Operational Emissions	No	No	Yes	No	No	N/A	Yes
Type 3	**BIM integration**	No	No	Yes	No	No	Yes	N/A
	Web-based/ Stand-alone	Standalone	Web-based	Web-based	Web-based	Web-based	Web-based	Web-based
	User Interface/ Visualization	2D report analysis	2D statistics	2D report analysis	2D statistics	Well-designed spreadsheet	2D statistics	2D report analysis
	Reference	(Ammouri et al., 2011)	(BuildCarbonNeut ral, 2007)	(eTool, 2021)	(Erasmus+, 2021)	(BuildingTranspar ency, 2021)	(i-Tree, 2021)	(Climatepositiv edesign, 2021)

5. CONCLUSIONS

In this study, the current environmental issue of carbon footprint emissions in the AEC/FM industry has been addressed. We proposed a four-step method to review the maturity of digital tools for practical uses from the infrastructure-oriented scope and building-, city-level and landscape-oriented scope. Three types of attributes (11 attributes in total) were generated to comprehensively review each selected tool. Detailed results and analysis were given to illustrate the state-of-the-art of the tools and research gaps regarding carbon management in the industry. Moreover, three potential future trends were specified in the discussion session. In the future, more thorough research and analysis can be conducted based on the results of this review.

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