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Rethinking system boundaries of the life cycle carbon emissions of buildings

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ABSTRACT

There is a strong consensus that carbon emissions attributed to buildings are a major contributor to global warming. Reducing buildings' carbon emissions becomes a matter of urgency and importance. However, despite the burgeoning body of knowledge of addressing buildings' carbon emissions in the life cycle assessment (LCA) approach, the system boundaries of buildings' carbon emissions and actually of their relevant research had never been made explicit systemically. As a result, the definitions of buildings' life cycle differ considerably and the methods and models of analyzing buildings' life cycle carbon emissions (LCCa) vary; all these lead to discrepancies in reported buildings' LCCa and suggest a significant knowledge gap in effectively addressing the complex socio-technical features of buildings' LCCa. This paper aims to provide a fundamental rethink of the boundaries of buildings' LCCa for achieving meaningful benchmarking and learning in the future. The paper proposes a conceptual framework of system boundaries of buildings' LCCa, and develops a regression model to predict such LCCa with strategies for enhancing the validity and reliability of the prediction. The framework elaborates the boundaries of buildings' LCCa in the temporal, spatial, functional and methodological dimensions which together contain twelve variables, namely, life cycle stage, lifespan, climatic zone, geographic scope, LCA method, research method, unit of analysis, sources of emissions, building typology, level of prefabrication, building material, and density. The regression model is validated utilizing six representative cases of buildings' LCCa selected globally. Inconsistent system boundaries adopted were found to have contributed to the discrepancies between the resultant buildings' LCCa. The reconstructed system boundaries and developed regression model should facilitate a paradigmatic improvement in the body of knowledge of buildings' LCCa.

1. Introduction

Carbon emissions are alleged as a major contributor to anthropogenic climate change. Buildings worldwide consume 40% of energy and contribute 33% of carbon emissions [1]. Apart from operation and maintenance, buildings also demand a large amount of energy and materials for their associated intensive procurement and onsite construction processes. Reducing carbon emissions of buildings is thus a matter of urgency and importance, which has stimulated a significant amount of research. Some researchers pointed to the need to adopt the life cycle assessment (LCA) approach to analyzing buildings' carbon emissions through their life cycle stages. However, despite the burgeoning body of knowledge of addressing buildings' carbon emissions in the LCA approach, the system boundaries of buildings' carbon emissions and actually of their relevant research had never been made explicit systemically. As a result, the definitions of buildings' life cycle differ considerably and the methods and models of analyzing buildings' life cycle carbon emissions (LCCa) vary; all these lead to discrepancies in reported buildings' LCCa. For example, the buildings' LCCa reported by Pons and Wadel [2], Aye et al. [3], and Alshamrani [4] were 1106, 3176, and 6048 $kgCO_2/m^2$ floor area, respectively. Also, although researchers suggested systematically addressing the issues related to energy supply and demand [5,6], the systems approach has seldom been made explicit in research on buildings' LCCa. There is thus a strong need for a fundamental rethink of the boundaries of buildings' LCCa for achieving meaningful benchmarking and exploration in the future and for addressing the complex socio-technical features of buildings' LCCa.

With the motivation outlined above, this paper contributes an innovative theoretical approach to rethinking the system boundaries of the LCCa of buildings. The aim of this paper is to develop a conceptual framework of the system boundaries of buildings' LCCa and a regression model of relating buildings' LCCa to their system boundaries. Following this introduction, the paper critically reviews the models of system boundaries available in the wider literature and examines their theoretical grounds. Drawing on the results of the theoretical examination the paper then develops the conceptual framework and the regression model which is validated using six representative cases of buildings' LCCa selected globally. The paper finally discusses the implications of

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Nomenclature

LCA	Life Cycle Assessment
LCCa	Life Cycle Carbon Emissions
IR	System Boundaries' Inconsistency Ratio
DR	Buildings' Life Cycle Carbon Emissions Discrepancy Rate
ISO	International Organization for Standardization
C_i	i^{th} Case
B_k	Value of the k^{th} Boundary
$\overrightarrow{W}$	Vector of Weighting Values of the 12 Boundaries
w_k	Weighting Value of the k^{th} Boundary
$\overrightarrow{P_i}$	Vector of System Boundary Values of the i^{th} Case
P_{ik}	Values of the k^{th} Boundary in referring to the Reported i^{th} Case
$IR_k(C_i, C_j)$	System Boundaries' Inconsistency Ratio between i^{th} Case and j^{th} Case in regard to the k^{th} Boundary
$IR(C_i, C_j)$	System Boundaries' Inconsistency Ratio between i^{th} Case and j^{th} Case
$DR(C_i, C_j)$	Buildings' LCCa Discrepancy Rate between i^{th} Case and j^{th} Case
δ	Other Valuables that Impact the Prediction of Buildings' Life Cycle Carbon Emissions Discrepancy Rate

the developed model for future research, policy and practices, and draws its conclusions.

2. System boundary

2.1. The concept and theory of system boundary

In the wider literature of system research, the concept of system boundary has attracted a number of definitions. For examples, von Bertalanffy [7] in developing general system theory defined system boundary as an interaction interface where information, energy, or material transfers into or out of the system. Luhmann [8] in elaborating system as difference denoted system boundary to be a set of valuables that delineate a system and distinguish it from other systems in the environment. Comparatively, the specific literature of LCA defines system boundary in a much narrower scope in process. For example, the International Organization for Standardization (ISO) [9] described it as a set of criteria that specify which unit processes are part of a product system.

The concept of system boundary is grounded in various system theories including open system theory [7], societal system theory [8] and dialectical system theory [10]. According to open system theory, an open system is a system that has external interactions [7]. Such interactions can take the form of information, energy, or material that transfers into or out of the system boundary. Thus, the system boundary defined in open system theory is the point at which flows of information, energy, or material transfer from one system to another [7]. According to societal system theory, every system is delineated by its spatial and temporal boundaries, surrounded and influenced by its environment, described by its structure and purpose, and expressed in its functioning [8]. Thus, the system boundary defined in societal system theory is the barrier that defines a system and distinguishes it from other systems in the environment [8]. According to dialectical system theory, a dialectical system can be defined as "a network/system of essential interdependent viewpoints of consideration," which tries to influence the feeling of users rather than just provides a practical tool [11]. Therefore, humans can apply the law of requisite holism on their observation, perception, thinking, emotional and spiritual life, decision making, and action [12]. The balance between the impossible total system (full, real holism) and the dangerous one-viewpoint system (fictitious holism) can thus be achieved by applying this theory [13].

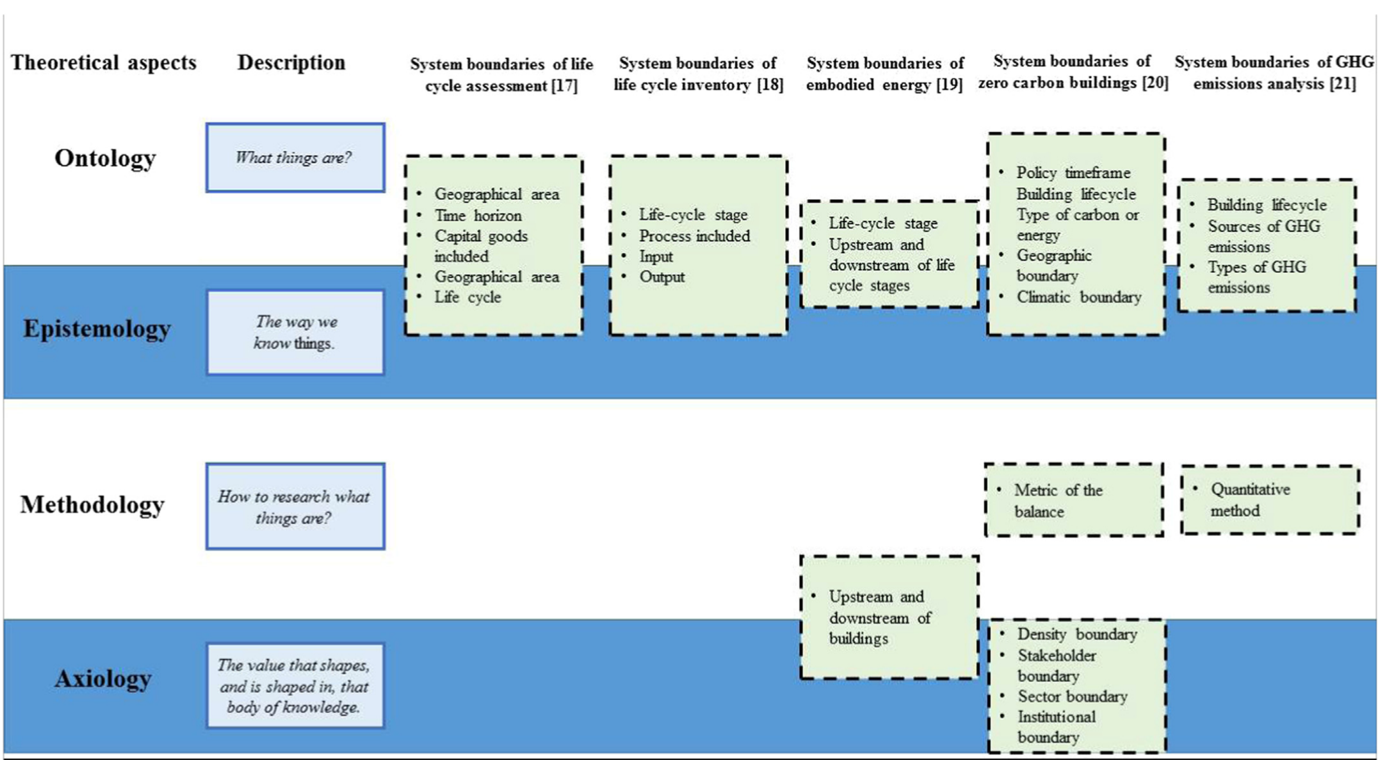

Fig. 1. Mapping of System boundaries addressed in previous studies.