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LCA calculation methods using BIM at the basic design stage: A focus on matching BOM and CO2 norm data using Uniclass and IDEA

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Abstract:
The construction sector is known as a main source of increased CO2 emissions, and BIM-LCA integration is expected to reduce the environmental burden by helping to control emissions and energy during the basic design stage. However, numerous studies showed that LCA is complicated as it requires great efforts in creating BOQ and linking multiple databases together. In addition, a precise LCA requires LOD 300, a level of detail that often takes a lot of effort to establish at the basic design stage. To address this issue, this study proposes a BOM-based BIM-LCA integrated model that uses a combination of Uniclass, IDEA, and the Calculation Formula Library, which focuses on the development and exploitation of information, even if the 3D Object's Level of Detail is low. The model allows the decomposition of the building information in order to create BOM and BOQ at a high level of detail from the basic design stage onward. Furthermore, it allows the flexible connection of data sources to perform LCA in a systematic manner.

Key words: Uniclass, BOM, IDEA, BOQ, Calculation Formula Library

1. INTRODUCTION

Building construction is a major contributor to climate change and greenhouse gas (GHG) emissions [1] [2]. Building production and operations account for 40% of primary energy demand and one third of global emissions [3] [4]. For that reason, the implementation of Life Cycle Assessment (LCA) to control energy, resources, and emissions during the construction process is increasingly needed [5] [6].

In recent years, the integration of BIM-LCA is expected to provide an easier LCA implementation throughout the project life cycle. In particular, LCA evaluation at the design stage is arguably the most important because it has a great influence on decisions related to environmental impact and changes in the later stages [7] [8]. Therefore, efforts towards BIM-LCA integrated solutions in the design stages are emerging [9] [10]. However, an existing challenge is still remaining with the complicated requirements of LCA calculation which requires huge efforts in creating BOQ and linking databases [11] [12] and the unavailable solution to use low Level of Development/Detail (LOD) for a precise LCA calculation [13].

To address the problem, this study proposes a BOM-based BIM-LCA integration model to perform detailed LCA at the basic design stage with a low Level of Detail (around LoD 200; consider the geometrical aspect of 3D objects). The development Level of Information (LOI) is focused on using a combination of Uniclass, Inventory Database for Environmental Analysis (IDEA), and Calculation Formula Library to establish the Bill of Materials (BOM) and Bill of Quantity (BOQ). This new model allows designers to flexibly scrutinize LCA to select the most optimal materials. Notably, the open approach to linking various data sources in the model allows a flexible integration of BIM-LCA with various software programs.

The remainder of this study is as follows. Chapter 2 presents the literature review to clarify trends in BIM-LCA integration research and raises outstanding issues. Chapter 3 presents the conceptual model and the model specification. Chapter 4 presents a case study to demonstrate the workability of the proposed model. Discussion and conclusions are presented in Chapter 5 and Chapter 6 respectively.

2. LITERATURE REVIEW

BIM-LCA integration is a powerful approach to support LCA implementation in the design process, especially with the emerging development of application tools for BIM-based LCA implementation [14] [15]. Among them, the Dynamo application to automatically transfer data from BIM model to LCA [16], One Click LCA and Tally commercial software [17] [18] are widely known. These tools are making an effective contribution to minimize time and effort spending for BOQ creation and calculations. However, they have some limitations, such as copyright requirements, depending on (1) local software or (2) Level of Development or Level of Detail/Development (LOD), etc. [19].

Along with the development of tools to enhance automation, solutions for implementing LCA with high accuracy at the early stage of the design process have also received attention from researchers [20] [21]. A study by [22] showed that LCA implementation at the early stages of design, especially stages A1-A3 needs to be based on BOM data. However, at the early stages, LOD is often at low levels, creating difficulties in developing needed information for LCA calculation. Moreover, studies showed that LOD 300 is considered necessary to meet geometry and information requirements to ensure accuracy, while LOD 200 is insufficient for that purpose [23] [24].

In addition, several studies have suggested using Industry Foundation Classes (IFC) and the UniFormat classification system to overcome the problem [25] [21]. However, IFC does not own a materials database, so it is difficult to provide a platform that allows a systematic separation of building information [26]. Meanwhile, UniFormat alone is not enough to decompose into the material levels, and UniFormat is often used in conjunction with MasterFormat to perform that. Finally, the existing combination between UniFormat and MasterFormat does not show coherent logic [27].

3. METHODOLOGY

3.1. Conceptual model

The BOM-based BIM-LCA integrated model proposed in this study uses an open approach that connects BOM-based database sources. It comprises four modules. Details of the modules are presented in Figure 1.

Module 1: The aim of this module is to establish BOM establishment. In particular, 3D objects are broken down to the material/component level in the basic design stage using a combination of three tables of Uniclass including Elements/Functions (symbol: EF), Systems (symbol: Ss), Products (symbol: Pr).

Module 2: The aim of this module is to combine BOM and IDEA to obtain norms of CO_2. The CO_2 norms are then used to compute LCA values.

Module 3: The aim of this module is to establish Bill of Quantity (BOQ). The BOQ is then used to compute LCA values.

Module 4: The aim of this module is to estimate LCA values. The model performs calculations for the stages of LCA based on EN15978 [28].

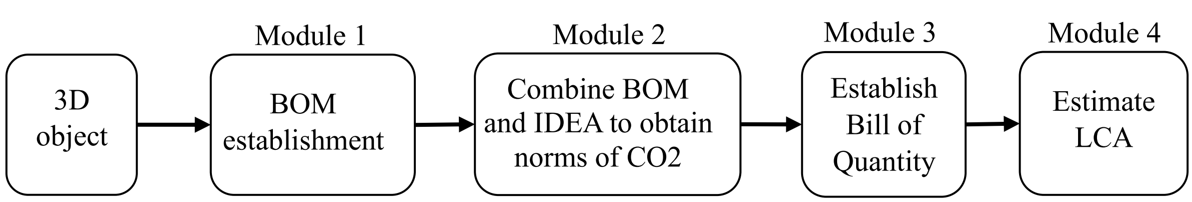

Figure 1: The concept model

3.2. Model specification

3.2.1. Module 1 - BOM establishment

Uniclass is a classification system managed by the UK's NBS, widely used around the world [29], and considered BIM compatible [30] [27]. Uniclass includes 14 tables, some tables can be linked together through Group and/or Type-of and/or Part-of relationships [30] [31].

To create a BOM, this study uses three tables, including EF, Ss, Pr. In which, the EF has three levels, including Group, Sub-group and Section. The Ss and Pr have four levels, including Group, Sub-group, Section and Object. The EF's Group and Ss's Group are directly connected to each other. In addition, the EF's Group can connect to the Ss's Object through Type-of relationships. As such, it is possible to determine the connection between the EF's Section or Sub-group and the Ss's Object. Moreover, the Ss and Pr can be connected through Type-of and Part-of relationships. In particular, a Pr is a part of an Ss, and a combination of Pr (set Pr) is a type of Ss. This study uses Type-of relationships to connect "Ss" and "set Pr" because they have similarities in defining 3D objects and the combination of materials/components of 3D objects. In other words, "Ss" - "set Pr" can be used to break down 3D objects to the material/component level. Our proposed procedure to establish BOM using EF-Ss-Pr is carried out in 3 steps.

Step 1: Classify and determine functional requirements for 3D objects

First, the 3D objects are categorized using the final level of the EF table, which usually uses Section level, in some cases, Subgroup level is used. Next, the functional requirements of each of the 3D objects are determined based on the building's functional constraints according to the law of construction design standards (such as building size, construction area, main structure, etc.) and other information from the site layout plan. The performance requirements for each of the 3D objects can be standardized using IfcCommonPropertySet [32].

Step 2: System definition for 3D objects using Ss

Next, the final level EF code traces back to the Group level to determine the corresponding EF Group code, then through the Group relationship to define scope of corresponding Ss. And then, through the Type-of relationship to select the last level Ss code corresponding to the EF Group code within the scope of the defined Ss. This is done by comparing all final level Ss codes with the functional/performance requirements defined in IfcCommonPropertySet to eliminate Ss codes that do not meet the requirements and find the Ss codes that are considered most satisfactory.

Step 3: Selection of the corresponding material combination using Pr

Based on the selected Ss code and functional/performance requirements for the 3D object, select the most suitable material combination (set Pr).

3.2.2. Module 2 – Combine BOM and IDEA to obtain norms of CO2

The IDEA is developed and maintained by the National Institute of Advanced Industrial Science and Technology (AIST) and the Japan Environmental Management Association for Industry (JEMAI) [33]. IDEA provides a database of CO2 ratings for most businesses and industrial sectors in Japan. IDEA Ver 3 is a data combination of 99 industries with a total of 4665 items and is composed of 4 levels, including: "medium level <2 digits>", "minor level <3 digits>", "detailed level<4 digits>", and "sub-detail level <6 digits>". In this study we use levels 3 and 4 of IDEA to combine with the final level of BOM (Pr level 4) for obtaining CO2 norms. The reason for using these levels is that they are similar to the level 4 of Pr.

To accommodate LCA calculations, the connection between IDEA and BOM is considered in project phases in accordance with EN15978. There are three cases considered for the connection.

Case 1 (Connect 1-1): In this case, one Pr code can connect to one IDEA code.

01 Pr code level 4 connects with 01 IDEA code (level 03 or level 04).

Case 2 (Connect n-1): In this case, multiple Pr codes can connect to 1 IDEA code.

More than 01 Pr code level 4 connect with 01 IDEA code (level 03 or level 04)

Case 3 (Connect 1-n): In this case, one Pr code can connect to multiple IDEA codes.

01 Pr code level 4 connects with more than 01 IDEA code (level 03 or level 04)

After connecting, CO2 norms will be linked to each Pr code for LCA calculations. However, it should be noted that the connection between Pr and IDEA will be different for each stage depending on the energy, resources, etc., required of that stage using the corresponding items in IDEA.

3.2.3. Module 3: Establish Bill of Quantity (BOQ)

The BOQ is established based on the BOM associated with the CO2 Norm unit for each material type defined in IDEA. To calculate the mass of each material in the BOM with a low LoD, we propose a method using a library of calculation formulas. In which, the calculation formula library is created based on the combination of basic dimensions of the object at LoD 200 extracted according to IfcQuantitySet along with scale factors. Each calculation formula will be created in accordance with the material type associated with the unit type defined in IDEA. Depending on the characteristics of each material and each object, the calculation formulas can be used for a single object or can be used flexibly for many different objects.

For example, the case of steel reinforcement materials and concrete. These are two types of materials commonly used to form structural objects of buildings such as columns, beams, floors, etc. Compared with the standard units specified in IDEA, the units can be determined. The unit of calculation for concrete is cubic meter, the unit of calculation for reinforcement is Kg. From there, the volume of concrete and reinforcement in the objects is calculated according to the formula: M_{Rebar}=NetVolumn*125 (Kg), $V_{concrete}$=NetVolumn (m^3). In other words, when calculating the volume of concrete and reinforcement for structural objects such as columns, beams, floors, etc. made up of a combination of concrete and reinforcement, we can use the general formula: M_{Rebar}=NetVolumn*125 (Kg), $V_{concrete}$=NetVolumn (m^3)

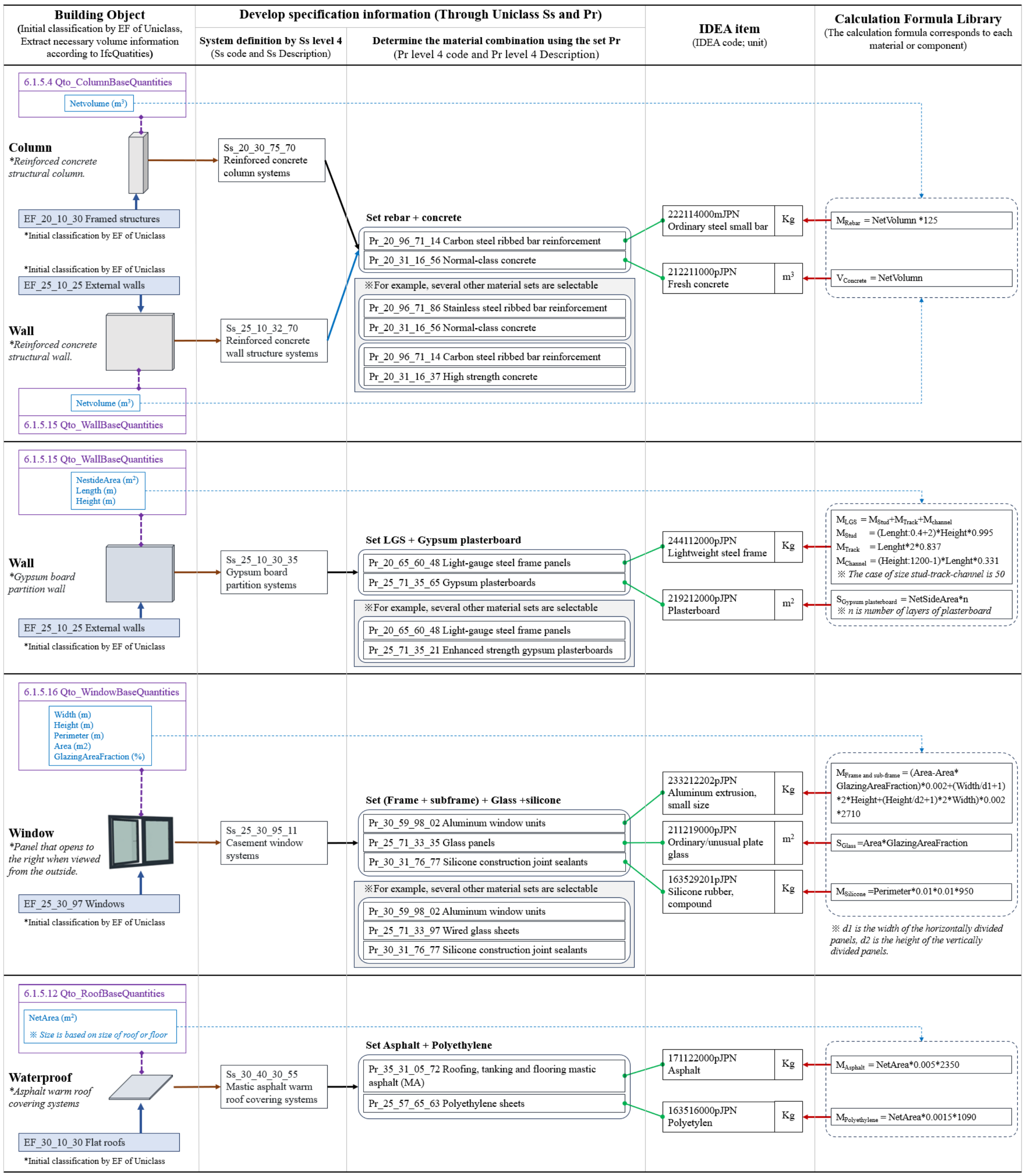

Figure 2: Example of BOQ setup based on BOM linked to IDEA and calculation formula library

The specifics of this material separation and connection to the formula library can be reflected through the use of Uniclass and are detailed in Figure 2.

This approach allows flexible material volume calculations even at low LoD without the need to develop a high level of detail to separate each layer of material for calculation based on its geometric resolution.

3.2.4. Estimate LCA

Because LCA consists of many stages, each of the stages has different characteristics of the activity and associated factors. Therefore, LCA implementation needs to be broken down into corresponding calculations. The LCA calculation is done by multiplying the volume or amount of energy/fuel required by the corresponding emission rating. The calculation formulas for each period are presented in Table 1.

The results of the LCA will be calculated relative to the Pr list in the BOM. And then, this result can be aggregated in two directions: (1) aggregated according to each stage based on EN15978 or the entire life cycle; (2) aggregate by Ss and EF based on Type-of, Part-of, Group relationships between tables.

Table1: The calculation formula corresponds to the stages of LCA [28], [34]

Life Cycle Stage	Calculation formula
A1 Raw material extraction	Purchase amount or weight of purchased goods and services × Emission intensity
A2 Transport to manufacturing site	Transportation cost or (transportation weight × transportation distance) × Emission intensity
A3 Manufacturing	Amount of heat/energy to use × Emission intensity
A4 Transport to construction site	Transportation cost or (transportation weight × transportation distance) × Emission intensity
A5 Installation/Assembly	Amount of heat/energy to use for Installation/Assembly × Emission intensity
B1 Use	Amount of heat/energy to use for Use × Emission intensity
B2 Maintenance	Amount of heat/energy to use for Maintenance × Emission intensity
B3 Repair	[Purchase amount or weight of purchased goods and services × Emission intensity] + [Transportation cost or (transportation weight × transportation distance) × Emission intensity] + Amount of heat/energy to use for Installation/Assembly × Emission intensity
B4 Replacement	Amount of heat/energy to use for Replacement × Emission intensity
B5 Refurbishment	Amount of heat/energy to use for Refurbishment × Emission intensity
C1 Deconstruction & Demolition	Amount of heat/energy to use for Deconstruction & Demolition × Emission intensity
C2 Transport	Transportation cost or (transportation weight × transportation distance) × Emission intensity
C3 Waste processing	Amount of heat/energy to use for Waste processing × Emission intensity
C4 Disposal	[Transportation cost or (transportation weight × transportation distance) × Emission intensity] + Amount of heat/energy to use for Disposal × Emission intensity

4. CASE STUDY

4.1. Introduction

This study conducted a verification of an elementary school building built in Japan with detailed information published in [35]. The basic information about the building determined at the basic design stage includes: (1) Building's use: School (Provide classrooms for primary school), (2) Building's scale: 03 floors, 01 attic with a total construction area of 1936.68 m^2; (3) Main structure: reinforced concrete, ramen frame with load-bearing walls; (4) Foundation: the foundation used is a pile foundation, based on the survey results obtained by the pre-boring expansion foot hardening method at 2 locations.

This study examines the establishment of BOM and BOQ for 13 systems of building. The 13 systems include: pile system, footing beam system, column system, beam system, wall system (including interior wall and exterior wall), floor system, ceiling system, roof system, roof waterproofing system, door system, window system, stair system, and railing system.

Besides, this study only considered the embodied carbon of materials at the A1-Raw material extraction stage.

4.2. Technical requirements

Based on the building information presented in section 4.1, basic functional requirements were identified. According to Article 107 of the Law on the Implementation of Architectural Standards, the combination of information (1) Building's use: School, and (2) Building's scale: 3 floors allow the determination of the type of building requiring fire protection. From this, it is possible to determine the refractory requirements for systems as follows: Columns, beams, and floors require 1 hour of fire resistance; roofs and stairs require 30 minutes of fire resistance. External walls (limit load-bearing walls) and internal partition walls (limit load-bearing walls) need to ensure a fire resistance time of 1 hour. In addition, based on the layout plan of the premises, it is possible to determine other functional requirements for each object, such as the position of the object is internal or external, the opening and closing method of doors or windows, etc.

4.3. Tools and data processing process

This study uses Autodesk's Revit software to create 3D models, and Microsoft's Excel software to link and process different types of data. Regarding data processing, after the building is modeled, 3D objects will be classified according to the Uniclass's EF. This classification code, along with the 3D object's corresponding feature request information, will be entered into the related properties. Then all necessary data such as classification codes, dimensions, functional requirement information, etc. will be exported from Revit to Excel. In Excel software, several tasks are conducted including (1) developing data from EF to Ss, (2) developing data from "Ss" to "set Pr", (3) calculating various types of quantities to establish BOQ, (4) connecting BOM and IDEA, and (5) LCA calculation.

4.4. Estimating results

From the performance requirements information for each of the objects, based on the proposed procedures in 3.2.1, 3.2.2, and 3.2.3, the results of BOM and BOQ for 13 systems are obtained, as shown in Table 2. In addition, the results of the embodied carbon of LCA implementation at stage A1-Raw material extraction according to Pr, Ss, and EF can also be found in tables 2, 3, and 4.

Table 2: LCA results according to Pr at stage A1 based on BOQ and BOM

List of Pr level 4 item used in this case study (BOM)		Quantity	Unit	IDEA item		CO2 result (Kg)
Pr code	Description			IDEA code	Description	
Pr_20_31_16_56	Normal-class concretes	1376.8	m3	212211000pJPN	Fresh concrete	5459.48
Pr_20_76_06_83	Stainless steel balusters and newel posts	26407.0	Kg	222114000mJPN	Stainless steel	1518.28
Pr_20_96_71_14	Carbon steel ribbed bar reinforcement	200467.7	Kg	222114000mJPN	Ordinary steel small bar	11525.95
Pr_30_59_98_02	Aluminum window units	581.6	Kg	233212202pJPN	Aluminum extrusion, small size	83.29
Pr_35_31_66_50	Mastic asphalt (MA) primers	3177.47	kg	171122000pJPN	Asphalt	0.08
Pr_20_65_60_48	Light-gauge steel frame panels	16179.7	kg	244112000pJPN	Lightweight steel frame	923.56
Pr_25_30_36_84	Stainless steel handrails	5161.0	kg	222114000mJPN	Stainless steel	296.73
Pr_25_57_65_63	Polyethylene sheets	1473.8	kg	163516000pJPN	Polyethylene	35.06
Pr_25_71_33_35	Glass panels	311.5	m2	211219000pJPN	Ordinary/unusual plate glass	581.47
Pr_25_71_35_21	Enhanced strength gypsum plasterboards	1018.7	m2	219212000pJPN	Plasterboard, Same product	313.80
Pr_25_71_35_65	Gypsum plasterboards	3061.8	m2	219212000pJPN	Plasterboard, Same product	943.18
Pr_30_31_76_77	Silicone construction joint sealants	40.0	kg	163529201pJPN	Silicone rubber, compound	130.31
Pr_30_59_23_02	Aluminum door frames	506.5	kg	233212202pJPN	Aluminum extrusion, small size	202.81
Pr_30_59_23_03	Aluminum door leaves	406.5	kg	244321000pJPN	Aluminum door	162.77
Pr_30_59_23_96	Wood door frames	1.2	m3	122211000pJPN	Ordinary plywood	34.31
Pr_30_59_23_97	Wood flush door leaves	4.0	m3	122211000pJPN	Ordinary plywood	113.25

Table 3: LCA results according to Ss compiled from BOM

Ss level 4 item		CO2 result (Kg)
Ss code	Description	
Ss_20_05_15_71	Reinforced concrete pile cap and ground beam foundation systems	3462.67
Ss_20_05_65_24	Driven precast or prestressed concrete piling systems	673.63
Ss_20_20_75_70	Reinforced concrete beam systems	3301.65
Ss_20_30_75_70	Reinforced concrete column systems	1428.87
Ss_25_10_32_70	Reinforced concrete wall structure systems	1235.79
Ss_25_50_75_10	Canopy systems	55.44
Ss_25_10_30_35	Gypsum board partition systems	1104.73
Ss_25_10_32_70	Reinforced concrete wall structure systems	276.22
Ss_25_30_20_22	Door assembly systems	25.19
Ss_25_30_20_39	Hinged doorset systems	571.05
Ss_25_30_20_77	Sliding doorset systems	159.04
Ss_25_30_95_75	Sash window systems	514.60
Ss_25_30_95_95	Window systems	38.34
Ss_25_60_05_05	Balustrade and guarding systems	1518.28
Ss_25_60_05_35	Handrail systems	296.73
Ss_30_12_85_70	Reinforced concrete deck systems	2712.11
Ss_30_40_30_55	Mastic asphalt warm roof covering systems	35.14
Ss_30_12_85_70	Reinforced concrete deck systems	3611.96
Ss_30_25_10_35	Gypsum board suspended ceiling systems	1075.82
Ss_35_10_85_15	Concrete stair systems	227.08
Ss_20_05_15_71	Reinforced concrete pile cap and ground beam foundation systems	3462.67

Table 4: LCA results according to Ss compiled from BOM

Ss level 4 item		CO2 result (Kg)
Ss code	Description	
EF_20_05_30	Foundations	4136.30
EF_20_10_30	Framed structures	4730.53
EF_25_10_25	External walls	1291.23
EF_25_10_40	Internal walls	1380.95
EF_25_30_25	Doors	755.28
EF_25_30_97	Windows	552.93
EF_25_55_30	Fixed barriers	1815.01
EF_30_10_30	Flat roofs	2747.25
EF_30_20	Floors	3611.96
EF_30_25_12	Ceilings	1075.82
EF_35_10_40	Internal stairs	227.08

5. CONCLUSION

This study has successfully proposed a BOM-based BIM-LCA integrated model to calculate LCA in detail from the basic design stage. The solution to break down building information into material levels to create BOM and from BOM to create BOQ proposed in this model allows the involvement of LoD 200 in the basic design step, which significantly reduces the unnecessary efforts of using LOD 300 in traditional methods as well as supporting designers to be aware of their design outcomes. Notably, the proposed model follows an open-access approach that allows LCA to be performed on various software. This allows small and medium-sized companies that do not have the expense of licensing expensive software to still implement LCA. Besides, this study supports countries that do not have the ability to standardize the Environment Product Declaration (EPD) like Western countries to perform LCA using their own national databases. Finally, this study opens a possibility of creating semi-automatic data linkage programs to quickly integrate BIM-LCA. This allows architects and managers to capture real-time LCA values.

Several limitations of this study should be addressed. First, it relies on IDEA, which is only used in Japan. Second, although this study has made some efforts to provide calculation equations in the apple calculation formula library, it is not complete and needs to be considered and expanded further. Finally, a better case study should be considered to demonstrate the workability of this model.

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