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学位論文の要旨（論文の内容の要旨）
Summary of the Dissertation (Summary of Dissertation Contents)

論　文　題　目
Dissertation title

Life Cycle Assessment of Energy and CO_2 Emissions for Residential Buildings in Major Cities of Indonesia

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The objective of this study was to provide fundamental database of life cycle energy and CO_2 emissions for urban residential buildings in Indonesia with the aim to propose future visions for achieving low energy and carbon residential buildings in major cities of Indonesia. Two major cities, Jakarta and Bandung, were selected for case study cities, and landed urban houses focusing on unplanned houses were selected because they are typically the largest urban houses in Jakarta (74%) and Bandung (89%).

Chapter 2 reviews previous life cycle assessment (LCA) studies, focusing on their applications in buildings. In general, the use of LCA on buildings can determine environmental impacts in whole process construction (WPC) or for only building material component combinations (BMCCs), depending on the purpose of the LCA. Obtaining data for LCAs differs among countries because availability varies. Data are not so easily collected in developing countries. Process, input-output (I-O), and hybrid methods are commonly used no matter the location. In developed countries, LCA is a common analytical tool to assess environmental impacts, but relatively few LCAs are conducted in developing countries. Those conducted in Indonesia have focused on planned houses and apartments and used process-based analyses. They typically analyzed environmental impacts for BMCCs because data are lacking for buildings, the environment, and the economy, which are necessary for more complete LCAs. Therefore, it is worth to construct comprehensive database necessary for conducting LCA study for WPC in unplanned houses in major cities of Indonesia.

Chapter 3 covers statistical data for residential buildings in Indonesia in which most of the urban houses are unplanned houses. These houses, especially in urban areas, are located in *kampungs* without proper service and infrastructure because growth stimulated by rapid urbanization was not followed by urban development policy. Landed houses can be categorized based on lot size and construction cost into simple, medium, or luxurious houses. Unfortunately, the proportions between these categories were not available from Indonesian statistical data. Housing policy is primarily fulfilled by the government through the Ministry of Public Housing, which provides affordable houses. The private sector has a primary role to fulfill medium and luxurious houses. Because the need for houses has yet to be met, people construct their own houses, and these eventually become unplanned houses.

Chapter 4 describes the methodology of obtaining two necessary pieces of information for LCAs, material inventory data and household energy consumption profiles. A pilot survey was conducted in 2011 to investigate methods of obtaining this information. Two large surveys followed in Bandung in 2011 and Jakarta in 2012, to obtain consumption data for urban houses, focusing on unplanned houses. Detailed environmental and economic data were available only at the national level. On-site building measurements were taken to obtain material inventories and household energy consumption figures due to unavailability data. Estimating building material inventory and future demolition waste are described. The input-output method was utilized to analyse embodied energy and CO_2 emissions. Embodied energy and household energy consumption were measured in primary energy unit. Both embodied energy and household energy consumption were compared with values found in other studies. Scenario analysis was conducted to evaluate future demolition waste using various reuse/recycling rates of building materials.

Chapter 5 provides profiles of sample houses in each city based on house category and household cluster. A total of 297 and 247 houses were investigated in Jakarta and Bandung, respectively. In both cities, the average household size was approximately 4.5 to 5.0 persons, but in luxurious houses, it was about 5.5 persons. The average income in Jakarta was slightly higher than in Bandung. In general, household income increased as the category changed from simple to luxurious. The total area increased with house category in both cities. The major building materials used were found to be the same among the three categories, though slight differences were observed in terms of flooring and roofing materials.

To determine the socio-economic and demographic characteristics that affect embodied energy and household energy consumption patterns, an exploratory factor analysis with principal axis factoring and cluster analysis using factor scores of selected factors (wealth and household size) was carried out for combined whole samples from each city. Three household clusters were determined for each city.

Chapter 6 evaluates the current building material stock and future demolition waste for urban residential buildings based on house category. The value of η^2 (Eta square) showed that house category had larger effects (0.76) on embodied energy than household cluster (0.60). Overall, the average quantity per m^2 used for houses was less in Bandung (2.06 ton/m^2) than in Jakarta (2.14 ton/m^2). The current total material stock for urban houses in Jakarta was 232.0 million ton, while it was 77.2 million ton in Bandung. If both reuse/recycling rates are assumed to be zero, then the total demolition waste of unplanned simple houses in Jakarta will be 41.5 million ton between now and 2020; the corresponding amount is 12.6 million ton in Bandung. The difference resulted from relatively fewer simple houses in Bandung. Future expansion of unplanned residential areas by demolition and transformation of current unplanned simple houses into medium houses is expected to increase the floor area by 20.0 km^2 in Jakarta and 5.7 km^2 in Bandung by 2020. This expansion would force the cities to extend their boundaries into the surrounding suburbs, accelerating urban sprawl. Scenarios simulating minimum and maximum reuse/recycling rates of materials were applied for unplanned houses in Jakarta to examine the effect of reuse and recycled techniques on demolition waste and embodied energy and CO_2 emissions. The results showed that maximizing reuse/recycling rates would decrease material waste by 37% to 41% and embodied energy and CO_2 emissions by 27% to 28%. A combination of closed/opened-loop material flow techniques increased material recovery and reduced material waste sent to landfills. The promotion of reuse/recycling was demonstrated to effectively reduce embodied energy and CO_2 emissions of building materials.

Chapter 7 investigates detailed household energy consumption and CO_2 emissions profiles. The value of η^2 for house category indicated slightly higher effect (0.37) than that for household cluster (0.35) on household energy consumption. In general, the ownership levels

of appliances increased from simple houses to luxurious houses. Overall, the average annual energy consumption of all samples in Jakarta was approximately 44.2 GJ, which was 14.9 GJ larger than that of Bandung. The difference is attributed primarily to the use of air-conditioning in Jakarta. In Bandung, energy consumption for cooking, lighting, entertainment, etc. largely affected overall energy consumption. The average annual CO_2 emissions in Jakarta were estimated to be 7.8 ton of CO_2-equivalent, while that of Bandung was 4.8 ton of CO_2-equivalent. If the CO_2 emissions from air-conditioning were excluded, the difference between the two cities would be insignificant. This clearly indicates that the use of air-conditioning dramatically increases household energy consumption and therefore, CO_2 emissions. Multiple regression analysis was carried out to further analyze the causal structure of household energy consumption. The results clearly indicated that greater household income, which had a strong relationship with category, increased building size thus increased total household energy consumption caused by major household appliances. This implies that household income increases with total household energy consumption as it will with the rise of middle class in the near future. It is important to avoid the tendency that building size increases straightforwardly simply because household income does.

Chapter 8 describes the analysis of life cycle energy and CO_2 emissions by house category. Total operational energy is much larger than the embodied energy in houses in Jakarta (80% to 90%) and Bandung (78 to 86%). In Jakarta, cooking was the largest contributor energy and CO_2 emissions (33% and 25%) in the simple houses, while it was air-conditioning that increased with house category and became the largest contributor in the medium (27% and 26%) and luxurious houses (36% and 41%). In Bandung, cooking was also the largest contributor in the simple houses (40% and 30%), but lighting increased with house category and became the largest contributor in the luxurious houses (20% and 25%).

Household energy consumption in major Indonesian cities is predicted to increase very sharply if proper energy-saving strategies are not implemented. Therefore, we recommend these potential energy-saving strategies for urban houses in Indonesia to decrease life cycle energy and CO_2 emissions, based on our analyses: (1) utilize reused/recycled building materials and increase the lifespans of buildings to reduce not only building material waste but also their embodied energy and CO_2 emissions, (2) provision of more apartments rather than landed houses that increase total floor area, to not only control urban sprawl but also avoid increasing building sizes and thus household energy consumption, (3) use natural lighting and energy-saving lighting such as LED lamps to decrease energy consumption caused by lighting, and (4) utilize passive cooling techniques wherever possible to decrease energy consumption caused by air-conditioning.

Finally, Chapter 9 summarizes the main findings of this study and recommends key areas for further study based on the limitations of this work.

Key words:

Life cycle assessment, Building materials, Building waste, Embodied energy, Input-output analysis, Household energy consumption, CO_2 emissions, Urban unplanned houses, Indonesia