sustainability

Sustainable Built Environment and Urban Growth Management

Edited by

Wann-Ming Wey

Printed Edition of the Special Issue Published in *Sustainability*

www.mdpi.com/journal/sustainability

MDPI

sustainability

MDPI

Article

Morphology Dependent Assessment of Resilience for Urban Areas

Kai Fischer [1,*], Stefan Hiermaier [1,2], Werner Riedel [1] and Ivo Häring [1]

1 Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, 79104 Freiburg, Germany; stefan.hiermaier@inatech.uni-freiburg.de (S.H.); werner.riedel@emi.fraunhofer.de (W.R.); ivo.haering@emi.fraunhofer.de (I.H.)

2 Institute for Sustainable Technical Systems, University of Freiburg, 79110 Freiburg, Germany

* Correspondence: kai.fischer@emi.fraunhofer.de; Tel.: +49-7628-9050-628

Received: 17 April 2018; Accepted: 28 May 2018; Published: 30 May 2018

check for updates

Abstract: The formation of new threats and the increasing complexity of urban built infrastructures underline the need for more robust and sustainable systems, which are able to cope with adverse events. Achieving sustainability requires the strengthening of resilience. Currently, a comprehensive approach for the quantification of resilience of urban infrastructure is missing. Within this paper, a new generalized mathematical framework is presented. A clear definition of terms and their interaction builds the basis of this resilience assessment scheme. Classical risk-based as well as additional components are aligned along the timeline before, during and after disruptive events, to quantify the susceptibility, the vulnerability and the response and recovery behavior of complex systems for multiple threat scenarios. The approach allows the evaluation of complete urban surroundings and enables a quantitative comparison with other development plans or cities. A comprehensive resilience framework should cover at least preparation, prevention, protection, response and recovery. The presented approach determines respective indicators and provides decision support, which enhancement measures are more effective. Hence, the framework quantifies for instance, if it is better to avoid a hazardous event or to tolerate an event with an increased robustness. An application example is given to assess different urban forms, i.e., morphologies, with consideration of multiple adverse events, like terrorist attacks or earthquakes, and multiple buildings. Each urban object includes a certain number of attributes, like the object use, the construction type, the time-dependent number of persons and the value, to derive different performance targets. The assessment results in the identification of weak spots with respect to single resilience indicators. Based on the generalized mathematical formulation and suitable combination of indicators, this approach can quantify the resilience of urban morphologies, independent of possible single threat types and threat locations.

Keywords: resilience quantification; resilience engineering; multiple threat assessment; urban form

1. Introduction

Cities are key drivers for technological, organizational, social and economic innovation and well-being for individuals and the society. Sustainable progress in these domains depends on the availability of infrastructures and buildings. This also holds true for the scale of interaction and connectivity.

Agglomerated areas comprise a high degree of critical infrastructure. At the same time, critical infrastructures specify significantly the resilience and the robustness [1]. It is clearly observable that systems, cities and infrastructures will become more complex and interconnected [2]. Due to this change, the failure of a single element increases the probability to produce cascading effects with unexpected consequences [3] as well as emergent threats.

Industrialization and population growth are the main reasons for an increasing urban population. This fact is clearly observable in different studies, as stated in the report of the United Nations [4]. It results in a changing density of population, a higher degree of urbanization and an increasing focus on hazard vulnerability reduction and resilience [5].

A further challenge is the formation of new threats. According to Branscomb [1], cities are increasingly vulnerable to three kinds of disasters:

- natural, like hurricanes, floods or earthquakes,
- technogenic, resulting from human error and failing infrastructure, like a power failure, and
- terrorism, "a growing and important asymmetric threat which can pick targets anywhere" [6].

In summary, the rising urbanization, growing complexity of critical infrastructure and formation and increase of new and old threats lead to the need to manage possible hazardous events and their corresponding consequences in an ever-increasing number, especially in urban areas. These aspects motivate the need of sustainable cities, which are able to cope with adverse events.

Based on the new challenges for urban areas, this paper focuses on how the built urban environment, urban spaces, buildings and infrastructure can better cope with potentially adverse and disruptive events. The overarching aim is to contribute from an engineering–technical science driven perspective to the sustainability of urban areas and infrastructures. Achieving sustainability requires the strengthening of resilience [7].

The concept of resilience is used in a great variety of interdisciplinary work concerned with the interaction of people and nature [8]. Examples can be found in social sciences [9,10] or engineering disciplines [11–13]. There are approaches which give a holistic overview but results in qualitative measures [14]. Other methods have no detailed information concerning the recovery behavior after a disruptive event [15,16] or focus on single scenarios and objects [17], which require a manual reapplication, if there are deviations or uncertainties. In summary, there is a need for the development of a clear analysis scheme for the quantification of resilience of urban areas. The assessment focusses on the identification on weak spots to circumvent a pure scenario-driven approach.

An urban area reflects a complex and dynamic composition of different zonings and functions, which defines the urban form and have a lasting effect on the sustainability, the resilience [18,19] as well as the coping capacity with disruptive events [10]. Within this paper, different urban footprints are evaluated to investigate the resilience depending on the morphology. Building density, building dimensions, construction types and object use are main parameter, which will be varied within the investigations and the introduced framework can give contributions to new development plans to reflect or incorporate resilience indicators and to shape a sustainable environment.

Section 2 introduces a generalized framework for the evaluation of resilience and Section 3 follows with a mathematical definition of single components of that framework. Certain analysis examples for different urban forms and the discussion of the assessment scheme are shown in Section 4. A summary and conclusion is given in Section 5.

2. Generalized Framework to Quantify Expected Losses and Recovery Processes

Findings from different approaches to evaluate resilience are sighted, compared and consolidated to propose a novel framework with the aim to quantify resilience, which requires a clear definition of terms. Based on the interdisciplinary research in the field of resilience, there are different interpretations concerning the definition and of that term [20]. Within the present work, the resilience cycle (Figure 1 left) according to Thoma [21] is used as definition. Therefore, resilience is defined as:

"The ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential adverse events. Those events are either catastrophes or processes of change with catastrophic outcome, which can have human, technical or natural causes."

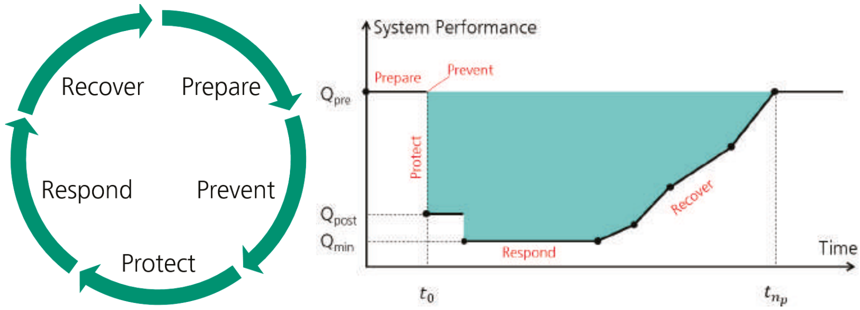


Figure 1. Five phases of the resilience cycle (**left**) according to [21] and their interpretation within a performance-time relation (**right**) for the quantification of resilience.

As shown by Bruneau [11] or Kröger [3], a performance-time relation can be used to describe the resilience of a system. A generalized and simplified shape of one such relation shows the right picture of Figure 1. A catastrophic event causes a disruption and a sudden performance loss at time t_0, which is followed by a response stabilization and recovery process. Resilience can be measured by the size of the expected degradation of performance over time, as indicated with the green area in the right diagram of Figure 1. Single phases of the resilience cycle can be assigned using performance-time diagrams for suitable system parameter and determine the effectiveness of single indicators and, if approved, to measure the resilience of the system. As indicated in Figure 1, measures of preparation and prevention will extend the time before disruptive events or avoid them completely. The drop of the system performance indicators is a measure of the level of protection and vulnerability. Efficient response decreases the degree of disruption and helps to start to bounce back quickly after the shock event. Finally, the resilience phase recovery describes all the aspects of relaxation, recovery and possible learning and the preparation for future events.

Based on the definitions in [22] and Figure 1, the aim of the proposed framework is the characterization of a performance target over time as basis for resilience quantification. Several components are integrated to achieve this objective and a generalized overview is given in Figure 2. The assessment scheme can be separated into two main parts. Under the assumption of a threat occurrence, the deterministic part uses physical models to quantify the intensity of a hazard source and the corresponding damage effects (vulnerability). A certain degree of recovery is required based on the resulting damage effects. The deterministic realm is applicable to derive a performance-time relation for a single threat, but requires the definition of a decisive scenario. Based on uncertainties that a certain threat event occurs, the deterministic part is coupled with a probabilistic realm. Stochastic methodologies are applied to evaluate the frequency and the exposition of a threat within the susceptibility approach. The combination of susceptibility and potential damage effects results in a risk-based vulnerability. Averaged results for multiple threat scenarios moves the approach from a scenario driven to a consequence based analysis for the identification of weak spots. The combination of weighted (risk-based) vulnerabilities and corresponding recovery processes consider a multitude of random scenarios and results in an averaged performance-time relation to characterize the resilience of a system, e.g., an urban surrounding. Single components of this framework can operate single phases of the resilience cycle (Figure 1).

Bruneau [11] states that resilience can be conceptualized "as encompassing four interrelated dimensions: technical, organizational, social and economic". With regard to Bruneau, the introduced framework including the quantification of susceptibility and vulnerability cannot cover all aspects concerning the resilience of urban areas but can give essential contributions.

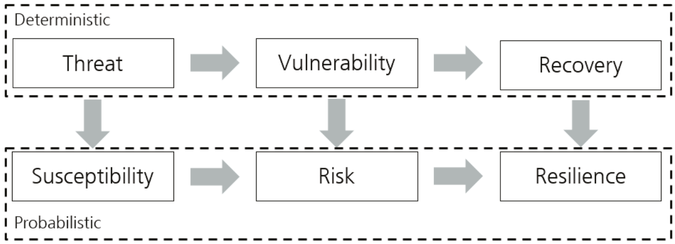


Figure 2. Proposed framework to assess the occurrence of adverse events and the expected losses as basis for resilience quantification according to [22].

First results within the susceptibility and vulnerability approach of Figure 2 are published in [23] to evaluate terroristic explosive events in urban areas. Pre-defined construction types are applied to assess the physical damage effects of buildings with the use of engineering models [24,25], if an adverse event occurs. The susceptibility, i.e., the frequency of a hazardous event and the exposition of single urban objects, is derived with historical statistical data from the Terror Event Database [26,27], depending on the object use, the threat type and the region. Based on these essential findings, the approach is in this paper subsequently enlarged to compare the risk-based results between different morphologies in a quantitative way. Furthermore, the consideration of time scales allows the assessment of a recovery process to result in a single quantity for the resilience of urban objects. Subsequent, a mathematical formulation will introduce the interaction of single components of the presented framework.

3. Mathematical Formulation

In alignment to the introduced framework in Figure 2, an abstract model of an urban area U is defined as a superset including a finite number of subsets, like free spaces a_m or buildings b_k

$$U = (a_m, b_k),\ m = 1, \ldots, n_{area};\ k = 1, \ldots, n_{building}. \tag{1}$$

A single building b_k, $k = 1, \ldots, n_{building}$ is characterized by a position $\vec{r}_{b_k}$, a spatial extension dimension $L(b_k)$ and a type of object use $u_l(b_k)$, $l = 1, \ldots, n_{object\ type}$, like residential or office, for example.

A security relevant event, such as an explosion source or an earthquake within or close to an urban environment is defined as threat T_i. A threat can have different forms and the various threat types are expressed with the running index $i = 1, \ldots, n_{threat}$. A threat can occur at a number $j = 1, \ldots, n_{position}$ of possible locations $\vec{r}_j$. The physical hazard potential of a threat is described within a hazard model $H\left(T_i, \vec{r}_j; P\right)$ [22], as indicated in Equation (2). This model relates the threat type T_i and the event location $\vec{r}_j$ to the urban environment U. The physical properties are defined within the attribute P to characterize the (time dependent) hazard potential, like the magnitude of an earthquake, for example.

Depending on the intensity and the exposition, the occurrence of a threat can cause a certain type of consequences D_g, $g = 1, \ldots, n_{consequence\ type}$ at different locations in the urban surrounding $\vec{r}_o$, $o = 1, \ldots, n_{consequence\ position}$. Possible consequences of type D_g, like direct structural or non-structural damage at a building, at location $\vec{r}_k$ are characterized within the local what-if vulnerability $V\left(\vec{r}_k, D_g\right)$. An exemplary assessment of structural building damage can be realized with the use of single degree of freedom models [24] as basis for the collapse behavior of buildings [25]. Further details of the vulnerability assessment are described in [22].

Based on the degree of damage or loss of functionality, a certain degree of recovery is required to reach normal community activities and the initial performance of the investigated system, like an urban environment. The rebuild and recovery function $Q_{n_p}(t)$ characterize the time-dependent behavior as a stepwise linear function considering $n_p,\ p = 1, \ldots, n_{phases}$ recovery phases. A generalized sketch of this function is shown in the right picture of Figure 1.

This causal chain of threat occurrence, resulting vulnerability and required time-dependent recovery is summarized as

$$H\left(T_i, \vec{r}_j; P\right) \rightarrow V\left(\vec{r}_k, D_g\right) \rightarrow Q_{n_p}(t) \tag{2}$$

and expresses the deterministic part of the introduced methodology in Figure 2. This mathematical expression is valid to describe arbitrary threat types and investigated systems. The application of physical or engineering models results in quantitative measures as basis for decision makers. In particular, for each building type and damage level, a recovery function with respective recovery phases is defined, e.g., by resorting to typical planning and construction times and respective subsystem availabilities. Exemplary construction type dependent recovery times are shown in the Appendix A in Table A1.

The prediction of a single threat type scenario can be fraught with inaccuracies because it is difficult to estimate the threat position and the threat intensity can vary. Based on this fact and in alignment to the generalized framework in Figure 2, the frequency that a certain threat T_i occurs at a certain position $\vec{r}_j \in A_j$ is summarized within the susceptibility $S(T_i, A_j)$ and hence the causal chain in Equation (2) can be weighted with a probability that such an event occurs on A_j in the urban surrounding. This step incorporates the probabilistic realm of the assessment scheme.

The introduction of an averaged time-dependent recovery process (Equation (3)) considers multiple threat types and intensities (index i), threat positions (index j) and urban objects (index k). Each combination is weighted with the corresponding susceptibility $S(T_i,\ A_j)$. Equation (3) quantifies the averaged loss and recovery with respect to all possible threat events and urban objects, if a single event occurs:

$$Q(t; n_p,\ D_g) = \sum_i \sum_j \sum_k Q_{n_p}\left(t \middle| V\left(H\left(T_i, \vec{r}_j; P\right), \vec{r}_{b_k}, D_g\right)\right) \cdot S(T_i, A_j)\ . \tag{3}$$

The summation of the performance-time relations in Equation (3) results in a single quantity to describe the resilience of urban environments. The recovery function Q for a single scenario is characterized with the deterministic part of the framework in Figure 2. The consideration of multiple scenarios and the corresponding probabilistic susceptibility weighting transfers the approach from a scenario driven to a consequence based approach.

The introduced framework combines statistical data and physical approaches to evaluate urban environments with respect to the region and the geo-spatial information of the urban surrounding as well as properties of single urban objects, like the object use, constructional details, person densities or the asset value.

Single elements of the introduced approach are validated in [22] and enable a postulation of a resilience quantity for an arbitrary city. Furthermore, single resilience phases, like preparation, prevention, protection or recovery can be evaluated with this structured methodology. In particular, the susceptibility quantity, a generalized frequency of event an exposure measure, is an indicator for preparation and prevention, the vulnerability quantity, a generalized damage expression characterizes robustness and the recovery quantity characterizes response and recovery.

The presented framework intends to provide a quantitative methodology to achieve more robust and sustainable cities. Subsequently, different urban forms are investigated with the introduced approach. Based on the fact of a growing urbanization, the results should give insights for a sustainable growth of agglomerated areas.

4. Analysis Examples of Different Urban Forms

An urban environment reflects a complex interaction of different zonings and functions. Physical footprints are categorized in buildings, open spaces, traffic routes and landscapes and characterize the morphology [28]. Zonings distinguish between residential, retail, commercial, financial, industrial or educational objects. The variables of a city describe the physical and social characteristics and are dynamic in nature. Examples are physical constraints, growth, population (e.g., age, education or health), economic activities, environmental characteristics or community facilities.

The dynamic growth influences the footprint of a city and can result in a change of the zonings and variables. Urban planning processes encompass a variety of technical and political challenges to characterize and design the environment with respect to the well-being of the population and the natural habitat. To manage the growth and the shaping for tomorrow, new development plans are multi-dimensional in nature and match different variables.

The economic size of a city depends on the available infrastructure, for example. The mixture of different social groups results in a stable community of an urban area (social cohesion). A pedestrian area can give space for human interaction and creativity. The presented resilience framework can be integrated to consider safety and security aspects. The challenge is to achieve a secure and sustainable environment, which still allow for convenient living conditions. New development plans should include policies and objectives to reflect or incorporate the needs of the five phases of the resilience management cycle according to Figure 1 left. These aims have to be adopted depending in particular on the physical layout and the dynamic urban variables, i.e., demographic, social, economic or environmental.

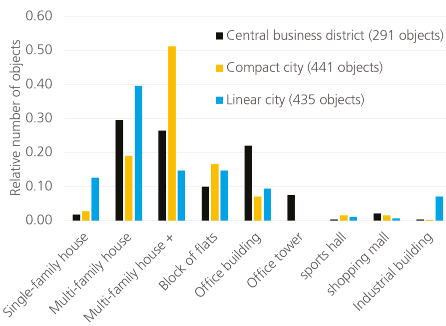
4.1. Characterization and Modelling of the Urban Surroundings

The introduced framework is applied to three different examples representing main urban forms which are oriented to existing cities. The comparison of a compact and a linear city model investigates the resilience depending on the urban footprint. A further assessment describes a central business district to investigate variations of object and construction types. The generated information is intended to provide decision support for urban planning activities to integrate security and sustainability aspects aligned with a dynamic and sustainable growth of agglomerated areas.

As introduced in Section 3, single buildings of the urban surrounding can be abstracted characterized with a certain number of attributes. The consideration of each individual building within a city would exceed the effort of investigation. The introduced framework uses, a set of 10 pre-defined and fully designed buildings [29]. Possible designs are oriented to the categories in the left bar diagram of Figure 3. For each construction type, the physical properties are available to characterize the robustness and hence certain structural damage effects in case of a disruptive event occurrence [25]. Furthermore, the periods for planning and construction are available depending on the building type and result in quantities to estimate the required recovery for the introduced formulation in Equations (2) and (3). Table A1 in the Appendix A gives a detailed overview of the used building types and time scales to estimate the recovery process.

Figure 3 (left) compares the three application cases concerning their construction types in accordance to the list of pre-defined buildings. Based on the high connectivity and the mixture of residential with other uses, the compact city includes a high degree of multi-family houses with commercial use in the ground floor, indicated with "multi-family house +" in the left diagram of Figure 3. Due to the clear separation of zonings, the linear city includes areas with a higher number of industrial buildings and residential areas with single- or multi-family houses. Characteristic for a district with specific task assignment, the central business district includes an increased number of office buildings and office towers.

Next to the constructional characterization, a further description of the three city models includes the description of building use types. The properties of the compact city become apparent by comparison of the object use types, as shown in the right diagram of Figure 3. A high degree of residential objects is mixed with a wide range of different other types within all sectors. Dual use objects (residential and commercial) are considered as commercial use and result in the higher degree of objects for retail and service. The linear city is dominated by approximately two thirds of residential objects. Besides this object type, buildings dedicated to finance, trading, retail and service dominate the central business district.



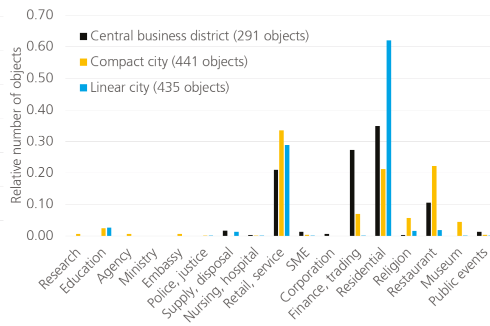


Figure 3. Distribution of construction types (**left**) and object use types (**right**) depending on the investigated city model.

4.2. Empirical and Spatial Distributed Evaluation of Disruptive Events

In alignment to the already published parts of the approach [22,23], the introduced framework is applied to evaluate possible terroristic events in the considered urban forms. As shown in Figure 2, a first step includes the quantitative susceptibility analysis. Statistical information from the Terror Event Database [26,27] are combined with the geospatial characteristics of a city to evaluate possible threat positions. Figure 4 visualizes the results with historical data of Western Europe and give the information of possible locations with higher susceptibilities. The color code indicates locations with the highest probability, if a single event occurs.

The results underline the characteristics of the three urban forms. A compact city includes a high mixture of object types, no clear zonings and a higher building density, which is apparent in the upper picture of Figure 4. There are several hotspots with a relative high susceptibility. The clear separation of different zonings within the linear city results in area-covering susceptibilities within an elongated area as shown in the middle picture of Figure 4. Broader areas with residential use generate low criticalities. Finally, the lower picture shows the empirical area distributed results for the central business district. Based on the clear assignment of object types, there are many objects with a similar criticality. In opposite to the linear model, the derived susceptibility is slightly higher and there is no local maximum.

The susceptibility approach in Figure 4 allows an efficient evaluation of possible threat types at certain locations within a single quantity $S(T_i,\ A_j)$. The frequency of a disruptive event depends on the empirical data of the threat type and object use. This information is distributed on possible event positions in alignment to the investigated city models [22]. This probability quantity is combined with the vulnerability approach to evaluate expected damage effects at certain positions $\vec{r}_o$ in the city model of a certain damage type D_g, as introduced in the general overview of Figure 2.

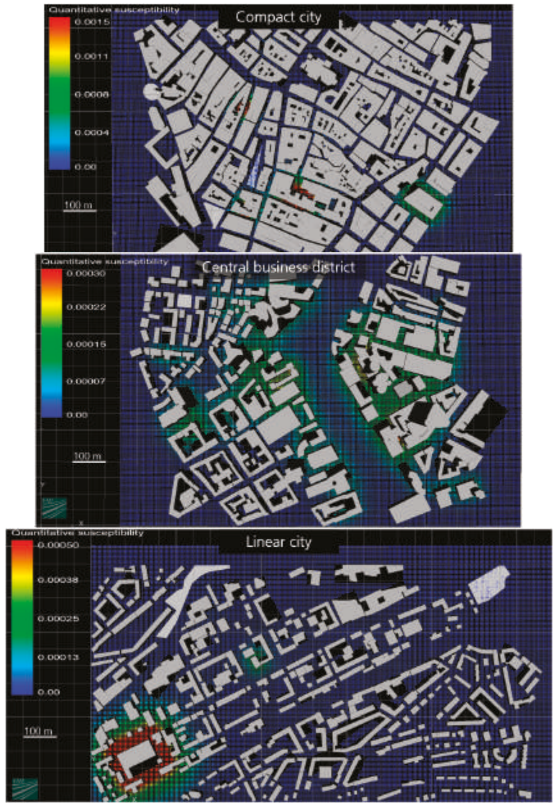


Figure 4. The quantitative susceptibility analysis combines statistical data per object use with the geospatial information of an urban surrounding to evaluate possible threat positions. Comparison of the three investigated urban forms. The susceptibility is given as probability of any dangerous event per area of size, in case of an occurring disruptive event.

4.3. Quantitiative Risk Assessment in F-N Diagrams

The introduced methodology [22,23] uses physical and engineering models to assess expected damage effects. Each combination of threat position A_j, as shown in Figure 4, threat type and intensity T_i causes a certain degree of damage and is weighted with the derived susceptibility $S(T_i, A_j)$ that this event occurs. The results can be counted to events with N or more damaged buildings and a corresponding cumulated frequency of occurrence. This information is collected for each investigated urban form of the application examples within a frequency-number (F-N) diagram, see Figure 5. Based on the investigated urban areas, combinations of buildings, threat types and threat positions results in tens of millions possible combinations with respect to the formulations in Equations (2) and (3) which exceeds the capacity of spreadsheet applications. Therefore, the investigated city models are separated into single areas, which results in certain dispersion for each city in the diagram of Figure 5.

The dotted lines separate the diagram into regions for acceptable (green line) or not acceptable (red line) risk quantities. The area between these two criteria marks the "ALARP" region, meaning as low as practicable possible and optional mitigation measures should be considered in relation to their efficiency [30]. Different criteria define the level of acceptance [31]. In this diagram, the "Groningen criterion" according to [30] is chosen.

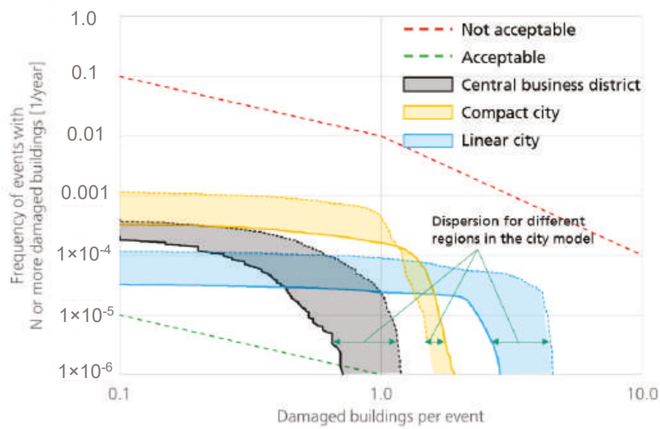


Figure 5. Comparison of the investigated city models within a frequency-number diagram concerning the expected damage and the comparison to criteria of acceptance. Based on the composition of construction types and object uses, each city model results in varying probability that an event with N or more damaged buildings occurs.

The central business district is characterized with many equal object types, which result in a relatively uniform distribution of susceptibility, as indicated in the empirical approach in Figure 4. This city model includes many robust construction types, like the high-rise buildings and results in low vulnerabilities with rather restricted local building damage effects and these characteristics result in the lowest quantitative risks of the three considered city models.

A larger proportion of construction types with a high vulnerability, e.g., single-family houses, results for the linear city in the highest criticality of all three examples. The large areal dispersion and the higher percentage of uncritical object types result in the lowest frequencies.

The compact city model includes a high mixture of different object types, a high building density and results in several local hotspots. Different construction types lead to a varying severity concerning the vulnerability. The lowest criticality of the compact city is higher rated than the maximum values of the central business district, which is observable with the yellow and black curves on the ordinate in Figure 5, for example.

Beside the derived risk quantities, the introduced framework enables the consideration of recovery processes, which is quantitatively described as performance over time [22]. The performance is oriented to the usability of an object and depends on the derived degree of damage.

4.4. Analysis of Recovery and Overall Resilience

The results for the response and recovery processes depending on the urban configuration are compared in Figure 6. The application of Equation (3) is visualized in this diagram, meaning the averaged loss of performance for a certain city model, if an adverse event occurs with respect to all possible threat types, threat positions and buildings. The dispersion of risk, as shown in the risk diagram of Figure 5 is eliminated in the performance-time relation by building the average.

In Figure 6, the high vulnerability for the linear city model is present with the strongest drop of performance at the time of the impact. The smallest discontinuity at $t = 0$ underlines the robust behavior of the central business district, which is congruent with the results of the risk analysis in Figure 5. Full recovery time of the building usability of the central business district is twice as long as in case of the linear model, which shows a relative short recovery behavior. This circumstance is due to the fact that high-rise buildings have a longer construction time than multi-functional and single-family houses, as shown in the overview in Table A1. Hence, the mixture of different object and construction types of the compact city is also reflected with the performance-time relations.

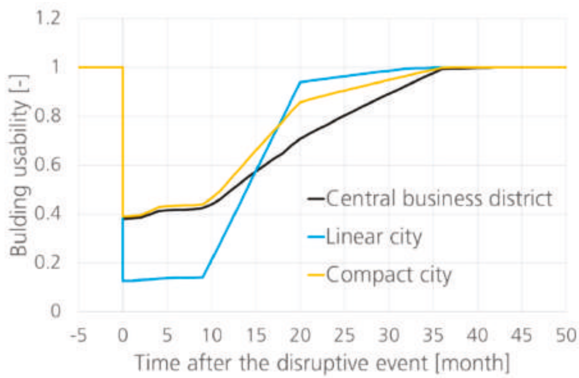


Figure 6. Comparison of the performance-time relation of the three investigated city models based on the average of the derived risk quantities in combination with expected recovery times.

Per the definition, as shown in Figure 1 (right), an often used single quantity to measure the resilience of a system is realized by integration of the performance loss over time or the loss per time is often used [11,32]. The recovery capabilities are determined in the following with respect to a performance loss function per duration time of disruption (second division by $t_{n_p} - t_1$), a kind of performance function loss gradient,

$$R_Q = \frac{1}{Q_{max}\left(t_{n_p} - t_1\right)^2} \sum_{p=0}^{n_p - 1} \int_{t_p}^{t_{p+1}} (Q_{max} - Q(t))dt \tag{4}$$

Additionally, to the pure risk assessment, the recovery behavior influences the target quantity of acceptable resilience. The elongated form of the linear city results in areas, which will be not affected by critical objects and hence small susceptibilities. Many of the residential objects are constructed as a single-family house with masonry wall constructions and result in strong vulnerabilities and hence in critical risk values. The simple construction types include short recovery to reach the initial usability, which has a lasting effect on the defined resilience quantity. The application of Equation (4) shows that the linear city ($R_Q = 0.27$ [*loss per time*]) has almost the same averaged performance loss per time than the central business district ($R_Q = 0.26$ [*loss per time*]). Because of the larger proportion of similar object use types, the central business district includes no single hotspots. The averaged risk depends mainly on the vulnerability. The considered construction types to the larger extent of office buildings or towers include longer recovery phases, which is the reason for similar resilience quantities compared to the linear city.

Small free spaces and a high mixture of object types are the main reasons for an aerial susceptibility with several hot spots within the compact city model. A great variety of construction types result accordingly in a broad spread concerning expected damage effects but also in parts with robust behavior and short recovery phases. Within the three applied models and in alignment to the introduced methodology, the outcomes point out that the compact city ($R_Q = 0.22$ [*loss per time*]) results in the smallest quantities concerning the averaged performance loss over time. This is a very interesting result, since the compact city is also favored from many other perspectives including sustainability and quality of living.

The three application examples underline the benefit of a susceptibility, vulnerability driven and risk-informed resilience assessment. The extension on the further dimension of recovery allows a more precise and deeper evaluation compared to classical risk assessment schemes. Low vulnerability or a high susceptibility results in critical risk values. However, in combination with short recovery phases, such systems can still be comparatively resilient despite critical risk quantities. From a risk perspective, the costs of the overall recovery phase have to be quantified adequately. From a resilience management perspective, classical susceptibility, vulnerability and risk cover only parts of the resilience management cycle. Hence, a correlation between risk and resilience is not mandatory.

The new framework allows a quantification which resilience phase is more effective for the considered urban area. Based on the multi-dimensional and complex characteristics of a certain city type, generalized statements about a most effective resilience improvement measure are not available and requires an individual investigation per city and the examination of different resilience phases. If the assessment results in relatively high susceptibilities, preparation or prevention measures will be more powerful. Protection measures are adequate, if the considered system exhibits high vulnerabilities. Decreasing damage effects result in smaller recovery efforts and require lower efforts concerning the response.

The response and recovery perspective, with focus on reconstruction offers the additional quantification of resilience in terms of recovery times, recovery slopes and expected loss. A steeper slope of the performance function results in a faster recovery and is considered in the applied expression to give an idea of rapidity within the recovery phase. The introduced formulation in Equation (4) results in a single quantity and gives the option of comparability between different cities or resilience improvements.

5. Summary and Conclusions

Within this paper, a risk-based method, as introduced in [22], is applied to three different urban forms and expanded to the aspect of recovery to get insights concerning the resilience of urban areas. Based on a decisive definition of the terminology, the present paper introduces a mathematical concept for the quantification of resilience. Different quantities are identified to be most relevant for the five resilience management phases. Urban modelling quantities have a lasting effect on the preparation phase for resilience. The susceptibility analysis is able to evaluate the prevention phase. Protection measures can be matched with the vulnerability and risk quantities. Recovery processes can be matched with the estimation of time spans for different urban objects. Response measures are only indirectly matched with consideration of other resilience management phases.

The combination of risk quantities and recovery processes deliver a time dependent estimation of performance to quantify resilience. The application of different enhancement measures allows then the evaluation of the effectiveness for single resilience management phases. Preparation, prevention and protection measures can be directly addressed. The management phases of response and recovery are indirectly supported. An increased robustness results in smaller damage effects and hence in smaller efforts concerning response and recovery, for example.

Complex and mostly qualitative social aspects are not considered, but the derived approach delivers a precise estimation of expected losses in terms of loss and degree of recovery of built functionalities of urban objects. However, the performance of buildings is not yet quantified and prized.

The risk-based resilience approach is applied to three typical urban forms concerning the damage type building collapse. The building density, the mixture of object types and the applied construction types determine the various resilience management quantities. City quarters with a clear and homogeneous allocation of use types result in an approximately uniform distribution of susceptibility and the risk depends mainly on the vulnerability effects, as shown with the results of the central business district. Therefore, the application of protection measures would be most effective to result in a resilient surrounding.

The extension on recovery as a further resilience dimension shows that an increasing robustness or low risk values alone are not sufficient to qualify resilient systems. The example of the linear city results in stronger damage effects but a similar resilience quantity compared to the central business district, based on shorter recovery times. The approach allows a quantitative comparison, how effective the investigation of further resilience phases, like preparation of prevention, which could be an option if there are several hotspots at risk.

The high mixture of object and construction types within a compact city results in several hot spots but the composition results in a robust behavior an short recovery and hence in the most resilient morphology in terms of recovery behavior without application of enhancement measures. The inhomogeneous distribution repeals scenarios with strong damage effects or long recovery phases. This fits nicely with the often-attributed sustainability and societal acceptance of compact city forms.

Building density or the distribution of objects, free spaces, construction type or the use of a building are main attributes, which will influence the resilience of an urban surrounding. The results deliver information on how growing agglomerations can be sustainably designed also with regards to new threats. The overall framework and calculation methods builds a possible basis for urban planners, decision makers or insurance companies to analyze and optimize designs of city areas.

Within this paper, terroristic threats are exemplary evaluated. Based on the clear definition, this framework allows also an evaluation of other main kind of disasters. This requires the availability of statistical data and appropriate models to assess expected damage effects. Examples could be models in the range of earthquake events [33] or flood risks [34].

The introduced framework uses validated engineering models and the comparison to real events underline the accuracy of the statistical data. The estimation of recovery phases based on expert knowledge and results in capable quantities to postulate resilience. A possible deviation of recovery times is currently not considered and will be a point of reference for future research. Similar to social aspects, which are currently only indirect matched.

Author Contributions: Besides the work of K.F., the following contributions are provided by the coauthors: S.H. supervised the research that leads to the content of this paper. W.R. gave contributions within the application examples and the definition of the city models. I.H. helped to define the mathematical formulations, presented in this paper.

Acknowledgments: The research leading to these results has received funding form the European Commission's 7th Framework Programme within the EU project EDEN under grant agreement no. 313077 and VITRUV under grant agreement no. 261741. The contribution of Andreas Bach and Ingo Müllers (Schüßler-Plan Engineering GmbH) for the provision of the list with pre-defined construction types including the estimated time scales is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Overview of pre-defined building types, their construction and time-scales for planning and construction to estimate the recovery process [29].

Construction Type	Construction	Number of Floors	Recovery Time [month]	
			Planning, Approval	Construction
Single-family house	Masonry (walls) Reinforced concrete (slabs, beams)	3	9	11
Multi-family house	Reinforced concrete (walls, slabs, beams)	6	15	13
Block of flats	Reinforced concrete (walls, slabs, columns)	17	18	18

Table A1. *Cont.*

Construction Type	Construction	Number of Floors	Recovery Time [month]	
			Planning, Approval	Construction
Industrial building	Steel (beams) trapezoidal steel profiles (roof, walls)	1	18	14
Multi-family house, mixed use	Reinforced concrete (walls, columns, slabs) Steel (columns) Timber (girders)	4	15	13
Sports hall	Reinforced concrete (walls, columns, slabs) Steel (roof construction)	1	15	18
Shopping mall Office building Office tower	Reinforced concrete (walls, slabs, columns)	5 7 13	20 18 20	22 18 22
Public transport terminal	Reinforced concrete (walls, slabs, columns) Steel (roof)	1–2	24	24

References

1. Branscomb, L. Sustainable cities: Safety and Security. *Technol. Soc.* **2006**, *28*, 225–234. [CrossRef]
2. The Minerals, Metals and Materials Society (TMS). *Engineering Solutions for Sustainability, Materials and Rescources—Workshop Report and Recommendations*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
3. Kröger, W.; Zio, E. *Vulnerable Systems*; Springer: London, UK, 2011.
4. Department of Economic and Social Affairs. *World Urbanization Prospects*; The 2014 Revision; United Nations: New York, NY, USA, 2014.
5. Cross, J. Megacities and small towns: Different perspectives on hazard vulnerability. *Environ. Hazards* **2001**, *3*, 63–80.
6. Lin, C.; Liou, D.; Wu, K. Opportunities and challenges created by terrorism. *Technol. Forecast. Soc. Chang.* **2007**, *74*, 148–164. [CrossRef]
7. Tamvakis, P.; Xenidis, Y. Comparative Evaluation of Resilience Quantification Methods for Infrastructure Systems. *Procedia Soc. Behav. Sci.* **2013**, *74*, 339–348. [CrossRef]
8. Carpenter, S.; Walker, B.; Anderies, J.; Abel, N. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* **2001**, *4*, 765–781. [CrossRef]
9. Cutter, S.; Bernes, L.; Berry, M.; Burton, C.; Evans, E.; Tate, E.; Webb, J. A place-based model for understanding community resilience to natural disasters. *Glob. Environ. Chang.* **2008**, *18*, 598–605. [CrossRef]
10. Gallopín, G. Linkages between vulnerability, resilience, and adaptive capacity. *Glob. Environ. Chang.* **2006**, *16*, 293–303. [CrossRef]
11. Bruneau, M.; Chang, S.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.A.; von Winterfeldt, D. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
12. Chang, S.; Shinozuka, M. Measuring Improvements in the Disaster Resilience of Communities. *Earthq. Spectra* **2004**, *20*, 739–755. [CrossRef]
13. Cimellaro, G.; Reinhorn, A.; Bruneau, M. Framework for analytical quantification of disaster resilience. *Eng. Struct.* **2010**, *32*, 3639–3649. [CrossRef]
14. Jabareen, Y. Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities* **2013**, *31*, 220–229. [CrossRef]
15. Federal Emergency Management Agency. HAZUS—Methodology for Estimating Potential Losses from Disasters. Available online: http://www.fema.gov/hazus (accessed on 3 August 2015).
16. Quiel, S.; Marjanishvili, S.; Katz, B. Performance-Based Framework for Quantifying Structural Resilience to Blast-Induced Damage. *J. Struct. Eng.* **2015**, *142*, C4015004. [CrossRef]

17. Federal Emergency Management Agency. *FEMA-426: Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings*, 2nd ed.; U.S. Department of Homeland Security: Washington, DC, USA, 2011.
18. Curdes, G. Stadtmorphologie und Klimawandel—Welche Stadtstrukturen können den Klimawandel überleben? In Proceedings of the 17th International Seminar on Urban Form, Hamburg, Germany, 20–23 August 2010.
19. Jabareen, Y. Sustainable Urban Forms—Their Typologies, Models, and Concepts. *J. Plan. Educ. Res.* **2006**, *26*, 38–52. [CrossRef]
20. Adger, W. Social and ecological resilience. Are they related? *Prog. Hum. Geogr.* **2000**, *24*, 347–364. [CrossRef]
21. Thoma, K. *Resilien-Tech-Resilience-by-Design: Strategie für die Technologischen Zukunftsthemen*; Acatech, Deutsche Akademie der Wissenschaften: Berlin, Germany, 2014.
22. Fischer, K. Resilience Quantification of Urban Areas, an Integrated Statisitcal-Empirical-Physical Approach for Man-Made and Natural Disruptive Events. Ph.D. Thesis, University of Freiburg, Freiburg, Germany, 2018.
23. Fischer, K.; Häring, I.; Riedel, W.; Vogelbacher, G.; Hiermaier, S. Susceptibility, vulnerability and averaged risk for resilience enhancement of urban areas. *Int. J. Protect. Struct.* **2016**, *7*, 45–76. [CrossRef]
24. Fischer, K.; Häring, I. SDOF response model parameters from dynamic blast loading experiments. *Eng. Struct.* **2009**, *31*, 1677–1686. [CrossRef]
25. Müllers, I.; Fischer, K.; Nawabi, A.; Riedel, W. Design against Explosions and Subsequent Progressive Collapse. *Struct. Eng. Int.* **2015**, *25*, 319–325. [CrossRef]
26. Siebold, U.; Ziehm, J.; Häring, I. Terror Event Database and Analysis Software. In Proceedings of the 4th Security Research Conference, Karlsruhe, Germany, 29th September–1st October 2009.
27. Fischer, K.; Siebold, U.; Vogelbacher, G. Empirical analysis of security critical events in urban areas. *Bautechnik* **2014**, *91*, 262–273. [CrossRef]
28. Valente-Pereira, L. *Urban Form Definition in Urban Planning*; Simplissimo: Lisbon, Portugal, 2014.
29. Schüßler Plan Ingenieurgesellschaft mbH. *D4.4: Vulnerability Analysis of Generic Structures and Functional Units*; EU project VITRUV: Düsseldorf, Germany, 2013. Available online: www.vitruv-project.eu (accessed on 28 May 2018).
30. Proske, D. *Catalogue of Risks; Natural, Technical, Social and Health Risks*; Springer: Berlin, Germany, 2008.
31. Hunter, P.; Fewtrell, L. Acceptable Risk. In *Water Quality: Guidelins, Standards and Health*; Fewtrell, L., Bartram, J., Eds.; WHO by IWA Publishing: London, UK, 2001.
32. Cimellaro, G. *Urban Resilience for Emergency Response and Recovery—Fundamental Concepts and Applications*; Springer: Berlin, Germany, 2016.
33. Krawinkler, H.; Miranda, E. Performance-based earthquake engineering. In *Earthquake Engineering, from Engineering Seismology to Performance-Based Engineering*; Bozorgniam, Y., Bertero, V.V., Eds.; CRC-Press: Boca-Raton, FL, USA, 2004; pp. 1–59.
34. Büchele, B.; Kreibich, H.; Kron, A.; Thieken, A.; Ihringer, J.; Oberle, P.; Merz, B.; Nestmann, F. Flood-risk mapping: Contributions towards an enhanced assessment of extreme events and associated risks. *Nat. Hazards Earth Syst. Sci.* **2006**, *6*, 485–503. [CrossRef]

sustainability

MDPI

Article

Effects of Commercial Activities by Type on Social Bonding and Place Attachment in Neighborhoods

Byungsuk Kim [1] and Jina Park [2,*]

1 Department of Urban Planning, Hanyang University, Seoul 04763, Korea; bsk0728@nate.com
2 Department of Urban Planning and Engineering, Hanyang University, Seoul 04763, Korea
* Correspondence: paran42@hanyang.ac.kr; Tel.: +82-2-2220-0332

Received: 20 March 2018; Accepted: 24 May 2018; Published: 29 May 2018

check for updates

Abstract: Place attachment is an emotion that people experience in connection to a specific place and it is needed to maintain a sustainable neighborhood community. The emotion is affected by various factors, such as experience, function, environment, and satisfaction. This study focuses on commercial structures, which are one feature that characterizes the physical environments of neighborhoods. The aim of this study is to determine the effects of commercial activities in different commercial environments on social bonding and place attachment in residents. Two sites were selected for analysis due to their different commercial environments, and path analysis was used to examine the relationships among factors. The results indicate that commercial activities, which can vary according to commercial type, had both direct effects and indirect effects through social bonding between residents on place attachment. These results suggest that the commercial environment is an important element affecting the community and place attachment of residents in neighborhoods.

Keywords: place attachment; commercial types; commercial activities; social bonding; physical activities

1. Introduction

In light of the emotions, intimacy, and happiness that people feel in connection to their neighborhoods, there is more than functional and physical meaning to neighborhoods. The emotional ties of residents to the area in which they live can be defined as place attachment to a neighborhood. Analysis of such has been extensively addressed in looking at the emotional experiences of people and people's ties to places in terms of various factors of function and satisfaction [1–4]. Place attachment is a concept similar to residential satisfaction in terms of cognition about a physical environment, with one important distinction. If residential satisfaction is a functional evaluation of a place of residence from the viewpoint of the people living there, then place attachment is an emotional evaluation of the place of residence. In order to foster a salubrious neighborhood, it is necessary to consider not only the functional aspects of a place, but also the psychological and emotional demands of human beings. In this context, place attachment can be an important criterion of residential environment evaluation [5]. Since place attachment is formed when a person is psychologically connected to a specific place, it can be a source of relief for residents amid the rapid changes of modern urban environments.

Place attachment can be formed by various factors. In the work of Lewicka [6], which analyzed the studies of place attachment within the past 40 years, various variables including socio-demographic, social, and physical predictors are identified in place attachment. Many of the previous studies related to place attachment in neighborhoods have been conducted in terms of the influence of physical environment characteristics on place attachment in local residents [7–11]. This is because place attachment is basically an emotional bond that a person has with a place. On the other hand, some studies [4,7,9] have analyzed the influence of social bonds on place attachment, focusing on the social ties of residents of a neighborhood. Additional other studies [7,12,13] have investigated the influence of people's personal characteristics on place attachment.

Overall, research results show that physical environment characteristics such as place, personal characteristics of individual residents, and characteristics of social relationships between residents influence the formation of place attachment among locals. Based on these results, the focus of this study is the relationships among these various physical environment characteristics and place attachment. Beyond the influence of place attachment on individual variables, it is necessary to clarify the mechanism of the relationship of structural influence among the features of physical environments, the personal characteristics of residents, and social bonding. In order to establish the relationship between place attachment and its influencing variables, it is necessary to understand the interaction between people and place—as well as between people and people—in the physical features of neighborhoods. In this study, we focus on "activities" as a key parameter in our understanding of the relationships between the variables affecting place attachment.

From the perspective of environmental psychology, human activities arise in the context of an environment. Many studies have demonstrated the relationships between physical environment and people's activities [14–17]. If the neighborhood environment affects people's activities, and if the activities affect the level of place attachment, then it is possible to discuss which characteristics of a neighborhood environment ultimately promote place attachment. If the unique physical environment of a neighborhood increases the amount and types of activities pursued by its residents—thereby positively impacting place attachment—then physical environment characteristics stand to provide urban design implications for a salubrious neighborhood.

Among various activities that occur in a neighborhood, this study focuses on commercial activities. Commercial activities are basic, essential activities in people's daily lives. Depending on the type of commercial facility, however, the style of activities can be very different. Various types and characteristics of commercial facilities are identified based on their location, usage, and surroundings, but commercial facilities can be compared in two basic forms: street shops, which are located along the streets of residential environments, and mall-type shops, describing a configuration in which shops are concentrated in specific buildings (in contrast to street shops). In terms of the commercial environment of a neighborhood, this difference in commercial form can impact the commercial activities of residents. As a result, the distinction can manifest as a difference in neighborhood activities. In a neighborhood with small shops, small quantities of goods are frequently purchased. In contrast, in a neighborhood with large marts, large amounts of goods are purchased less frequently. Additionally, if an individual uses a car to purchase a large quantity of goods, then the individual may have fewer opportunities to come into contact with her or his neighbors and have less interaction with the neighborhood environment than when walking on foot. Thus, these differences in commercial activities may lead to differences in face-to-face opportunities among human beings. The activities of the residents in a neighborhood can be a driving force for local initiatives such as local revitalization and community spirit.

In this respect, commercial forms affect the physical activities of people and are, therefore, an important subject of study in terms of social bonding among residents in a neighborhood and the promotion of place attachment. Various physical elements of neighborhoods have been studied, including walkability [17,18], street connectivity [19], land-use mix [15,16], pedestrian and traffic safety [20], and recreation facilities and parks [16]. In contrast, however, few studies have focused on the physical elements of commercial activities and commercial types—one of the basic activities of people's daily lives. Indeed, there are no studies to analyze relationships among the influencing factors of place attachment, such as the effects of commercial form on people's commercial activities and the effects of commercial activities on social bonding and place attachment. Therefore, this study investigates the effects of "activities" as a function of commercial form in relation to the physical environment of a neighborhood, social bonding between residents, and place attachment.

2. Previous Studies

2.1. Place Attachment

The concept of attachment can be applied to explain the relationship between human beings and the environment (that is, our interest in a specific place or community), although the concept is mainly described in terms of people's connection to other people, such as infants and parents or family and friends. Recent research has focused on attachments and so-called place attachments in terms of "friendliness to physical places" in contrast to the relationship networks between people that are emphasized in sociological research. Place attachment can be understood in two dimensions: place identity and place dependence [21]. Proshansky [22] defines place identity as "a complex pattern of beliefs, values, feelings, expectations, and preferences relevant to the nature of the physical world," which is a complex cognitive structure of a person at a specific place. Place dependence is a functional relationship with a person's residence (or other specific area) and may be explained by comparing one place with another according to individual needs. In this sense, place dependence is defined in terms of whether a particular area or facility functions in accordance with a user's activities [23].

Place attachment is a complex concept that describes the interaction of emotional or symbolic relationships, emotions that are formed in a single physical environment, and human interrelationships and feelings occurring in that particular place. In other words, place attachment shows the ways in which a place is more than just a physical environment. Place attachment arises not only from the place itself, but also from emotions due to consciousness, experience, psychological reaction, symbolism, and other complex functions of cognition that people associate with the place [24]. Thus, we can define place attachment as being caused by empirical experiences that occur when people consistently interact with a specific place. From this point of view, if the residents in a neighborhood engage in continuous visits and activities in a specific place, a positive relationship may be found between people and place in the form of place attachment.

2.2. Place Attachment in Neighborhoods

Place attachment refers to an emotional factor between people and physical spaces. In this context, research trends related to place attachment have examined personal, social, and regional differences in place attachment, together with the factors affecting place attachment. Existing research mainly deals with personal and social variables (such as race, age, and economic power), time variables (such as duration of residence and satisfaction with the local environment), and spatial characteristics. This multifactorial lens suggests the complexity of the feeling of place attachment.

It is generally accepted that levels of satisfaction with people's residential environments are highly related to place attachment [7–11]. In order to maintain place attachment, certain neighborhood environment standards must be achieved. In declining residential areas, the level of attachment of people to their place of residence will decline, and relocation will be considered due to deterioration of the quality of life [25]. Place attachment occurs mainly through neighborhood environments and in bonding with neighbors. Neighborhood satisfaction, which is a passive, direct experience—as opposed to social bonding with neighbors (which needs to be actively pursued during settlement in a new local environment or following neighborhood redevelopment)—plays an important role in the formation of place attachment [4]. In addition, place attachment has different characteristics depending on the scale of a place, such as a city versus a smaller neighborhood [2,26].

In the physical environment of a neighborhood, place attachment changes according to the personal and social characteristics of the people directly experiencing place attachment. There are differences depending on whether people reside in a home of their own, on race [7], and on whether people are indigenous or immigrants [12]. If there is a link between residents and a neighborhood wherein place attachment is formed, positive effects are noted in the neighborhood environment. Home ownership, race parity, and indigenous people inspire a sense of belonging to an area. In this respect, bonding with neighbors is an important factor in place attachment. When this bond is strong, place attachment is positively affected [4,7,9]. On the contrary, if there is a low level of solidarity among residents and people move frequently, the formation of place attachment can be difficult [3]. To increase social bonding between neighbors, contact with neighbors and time spent together must increase. In other words, the accumulation of experience in the neighborhood is important, and experience is generally proportional to time. A variable that represents this relationship in the context of neighborhoods is duration of residence. Many studies have shown that residence period has an impact on place attachment [7,9,27,28].

In order to foster strong social bonding and place attachment among residents, residents should be active in their neighborhood, and the neighborhood environment should reflect their desires. The physical environment of various neighborhoods is related to the activities of people. Especially, focusing on commercial environments, it has been found that mixed-land use [15], retail floor area ratio [29], and commercial facilities [30,31] affect people's walking activities. Walking also positively affects resident bonding [32], and walking-friendly neighborhood conditions can improve people's sense of community [33,34]. This correlation explains the importance of a neighborhood's physical environment relative to the amount and types of activities that occur therein in the context of place attachment. Accordingly, this study aims to investigate the effects of commercial activities on social bonding by neighborhood commercial types, together with the impact on place attachment.

3. Methods

3.1. Study Areas

Neighborhoods characterized by different types of commercial structures were selected in order to analyze the relationship among commercial types, commercial activities, social bonding, and place attachment. The distinction is between commercial types of street shops or a shopping mall. First, Lancry in Paris, France, was selected to represent the street shops type (see. Figure 1). The whole area is characterized by medium-rise buildings with an average of six to seven floors. On the first floors of buildings, various small shops including commercial, service, and manufacturing shops are located along the street. The upper parts of the buildings are composed of residential living spaces. Lancry is included in a grouping of 11 regions that comprise the business district of Vital'Quartier, initiated in 2004 by the Société d'Economie Mixé d'Aménagement de l'Est de Paris (SEMAEST) as part of the commercial revitalization project in Paris. It can be seen as a commercial type of street shop.

Figure 1. Lancry.

The opening of large shopping malls in Paris is regulated by law as "La loi Royer" (1973) and "La loi Raffarin" (1996) and permission is required to open stores over 300 m^2 by Raffarin law. For this reason, mall-type commercial areas should be chosen outside of Paris. La Défense was chosen as a representative shopping mall type among commercial areas (as compared to street shop type). La Défense (see Figure 2) is a representative new town in France and has two large shopping malls (CNIT and Quaten Temps). Thus, unlike the street shops seen in Paris, large, mall-type commercial facilities are used by residents of La Défense for various shopping activities.

Figure 2. La Défense.

The average age of residents in Lancry is 37 years old and the population density is 38,160/km^2. There are 6.1 stores per 100 m among bars, cafes, and restaurants, and 26.8 stores per 100 m among all kinds of shops. The housing density in Lancry is 244 log./ha [35]. La Défense is distributed across three zones—Courbevoie, Puteaux, and Nanterre. In this study, the average values for Fb de l'Arche (Courbevoie), Gambetta (Courbevoie), and La Défense (Puteaux) were used. In the case of La Défense, the average age is 35.33 years with a population density of 17,836.67/km^2. There are, on average, 1.57 shops for bars, cafes and restaurants, with an average of 9.53 stores per 100 m. The housing density in La Défense is 94.67 log./ha [36]. This information indicates that Lancry has a higher density of shops than La Défense, which means that the residents in Lancry have a higher accessibility to shops than La Défense.

3.2. Variable Settings

First, the two commercial types were changed to dummy variables (street: 1, mall: 0) to determine the effects of the commercial types. The weekly shopping frequency of residents depending on the commercial type was measured to represent levels of commercial activities (1 to 5 points). Aspects of social bonding were established as variables to determine whether bonding among residents affects place attachment, and the items were related to levels of closeness among neighbors. Place attachment variables were measured using place identity (measured by a fundamental question about the extent to which residents feel attached to their neighborhood) and place dependence, which is a functional necessity.

By definition, place attachment is affected by levels of attachment in residents to a specific place. Accordingly, neighborhood environments and place attachment have been the main subjects of previous research. In this study, the following variables were set as environmental factors in order to scrutinize environmental factors through an analytical lens. First, parameters of "satisfaction with commercial infrastructure" and "satisfaction with commercial quality" were set in terms of commercial environment satisfaction. Two variables were set to determine whether the physical features of commercial environments influence place attachment or whether qualitative factors of shops have effects on place attachment. In addition, the variable of "satisfaction with neighborhood facilities" was set in order to confirm the effects of neighborhood environments in the findings of previous research on place attachment.

3.3. Questionnaires and Data Collection

Table 1 shows that questionnaires consisted of items about place attachment, social bonding, commercial satisfaction, and resident satisfaction with neighborhood facilities. The items related to place attachment and social bonding were reconstructed based on previous studies [9,11,37]. The items on commercial satisfaction and neighborhood satisfaction were constructed based on the activities and direct experiences of the residents in the neighborhoods. Complete questionnaires included five items on place identity, five items on place dependency, five items on social bonding, eight items on commercial satisfaction, and six items on neighborhood satisfaction. All of the above items were measured on a five-point scale.

Table 1. Questionnaire items.

Factors		Items
Place attachment	Place identity	This neighborhood is important in my life. I say that I live in this neighborhood when I introduce myself. If someone asks me about this neighborhood, I can answer the questions. I am proud to live in this neighborhood. This neighborhood is special to me.
	Place dependence	This neighborhood is suitable to my line of work. This neighborhood is better to live in than other neighborhoods I do many activities around this neighborhood. Leaving this neighborhood causes me to feel sad. I would live in this neighborhood even if I had the chance to move to other areas.
Social bonding		I know the residents of my neighborhood well. I have friendly neighbors to talk to. I have many friends in the neighborhood. I attend neighborhood gatherings often. I attend the event of neighborhood often.
Satisfaction with commerce		Number of shops, types of shops, necessary shops, price of products, service of shops, type and quality of products, distance to shops.
Commercial activities		Shopping frequency.
Satisfaction with neighborhood facilities		Green space, public and cultural facilities, public transportation, education services, safety, pedestrian environment.
Commercial type		Street shops-type neighborhood: Lancry. Mall type-neighborhood: La Défense.

Note. Place identity and place dependence items, as well as social bonding items, are in a designated order (e.g., identity 1, identity 2); Commercial type: Street shops = 1, Mall = 0.

Six surveyors performed surveys from 10 am to 7 pm in Lancry (26–27 June 2015). In La Défense, the same six surveyors conducted surveys from 10 am to 7 pm (30 June 2015). Sampling was conducted using a convenience sampling method, and data were collected evenly across age group and gender. Before starting the surveys, the surveyors ensured there was "agreement to participate in the questionnaire" and that the participants were "were residents of Lancry or La Défense." Here, 60% of respondents participated in the survey and a total of 164 questionnaires were collected. Of the returned questionnaires, 94 were collected from residents of Lancry and 70 from residents of La Défense. In Lancry, the questionnaire was distributed among local residents passing through the streets where the shops are located, whereas in La Défense, the survey was distributed in residential areas, squares, or parks in the greater La Défense area rather than the shopping mall itself. Since the large shopping mall in La Défense is a commercial center with mass appeal, local residents, in addition to people coming from distant areas to shop, were potentially involved in the survey. For accuracy of communication, the questionnaire was a non-English version conducted in French. The collected questionnaires were coded using SPSS 21 statistical software (IBM, NEWYORK, USA).

3.4. Research Design

This study focuses on the influence of commercial activities on social bonding and place attachment among residents of a neighborhood. To accomplish this, we performed the following two-step model setting process. First, note that commercial activities will affect social bonding between residents as well as place attachment; this is because a larger amount of activity in a neighborhood allows for more opportunities to meet neighbors and experience the neighborhood. Second, note that commercial activities are influenced by satisfaction with the commercial and physical environments according to different commercial types (e.g., street shops or mall types), which are likely to affect commercial activities.

This study uses two models. Model 1 analyzes each site individually to determine the effects of commercial activities on social bonding, as well as the direct and indirect effects of commercial activity on place attachment. A larger amount of commercial activities leads to higher activity in the neighborhood. The relationships between shop owners and neighbors are formed through the spaces in the neighborhood, such as shops and streets, and social bonding is an important factor that leads to attachment to the neighborhood. In addition, if people continue to use a space, they will develop feelings about that space, which can lead to place attachment. Model 2 analyzes the two sites combined to determine the different commercial types that affect commercial activities. The type of commercial environment, consisting of street shops or malls, can affect the commercial activities depending on accessibility. In the case of street shops, the shops are located near the houses and a pattern of frequent purchases of small quantities of goods will appear. However, accessibility in a mall-type commercial environment is lower than that for street shops, and instead exhibits a pattern of buying many goods at once.

3.5. Data Analysis Using Path Analysis

Based on the collected survey data, the following analysis process is conducted to confirm the purpose of this study. First, factor analysis is conducted based on questionnaire items to derive analysis factors. Second, correlation analysis is performed to analyze the correlation between factors and to remove factors with high relevance. Finally, analysis of the research model shown in Figure 3 is conducted through path analysis using the Amos program.

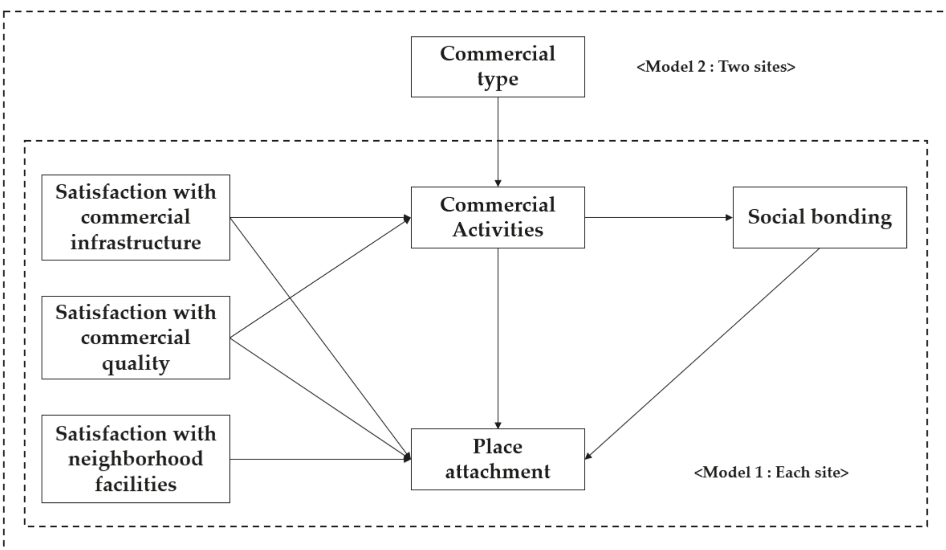


Figure 3. Research models.

Path analysis is a technique for explaining the causal relationships between variables in a non-experimental situation. The validity of the causal relationships between variables is examined using the collected data. The effects of any one variable on another variable are called direct effects, while the effects of one variable on one (or more) variable(s) by way of other variables are called indirect effect. The purpose of this study is to analyze direct and indirect effects of commercial activities on social bonding and place attachment, and effects of commercial types on commercial activities using path analysis based on collected data.

4. Results

4.1. Demographics and Factor Analysis

The demographic characteristics of the subjects were as follows (see Table 2). Of 164 total subjects, 87 were males and 77 were females. In terms of age distribution, the highest proportion of the sample was people in their 30s (24.4%), followed by those in their 20s (23.8%), and those in their 40s (14.6%). The average age of participants is 39.89 years old in Lancry and 34.22 years old in La Défense. The highest proportion of the sample claimed a residence period of 4–10 years in a neighborhood (31.7%), followed by 1–3 years (21.3%). In addition, 47% of the residents had lived for longer than 10 years in the neighborhood. Distribution according to site was 57.3% in Lancry and 42.7% in La Défense.

Table 2. Demographics.

Factors		Lancry	La Défense	Total
		N (%)	*N* (%)	*N* (%)
Sex	Males	51 (54.3)	36 (51.4)	87 (53)
	Females	43 (45.7)	34 (48.6)	77 (47)
	Total	94 (100)	70 (100)	164 (100)
Age	10s	7 (7.4)	15 (21.4)	22 (13.4)
	20s	23 (24.5)	16 (22.9)	39 (23.8)
	30s	20 (21.3)	20 (28.6)	40 (24.4)
	40s	17 (18.1)	7 (10.0)	24 (14.6)
	50s	16 (17.0)	4 (5.7)	20 (12.2)
	60s and over	11 (11.7)	8 (11.4)	19 (11.6)
	Total	94 (100)	70 (100)	164 (100)
Residence period	1–3 years	23 (24.5)	12 (17.1)	35 (21.3)
	4–10 years	26 (27.7)	26 (37.1)	52 (31.7)
	11–15 years	13 (13.8)	16 (22.9)	29 (17.7)
	16–20 years	16 (17.0)	10 (14.3)	26 (15.9)
	21 years	16 (17.0)	6 (8.6)	22 (13.4)
	Total	94 (100)	70 (100)	164 (100)

Factor analysis was performed twice. The first group included items related to commerce and neighborhood facilities, and the second group included items related to place attachment. The final factors are “satisfaction with commercial infrastructure” (SCI), “satisfaction with commercial quality” (SCQ), “satisfaction with ‘neighborhood facilities” (SNF), “place attachment” (PA), “social bonding” (SB) (see Table 3), and “commercial activities” (CA).

Table 3. Factor analysis.

Factors		Factor Loading	Cronbach's α
Satisfaction with commercial infrastructure	Necessary shops	0.840	0.758
	Number of shops	0.691	
	Distance to go to shops	0.683	
Satisfaction with commercial quality	Types of shops	0.676	0.618
	Type and quality of products	0.814	
	Price of products	0.689	
	Service of shops	0.654	
Satisfaction with neighborhood facilities	Green space	0.853	0.658
	Public and cultural facilities	0.760	
	Pedestrian environment	0.654	
Duration of residence	Place identity 5	0.797	0.891
	Place dependence 2	0.765	
	Place identity 4	0.764	
	Place identity 1	0.758	
	Place dependence 3	0.745	
	Place dependence 4	0.713	
	Place identity 3	0.663	
	Place identity 2	0.660	
	Place dependence 5	0.594	
Social bonding	Community 3	0.845	0.778
	Community 2	0.797	
	Community 1	0.757	
	Community 4	0.626	

Table 4 shows that the averages for the factors are different according to the site. For SNF, the value for La Défense (3.55) was higher than the value for Lancry (3.14). However, for the other factors of PA (Lancry: 3.52; La Défense: 3.04), SB (Lancry: 2.98; La Défense: 2.75), SCI (Lancry: 3.65; La Défense: 3.42), SCQ (Lancry: 3.44; La Défense: 3.23), CA (Lancry: 2.80; La Défense: 2.31), and residence period (Lancry: 13.38; La Défense: 10.54), the values for Lancry were higher than the values for La Défense. Especially, CA in Lancry (2.80) was higher than in La Défense (2.31), which means that CA can vary depending on the commercial presence.

Table 4. Average value of factors (*t*-test).

Factors	Site	*N*	Avg.	S.D.	S.E.	*t*
Satisfaction with commercial infrastructure	Lancry	94	3.65	0.63087	0.06507	2.140 **
	La Défense	70	3.42	0.76084	0.09094	
Satisfaction with commercial quality	Lancry	94	3.44	0.58294	0.06013	2.248 **
	La Défense	70	3.23	0.57972	0.06929	
Satisfaction with neighborhood facilities	Lancry	94	3.14	0.76911	0.07933	−3.487 **
	La Défense	70	3.55	0.69710	0.08332	
Social bonding	Lancry	94	2.98	0.75956	0.07834	1.846 *
	La Défense	70	2.75	0.83839	0.10021	
Place attachment	Lancry	94	3.52	0.67531	0.06965	4.495 ***
	La Défense	70	3.04	0.69590	0.08318	
Commercial activities	Lancry	94	2.80	1.08039	0.11143	2.956 ***
	La Défense	70	2.31	1.02918	0.12301	
Duration of residence	Lancry	94	13.38	11.51913	1.18811	1.931 *
	La Défense	70	10.54	7.25456	0.86709	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.2. Path Analysis and Indirect Effects

Path analysis was used to examine the effects of individual factors. Model 1 (Lancry model: $p = 0.303$, CMIN/df = 4.851, RMR = 0.032, RMSEA = 0.048, GFI = 0.983, AGFI = 0.912, NFI = 0.964, IFI = 0.994, CFI = 0.993; La Défense model: $p = 0.882$, CMIN/df = 0.295, RMR = 0.020, RMSEA = 0.000, GFI = 0.994, AGFI = 0.970, NFI = 0.974, IFI = 1.068, CFI = 1.000) is presented in Figure 4. CA (Lancry: $\beta = 0.179$, $p < 0.1$, La Défense: $\beta = 0.340$, $p < 0.01$) had a positive effect on SB, and SB (Lancry: $\beta = 0.660$, $p < 0.01$, La Défense: $\beta = 0.226$, $p < 0.1$) positively affected PA in both sites. However, the relationship between CA and PA is significant only in Lancry ($\beta = 0.124$, $p < 0.1$).

SCI and SCQ did not have significant relationships with CA in either site, but they did affect PA in the Lancry model (SCI: $\beta = 0.146$, $p < 0.1$, SCQ: $\beta = 0.161$, $p < 0.05$). On the contrary SNF ($\beta = 0.253$, $p < 0.05$) affected PA only in the La Défense model.

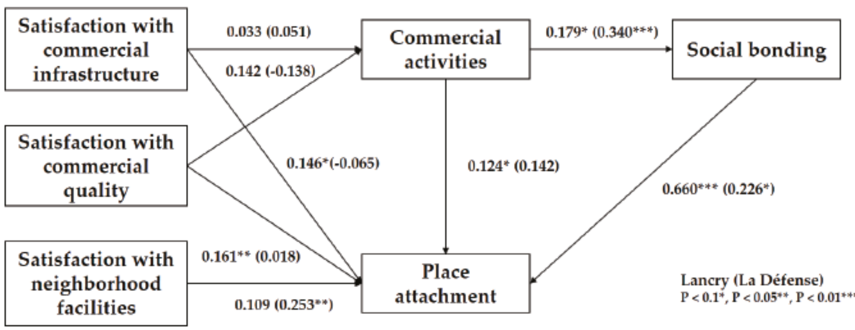


Figure 4. Path analysis of model 1.

Figure 5 presents a path analysis of model 2 for the two sites ($p = 0.003$, CMIN/df = 3.275, RMR = 0.025, RMSEA = 0.118, GFI = 0.968, AGFI = 0.849, NFI = 0.883, CFI = 0.907). The results show what factors affect CA. In this model, only CT ($\beta = 0.215$, $p < 0.01$) had positive effects on CA, while commercial satisfaction (e.g., SCI and SCQ) did not significantly affect CA. Further, CA affected SB ($\beta = 0.272$, $p < 0.01$), while PA ($\beta = 0.186$, $p < 0.01$) and SB ($\beta = 0.305$, $p < 0.01$) significantly affected PA. Especially, the relationship between CA and PA here is stronger than that in model 1; the reason for this is the variability of CA was expanded by combining the data of the two sites.

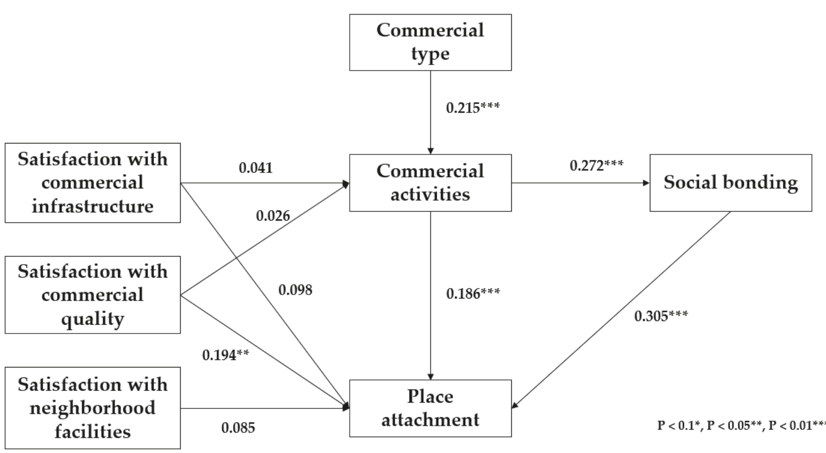


Figure 5. Path analysis of model 2.

Table 5 shows the indirect effects of CA through SB on PA. Analysis was conducted using two-tailed significance in Amos. First, in the Lancry case, the indirect effect of the path CA → SB → PA was 0.118 ($p < 0.05$), which was significant. In the La Défense, the indirect effect of CA → SB → PA was 0.076 ($p < 0.05$). Last, in the combined model, the indirect effect of CT → SB → PA was 0.083 ($p < 0.01$), which was statistically significant.

Table 5. Analysis of indirect effects.

Model	Site	Path	Direct Effects	Indirect Effects	Total Effects
1	Lancry	CA → SB → PA	0.124	0.118 **	0.242
	La Défense	CA → SB → PA	0.142	0.076 **	0.218
2	Two sites	CA → SB → PA	0.186	0.083 ***	0.269

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5. Discussion

Previous studies have mainly focused on the satisfaction of residents with a specific place in terms of the relationship between the neighborhood environment and PA. In contrast, this study finds that CT, which is the physical form of certain distinguishing characteristics in a neighborhood, affects the activities of people (such as CA) and that CA positively affects SB and PA. Place attachment (PA) refers to the emotions that a person has in connection to a specific place and his or her experience of activities therein. Accordingly, it was necessary to discuss not only people's primary satisfaction with the physical space, but also whether the characteristics of the physical environment led to certain types of human activity, thereby affecting level of PA. Therefore, this study analyzed the CT and CA, as well as SCI and SCQ as influencing factors of place attachment. The results are as follows.

First, PA was influenced by the satisfaction factors of the neighborhood environment, and PA differed in each case according to the neighborhood characteristics. Model 1 showed that Lancry and La Défense had different factors that influenced PA. Further, note that PA is a complicated emotion that is influenced by various factors. Therefore, high satisfaction with neighborhood environments can affect PA. In the case of Lancry, satisfaction with the commercial environment (SCI and SCQ) had a positive effect on PA because of the high density of shops and high accessibility. On the other hand, La Défense is a new city with appropriate walking areas (i.e., without cars), parks, green areas, and cultural facilities that have been well developed, thus, the neighborhood environment satisfaction (SNF) positively influenced PA.

Second, analysis of the neighborhood CT considering street shops and malls supports our hypothesis presented herein. It was confirmed that CT affects the CA of residents, however commercial satisfaction (SCI and SCQ) did not affect CA; this indicates that commercial satisfaction can improve the PA of people through emotional means, especially through the use of spaces. However, PA does not alter the pattern of shopping in daily life because people typically only buy products when they are needed. This finding confirmed that, in part, the higher value of CA of residents was found in the neighborhood with street shops than in the neighborhood with malls. From the standpoint of neighborhood design, this result shows that different types of commercial structures can produce different patterns of daily life in neighborhood residents. In a neighborhood with street shops, with a high shopping frequency, CT acts as a factor that increases opportunities among residents to meet with one another relative to these opportunities in neighborhoods with other commercial features. Therefore, it is expected that SB will increase in neighborhoods with street shops as well as the promotion of local affection among residents. This expectation is supported by the finding that CA has a positive effect on SB. Increased levels of activity lead to the accumulation of neighborhood experiences with other residents, which leads to the formation of bonds between locals and place attachment.

Finally, the most important factor in this study is the "activities" element. The results show that increased SB of residents is due to the CA of residents, which depends on the CT of neighborhoods. As a result of this study, we see that SB ultimately positively affects residents' PA to a neighborhood. The reason why SB is important in PA is not only the feelings of attachment that people have to a specific place, but also because the emotions felt by people identifying as members of a community through their relationships with neighbors is a factor in the formation of PA. The results show that SB has the greatest direct effect on PA ($\beta = 0.278$). Further, the mediating effects between CA and PA show the importance of SB in PA.

6. Conclusions

The results of this study confirm that the CA among people in neighborhoods is an influencing factor with respect to the SB and PA of local residents, and that CA can be varied by changing CT. Based on the results of the study, two measures could be proposed as measures to increase place attachment in locals for sustainable neighborhood environments. The accumulation of experiences in places and bonding among local people are the methods whereby place attachment is formed. These are items that can be promoted based on the activities of residents in a neighborhood. In particular, this study analyzes the daily activities of residents in terms of their commercial activities, which provides implications for community and neighborhood design with regard to commercial features. The commercial environments of neighborhoods and the commercial activities occurring therein are basic activities in the daily lives of people. Until now, the focus on commercial features in urban design and neighborhood environments has been solely on physical quality and satisfaction. However, the results of the study demonstrate that the commercial environment is not simply a place to facilitate purchase transactions among residents. The commercial environment is an important factor that increases bonding among the people in neighborhoods and strengthens the attachment of locals to their place.

In order to promote the commercial activities of residents in neighborhoods, it is necessary to design neighborhoods that consist of small-scale stores rather than large-scale mall-type stores. However, current commercial spaces are becoming larger than ever. As a result of the decline of small-scale stores—a potential place for interaction and communication among locals—opportunities for exchange activities among residents have decreased. In addition, when small-scale merchants are replaced by large shopping malls, independent stores with diverse personalities tend to disappear. Over time, the unique characteristics of each trade will be replaced by the uniformity of commercial franchises. From the point of view of residents, favorite shops are disappearing, and there are fewer places where they want to go. This can have a negative impact on the formation of place attachment, as the appealing features of neighborhood local commerce are lost.

In order to create neighborhoods that people want to live in, place attachment via social bonding should be strengthened, and urban design that increases the activities of residents in neighborhoods should be reflected. From this point of view, this study suggests that small commercial spaces, such as street shops, are more effective than large malls in enhancing local attachment.

Author Contributions: B.K. conceived the idea and designed this research. J.P. developed the idea for academic research and reviewed the manuscript as a corresponding author. All authors carried out data collection and analysis, and drafted the manuscript.

Acknowledgments: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A1A09000940) and modified based on "Effects of Commercial Environment on Community and Place Attachment in Neighborhoods", 2016 Spring Congress Korea Planning Association (proceeding), Seoul, Korea.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

PA	Place attachment
SB	Social bonding
CA	Commercial activities
CT	Commercial type
SCI	Satisfaction with commercial infrastructure
SCQ	Satisfaction with commercial quality
SNF	Satisfaction with neighborhood facilities

References

1. Low, S.M.; Altman, I. Place attachment. In *Place Attachment*; Springer: Boston, MA, USA, 1992; pp. 1–12.
2. Hidalgo, M.C.; Hernandez, B. Place attachment: Conceptual and empirical questions. *J. Environ. Psychol.* **2001**, *21*, 273–281. [CrossRef]
3. Bailey, N.; Kearns, A.; Livingston, M. Place attachment in deprived neighbourhoods: The impacts of population turnover and social mix. *Hous. Stud.* **2012**, *27*, 208–231. [CrossRef]
4. Liu, Y.Q.; Wu, F.L.; Liu, Y.; Li, Z.G. Changing neighbourhood cohesion under the impact of urban redevelopment: A case study of Guangzhou, China. *Urban Geogr.* **2017**, *38*, 266–290. [CrossRef]
5. Kim, D. A Study on the Place Attachment of Residential Environment-Focused on Multilevel Analysis Using SEM and HLM. Ph.D. Thesis, Seoul National University, Seoul, Korea, 2008.
6. Lewicka, M. Place attachment: How far have we come in the last 40 years? *J. Environ. Psychol.* **2011**, *31*, 207–230. [CrossRef]
7. Kaltenborn, B.P.; Bjerke, T. Associations between landscape preferences and place attachment: A study in Røros, Southern Norway. *Landsc. Res.* **2002**, *27*, 381–396. [CrossRef]
8. Brown, G.; Brown, B.B.; Perkins, D.D. New housing as neighborhood revitalization-place attachment and confidence among residents. *Environ. Behav.* **2004**, *36*, 749–775. [CrossRef]
9. Choi, E.; Yim, H. The perception and the determinants of place attachment. *J. Korea Plan. Assoc.* **2005**, *40*, 53–64.
10. Zhu, Y.S.; Breitung, W.; Li, S.M. The changing meaning of neighbourhood attachment in Chinese commodity housing estates: Evidence from Guangzhou. *Urban Stud.* **2012**, *49*, 2439–2457. [CrossRef]
11. Park, J.; Kim, B. Influence of residents' attachment to the community on participation in community-building activities-focusing on hannam 1 dong. *J. Urban Des. Insit. Korea* **2014**, *15*, 215–226.
12. Hernandez, B.; Hidalgo, M.C.; Salazar-Laplace, M.E.; Hess, S. Place attachment and place identity in natives and non-natives. *J. Environ. Psychol.* **2007**, *27*, 310–319. [CrossRef]
13. Nielsen-Pincus, M.; Hall, T.; Force, J.E.; Wulfhorst, J.D. Sociodemographic effects on place bonding. *J. Environ. Psychol.* **2010**, *30*, 443–454. [CrossRef]
14. Handy, S.L.; Boarnet, M.G.; Ewing, R.; Killingsworth, R.E. How the built environment affects physical activity-views from urban planning. *Am. J. Prev. Med.* **2002**, *23*, 64–73. [CrossRef]
15. Saelens, B.E.; Sallis, J.F.; Black, J.B.; Chen, D. Neighborhood-based differences in physical activity: An environment scale evaluation. *Am. J. Public Health* **2003**, *93*, 1552–1558. [CrossRef] [PubMed]
16. Rosenberg, D.; Ding, D.; Sallis, J.F.; Kerr, J.; Norman, G.J.; Durant, N.; Harris, S.K.; Saelens, B.E. Neighborhood environment walkability scale for youth (news-y): Reliability and relationship with physical activity. *Prev. Med.* **2009**, *49*, 213–218. [CrossRef] [PubMed]
17. Van Dyck, D.; Cardon, G.; Deforche, B.; Sallis, J.F.; Owen, N.; De Bourdeaudhuij, I. Neighborhood SES and walkability are related to physical activity behavior in belgian adults. *Prev. Med.* **2010**, *50* (Suppl. 1), S74–S79. [CrossRef] [PubMed]
18. Ding, D.; Sallis, J.F.; Kerr, J.; Lee, S.; Rosenberg, D.E. Neighborhood environment and physical activity among youth a review. *Am. J. Prev. Med.* **2011**, *41*, 442–455. [CrossRef] [PubMed]
19. Cerin, E.; Macfarlane, D.J.; Ko, H.H.; Chan, K.C.A. Measuring perceived neighbourhood walkability in Hong Kong. *Cities* **2007**, *24*, 209–217. [CrossRef]
20. Shigematsu, R.; Sallis, J.F.; Conway, T.L.; Saelens, B.E.; Frank, L.D.; Cain, K.L.; Chapman, J.E.; King, A.C. Age differences in the relation of perceived neighborhood environment to walking. *Med. Sci. Sports Exerc.* **2009**, *41*, 314–321. [CrossRef] [PubMed]
21. Williams, D.R.; Roggenbuck, J.W. Measuring Place Attachment: Some Preliminary Results. Available online: https://www.fs.fed.us/rm/value/docs/nrpa89.pdf (accessed on 18 May 2018).
22. Proshansky, H.M. The city and self-identity. *Environ. Behav.* **1978**, *10*, 147–169. [CrossRef]
23. Yoon, Y.; Kwock, Y. Residents' place attachment in evaluating tourism destination. *J. Hotel Resort* **2005**, *4*, 511–525.
24. Lee, E. The intrinsic attributes of place attachment: In case of a poem Dashi Elle ege (to Elle again). *J. Cult. Hist. Geogr.* **2006**, *18*, 1–10.

25. Li, X.; Kleinhans, R.; van Ham, M. *Ambivalence in Place Attachment: The Lived Experiences of Residents in Declining Neighbourhoods Facing Demolition in Shenyang, China*; IZA Institute of Labor Economics: Bonn, Germany, 2017.
26. Lewicka, M. What makes neighborhood different from home and city? Effects of place scale on place attachment. *J. Environ. Psychol.* **2010**, *30*, 35–51. [CrossRef]
27. Bonaiuto, M.; Aiello, A.; Perugini, M.; Bonnes, M.; Ercolani, A.P. Multidimensional perception of residential environment quality and neighbourhood attachment in the urban environment. *J. Environ. Psychol.* **1999**, *19*, 331–352. [CrossRef]
28. Pretty, G.H.; Chipuer, H.M.; Bramston, P. Sense of place amongst adolescents and adults in two rural Australian towns: The discriminating features of place attachment, sense of community and place dependence in relation to place identity. *J. Environ. Psychol.* **2003**, *23*, 273–287. [CrossRef]
29. Norman, G.J.; Nutter, S.K.; Ryan, S.; Sallis, J.F.; Calfas, K.J.; Patrick, K. Community design and access to recreational facilities as correlates of adolescent physical activity and body-mass index. *J. Phys. Act. Health* **2006**, *3*, S118–S128. [CrossRef] [PubMed]
30. Pate, R.R.; Colabianchi, N.; Porter, D.; Almeida, M.J.; Lobelo, F.; Dowda, M. Physical activity and neighborhood resources in high school girls. *Am. J. Prev. Med.* **2008**, *34*, 413–419. [CrossRef] [PubMed]
31. Nagel, C.L.; Carlson, N.E.; Bosworth, M.; Michael, Y.L. The relation between neighborhood built environment and walking activity among older adults. *Am. J. Epidemiol.* **2008**, *168*, 461–468. [CrossRef] [PubMed]
32. Wood, L.; Frank, L.D.; Giles-Corti, B. Sense of community and its relationship with walking and neighborhood design. *Soc. Sci. Med.* **2010**, *70*, 1381–1390. [CrossRef] [PubMed]
33. Leyden, K.M. Social capital and the built environment: The importance of walkable neighborhoods. *Am. J. Public Health* **2003**, *93*, 1546–1551. [CrossRef] [PubMed]
34. Kim, J.; Kaplan, R. Physical and psychological factors in sense of community-new urbanist kentlands and nearby orchard village. *Environ. Behav.* **2004**, *36*, 313–340. [CrossRef]
35. KelQuartier. Available online: http://www.kelquartier.com/ile_de_france_paris_paris_10_quartier_chateau_d_eau_lancry_75010-q100518/revenu_moyen.html (accessed on 18 May 2018). (In France)
36. KelQuartier. Available online: http://www.kelquartier.com/ile_de_france_hauts_de_seine_puteaux_quartier_la_defense_92800-q100352/revenu_moyen.html (accessed on 18 May 2018). (In France)
37. Kang, S. *The Impact of Community Attachment on the Attitudes toward Tourism Development*; Hanyang: Seoul, Korea, 2001.

sustainability

MDPI

Article

Analysis of Embodied Environmental Impacts of Korean Apartment Buildings Considering Major Building Materials

Seungjun Roh [1], Sungho Tae [1,2,*] and Rakhyun Kim [3,*]

[1] Sustainable Building Research Center, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan 15588, Korea; roh.seungjun@gmail.com

[2] Department of Architecture & Architectural Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan 15588, Korea

[3] Architectural Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan 15588, Korea

* Correspondence: jnb55@hanyang.ac.kr (S.T.); redwow6@hanyang.ac.kr (R.K.); Tel.: +82-31-400-5187 (S.T.); +82-31-436-8076 (R.K.)

Received: 7 April 2018; Accepted: 12 May 2018; Published: 23 May 2018

Abstract: Because the reduction in environmental impacts (EIs) of buildings using life-cycle assessment (LCA) has been emphasized as a practical strategy for the sustainable development of the construction industry, studies are required to analyze not only the operational environmental impacts (OEIs) of buildings, but also the embodied environmental impacts (EEIs) of building materials. This study aims to analyze the EEIs of Korean apartment buildings on the basis of major building materials as part of research with the goal of reducing the EIs of buildings. For this purpose, six types of building materials (ready-mixed concrete, reinforcement steel, concrete bricks, glass, insulation, and gypsum) for apartment buildings were selected as major building materials, and their inputs per unit area according to the structure types and plans of apartment buildings were derived by analyzing the design and bills of materials of 443 apartment buildings constructed in South Korea. In addition, a life-cycle scenario including the production, construction, maintenance, and end-of-life stage was constructed for each major building material. The EEIs of the apartment buildings were quantitatively assessed by applying the life-cycle inventory database (LCI DB) and the Korean life-cycle impact assessment (LCIA) method based on damage-oriented modeling (KOLID), and the results were analyzed.

Keywords: embodied environmental impact; apartment building; major building material; life-cycle assessment

1. Introduction

With the rising importance of sustainable development, efforts have been made in all industrial areas to reduce environmental impacts (EIs) [1–5]. In line with this, the construction industry has focused its research on cutting-edge technologies (e.g., highly efficient insulating materials, high-performance glass, high-air-tightness windows, and renewable energy systems) capable of dramatically reducing the energy consumption of a building during its operation stage in order to decrease operational environmental impacts (OEIs), which account for over 70% of the EIs of conventional buildings [6–10]. As a result, zero-energy buildings—energy-efficient buildings that use little energy during their operation stage—have been developed and successfully constructed in many countries [11–15].

As technologies to reduce the OEIs of buildings have been commercialized, research on the life-cycle assessment (LCA) of buildings—which considers the reduction in the OEIs of buildings as well as in the embodied environmental impacts (EEIs) caused by the production, construction, maintenance, and end-of-life stages of the building materials used—has been emphasized recently [16–22]. This is because additional building materials may be necessary for energy-efficient buildings compared with conventional buildings, thus increasing EEIs, but decreasing OEIs [17]. Results of previous LCAs of energy-efficient buildings showed that EEIs were higher than OEIs [23,24]. Hence, more research is necessary to assess and reduce the EEIs of buildings, as the importance and influence of EEIs have gradually increased [25,26].

Some of the previous studies on the analysis of EEIs are important in terms of their approach, methodology, and case studies [27–33]. Because they mostly analyzed only carbon emissions during the production stage of the building materials, their use has been limited. Therefore, for a study's results to be used as basic data for reducing the EEIs of buildings, these impacts must be analyzed by considering the following:

- The EEIs of a number of buildings must be analyzed according to the characteristics of those buildings. This is because the results of analyzing the EEIs for one or more buildings cannot be generalized as the EEI characteristics of all buildings.
- The assessment target must be expanded from carbon emissions to other EI categories. To achieve sustainable development, it is necessary to address not only global warming due to carbon emissions but also various other global environmental problems [34].
- The scope of assessment must be extended from the building material's production stage to a life-cycle perspective. This is because the overall EEIs of buildings must be examined quantitatively to be reduced [35].
- The EEI assessment results of buildings must be analyzed from a building-material perspective. In this way, EEIs can be reduced by identifying building materials that have the greatest influence on these EEIs.
- EIs must be assessed not only for EI categories, but also for safety guards. This is because the end-point-level damage to humans and ecosystems by each EI must be identified.

Therefore, the aim of this study is to analyze the EEIs of Korean apartment buildings on the basis of major building materials as part of research with the goal of reducing the life-cycle environmental impacts (LCEIs) of buildings.

2. Background

2.1. Embodied Environmental Impact

The LCEIs of buildings can be divided into EEIs and OEIs [24,27]. The EEIs of buildings correspond to the LCEIs excluding the EIs caused by energy consumption (e.g., heating, cooling, hot water, lighting, and ventilation). In other words, EEIs include EIs that arise from the building-material production stage and the building construction, maintenance, and end-of-life stages. EEIs for a building are calculated using Equation (1):

$$EEI = EI_{PS} + EI_{CS} + EI_{MP} + EI_{ES}, \tag{1}$$

where EEI denotes the life-cycle embodied environmental impact (LCEEI) of the building. EI_{PS}, EI_{CS}, EI_{MP}, and EI_{ES} are the EEIs of the building-material production stage, and the building construction, maintenance, and end-of-life stages.

2.2. Environmental Impact Categories

EI categories represent global environmental changes caused by human behavior or technology. Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), and abiotic depletion potential (ADP) are representative EI categories, which can be assessed quantitatively through various life-cycle impact assessment (LCIA) methodologies [36,37].

GWP represents climate change, that is, the rise in average temperatures of the earth's atmosphere, and causes environmental problems because of changing ecosystems in soil or water, or because of rising sea levels. AP represents the acidification of water and soil, mainly by the circulation of pollutants, threatening the survival of living organisms such as fish, plants, and animals. EP represents the harmful impacts on the marine environment, such as red tides resulting from the amount of nutrients abnormally increasing through the introduction of chemical fertilizers or sewage. ODP is a phenomenon in which the ozone in the ozone layer—located in the stratosphere 15–30 km above the ground—is destroyed and its density decreases. It can lead to diseases such as skin cancer because of the increase in ultraviolet radiation. POCP is a reaction between air pollutants and sunlight in which chemical compounds such as ozone (O_3) are created, in turn causing damage to ecosystems and human health and inhibiting the growth of crops. ADP represents the cause behind the destruction of ecosystem balance and environmental pollution caused by the excessive collection and consumption of resources.

2.3. Safety Guard and Damage Index

From an environmental ethics perspective, the "safety guard" represents the environment that the human race must protect. It can be classified into human and ecosystem items. The human items are divided into human health, which is required for humans to live a healthy life, and social assets, which support human society. The ecosystem items can be subdivided into biodiversity, which refers to the preservation of animals and plants, and primary production, which is essential for maintaining biodiversity [38].

The damage index quantifies the damage to the aforementioned safety guard (human health, social assets, biodiversity, and primary production) caused by EIs. For assessing damages to human health, disability-adjusted life years (DALY) are used. DALY is a damage index representing the number of years of healthy life lost as a result of EIs. For social assets, the mean economic cost (USD) for the suppression and depletion of crops; fossil fuels; and fishery, forest, and mineral resources is used. In addition, biodiversity is assessed through the expected increase in the number of extinct species (EINES) damage index, that is, the expected number of extinct species of vascular and aquatic plants. For primary production, the net primary production (NPP) is used as a damage index, assessing the amount ($kg/m^2 \cdot y$) of organic matter created by the photosynthesis of land plants and marine plankton. The damage index for each safety guard can be assessed through the end-point-level LCIA methodology, which systematizes damage indexes for each safety guard using research results from natural sciences. Figure 1 is an example of the LCIA method at the end-point level [39]. It shows the structures and degrees of the impacts of GWP caused by 1 ton of CO_2 emission on human health and social assets as safety guards. According to Figure 1, GWP caused by 1 ton of CO_2 emission adversely affects heat stress, exposure to infectious diseases, malnutrition, disaster damage, energy consumption, and agricultural production at the end-point level and ultimately causes a damage of 1.23×10^{-4} DALY and 2.5 USD to human health and social assets, respectively.

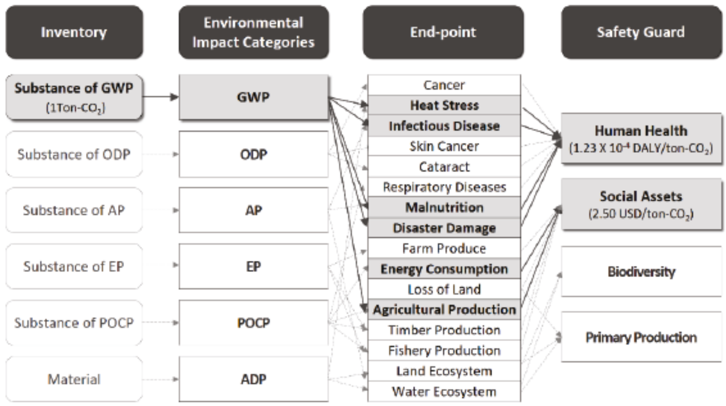


Figure 1. Example of the evaluation method for life-cycle environmental impacts (LCEIs) at the end-point level [38].

3. Materials and Methods

The section details the assessment of the EEIs of Korean apartment buildings on the basis of the major building materials using the sequential LCA methodology. For this purpose, in the goal and scope definition stage, the purpose of LCA and the scope of the system were defined. In the life-cycle inventory (LCI) analysis stage, the average inputs per unit area of major building materials were derived according to the structure types and plans of apartment buildings by analyzing the design and bills of materials of apartment buildings constructed in South Korea. In addition, a life-cycle scenario including the production, construction, maintenance, and end-of-life stage was constructed for each of the major building materials. In the LCIA stage, the EEIs of the six impact categories and damage indexes for each safety guard were quantitatively assessed by applying the life-cycle inventory database (LCI DB) and the Korean LCIA method based on damage-oriented modeling (KOLID) [38], an end-point-level LCEI assessment methodology.

3.1. Goal and Scope Definition

The purpose of performing LCA in this study was to analyze the EEIs of Korean apartment buildings on the basis of major building materials. As for a system boundary, building material production, the building construction, maintenance, and end-of-life stages were included, and six EI categories (GWP, AP, EP, ODP, POCP, and ADP) and four safety guards (human health, social assets, biodiversity, and primary production) were evaluated. Gross floor area (m^2) was established as the functional unit. The criteria used to determine the quality of the LCA results were classified into temporal, regional, and technical ranges, as described in Table 1. Furthermore, the building material inputs were analyzed on the basis of the building material quantities applied to the ground floor of the apartment buildings, and it was assumed that the total quantities of building materials specified in the bills of materials were used in the buildings.

Table 1. Data quality criteria.

Classification	Temporal Ranges	Regional Ranges	Technical Ranges
Internal data (Bills of materials)	Bills of materials prepared at the commencement of the work	Bills of materials prepared in South Korea	Six major building materials listed in the bills of materials
External data (LCI DB)	Latest LCI DB	LCI DB constructed in South Korea and Germany	LCI DB of same or similar building materials

3.2. Life-Cycle Inventory Analysis

3.2.1. Selection of Major Building Materials

To analyze the EEIs of buildings more efficiently, it is necessary to select building materials with the highest EIs. The construction of buildings includes more complex procedures than the production processes for general products, and the EEI analysis requires excessive time and labor, as more than 1000 building materials can be used in a construction project.

Therefore, this study analyzed the EEIs of apartment buildings using results from previous research [39] that derived six major building materials (ready-mixed concrete, reinforcement steel, concrete bricks, glass, insulation, and gypsum) accounting for over 95% of the six EI categories (GWP, AP, EP, ODP, POCP, and ADP) in accordance with the cut-off criteria of ISO 14040, an international standard for LCA.

3.2.2. Analysis of Major Building Material Inputs

A total of 443 apartment buildings in South Korea were selected as samples, and the inputs per unit area of the six major building materials were analyzed according to the structure types and plans of the apartment buildings. In this case, the structure types were divided into wall structures, frame structures, and flat plate structures, and the plans were classified into plate, tower, and mixed types. Table 2 lists the number of samples, and Table 3 represents the average input quantities per unit area of the major building materials according to the structure types and plans of the apartment buildings.

Table 2. Number of samples.

Classification	Wall Structure	Rigid Frame Structure	Flat Plate Structure
Plate type	118	22	6
Tower type	101	40	22
Mixed type	60	64	10

Table 3. Average input quantity of building materials by structure types and plans of apartment building.

Classification	Unit	Wall Structure			Rigid Frame Structure			Flat Plate Structure		
		Plate Type	Tower Type	Mixed Type	Plate Type	Tower Type	Mixed Type	Plate Type	Tower Type	Mixed Type
Ready-mixed concrete	m^3/m^2	0.77	0.73	0.75	0.71	0.60	0.70	0.68	0.58	0.68
Rebar	kg/m^2	98.13	101.35	99.92	118.34	145.26	131.55	127.52	158.40	149.24
Concrete brick	kg/m^2	90.87	90.81	86.52	90.52	89.98	86.89	89.77	88.85	85.54
Glass	kg/m^2	5.87	5.99	5.99	5.87	6.12	5.61	5.74	5.74	5.99
Insulation	kg/m^2	1.56	1.48	1.58	1.62	1.57	1.60	1.44	1.40	1.49
Gypsum board	kg/m^2	2.63	2.68	2.67	2.66	2.72	2.65	2.50	2.69	2.62

3.2.3. Construction of the Life-Cycle Scenario

For the analysis of LCEEIs, the EEIs of the six major building materials with the highest EIs were assessed in the production stage, and a life-cycle scenario was constructed so that the EEIs could be assessed in the construction, maintenance, and end-of-life stages on the basis of the major building material inputs in the production stage [40]. Figure 2 shows the case of ready-mixed concrete as an example of the EEI assessment on the basis of the constructed life-cycle scenario.

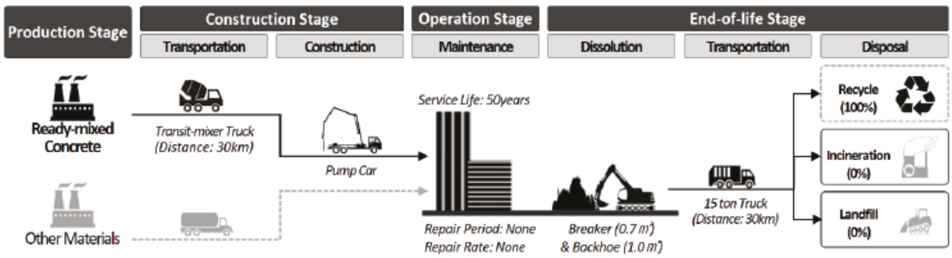


Figure 2. Example of scenario-based embodied environmental impact (EEI) evaluation.

(1) Production stage:

In the production stage, the EIs arising from the production of building materials are assessed. In this study, the EIs of the production stage were assessed using the average inputs per unit area of the six major building materials (ready-mixed concrete, reinforcement steel, glass, concrete bricks, insulation, and gypsum) derived from previous research in accordance with the cut-off criteria of LCA.

(2) Construction stage:

The construction stage is divided into the transportation process of building materials and the construction process of buildings.

In the transportation process, building materials are transported from their production sites to the construction site. In this study, freight vehicles for each of the major building materials were selected as shown in Table 4 on the basis of the standard estimation system for construction works [41]. In addition, the transport distance was assumed to be 30 km for all of the major building materials.

Table 4. Freight vehicles.

Classification	Ready-Mixed Concrete	Rebar	Others
Freight vehicle	Transit-mixer truck	20 ton truck	8 ton truck

The construction stage represents the EIs caused by the use of equipment during construction, and it was assessed using the LCI DB for the unit of construction work for each building material.

(3) Maintenance stage:

In the maintenance stage, the EIs arising from the production and transport of building materials that are periodically replaced in order to recover the status of aging buildings during their service life are assessed. In this study, the service life of buildings was set to 50 years, in accordance with the upper limit of the standard service life of the Enforcement Regulations of the Corporate Tax Act of Korea [42]. In addition, the EIs of the maintenance stage were assessed using the repair period and rate for each building material suggested by the standards for the formulation of the long-term repair plan in the Enforcement Regulations of the Multi-Family Housing Management Act of Korea. In other words, it was assumed that ready-mixed concrete, reinforcement steel, concrete bricks, glass, and insulation, among the selected six major building materials, were not replaced during the service life of the buildings and that 100% of the gypsum boards were replaced every 20 years.

(4) End-of-life stage:

The end-of-life stage is divided into the demolition process, the transportation process of waste building materials, the incineration process, and the landfill process.

In the dissolution process, the EIs of the equipment and machinery used for building demolition are assessed through fuel efficiency (diesel consumption per unit of work) information of the demolition machines after the number of machines is calculated on the basis of the amount of waste material generated in the demolition process. In this study, it was assumed that both crushers (0.7 m^3) and backhoes (1.0 m^3) were used as demolition equipment [19] and that the amount of waste material generated in the demolition process was the same as the input quantities of the six major building materials in the production stage.

In the transportation process, the EIs arising from transporting the waste materials generated in the demolition process to recycling centers, incineration plants, or landfills are assessed. In this case, it was assumed that the waste building materials were transported using 15 ton trucks in accordance with the standard estimation system for construction works [41] and that the distances from the demolition site to recycling centers, incineration plants, and landfills were 30 km.

In the end-of-life process, the EIs arising from incinerating or landfilling waste materials are assessed. In this study, the cut-off method imposed on recycling companies was applied to the EIs of the waste material recycling process, and only the EIs of the incineration and landfilling of non-recycled waste materials were assessed. For this, the construction waste processing data from waste statistics [43] published by the Korean Environmental Industry and Technology Institute were investigated, and the recycling, incineration, and landfill rates of each major building material were applied as shown in Table 5.

Table 5. Processing ratios of waste building materials.

Classification	Recycle Ratio (%)	Incineration Ratio (%)	Landfill Ratio (%)
Waste concrete	100.0	0.0	0.0
Waste rebar	100.0	0.0	0.0
Waste concrete brick	100.0	0.0	0.0
Waste glass	79.0	0.0	21.0
Waste insulation	46.7	53.3	0.0
Waste gypsum board	62.7	0.2	37.1

3.3. Life-Cycle Impact Assessment

3.3.1. Application of the LCI DB

For the assessment of LCEEIs, the LCI DBs for building materials used in buildings, freight vehicles for transporting building materials and waste materials, unit construction work for each building material, and incineration and landfill processes of waste materials must be applied.

In this study, LCI DBs were applied in the order of the Korean LCI DB [44] of the Ministry of Trade, Industry and Energy and the Ministry of Environment (ME) of South Korea; the National Database on Environmental Information of Building Materials of the Korean Institute of Civil Engineering and Building Technology [45]; and Oekobaudat [46] of Germany, considering regional, temporal, and technical correlations, which are the LCI DB selection criteria for LCA suggested by ISO 14040 (refer to Table 6). Furthermore, the EEIs of the six EI categories were assessed through the multiplication of the activity and the EI factor, as shown in Equation (2):

$$EI_i = \sum_{j=1}^{n} \left(A_j \times EF_{i,j}\right), \quad (2)$$

where EI_i are the EEIs of EI category (i), A_j are the building material and energy input quantity for activity (j), and $EF_{i,j}$ is the EI factor of EI category (i) for activity (j).

Table 6. Environmental impact (EI) factors.

Classification		Unit	GWP	AP	EP	ODP	POCP	ADP	Ref.
			kg CO_{2eq}/ Unit	kg SO_{2eq}/ Unit	kg $PO_4{}^{3-}{}_{eq}$/ Unit	kg $CFC11_{eq}$/ Unit	kg C_2H_{4eq}/ Unit	kg Sb_{eq}/ Unit	
Production stage	Ready-mixed concrete	m^3	4.09×10^{2}	6.82×10^{-1}	7.96×10^{-2}	4.65×10^{-5}	1.10×10^{0}	2.04×10^{0}	Ⓐ
	Rebar	kg	4.38×10^{-1}	1.40×10^{-3}	1.79×10^{-4}	1.04×10^{-8}	3.41×10^{-4}	2.79×10^{-3}	Ⓐ
	Concrete brick	kg	1.23×10^{-1}	1.56×10^{-4}	2.26×10^{-5}	4.71×10^{-9}	3.82×10^{-5}	3.02×10^{-4}	Ⓑ
Construction stage	Transit-mixer truck	$m^3 \times$ km	6.74×10^{-1}	6.50×10^{-3}	1.03×10^{-3}	2.44×10^{-7}	1.12×10^{-3}	4.47×10^{-3}	Ⓑ
	8 ton truck	kg $\times$ km	2.88×10^{-6}	2.17×10^{-8}	3.86×10^{-9}	1.06×10^{-12}	6.45×10^{-9}	1.94×10^{-8}	Ⓐ
End-of-life stage	Diesel	kg	6.82×10^{-2}	1.40×10^{-4}	9.55×10^{-6}	1.26×10^{-10}	1.18×10^{-5}	2.16×10^{-2}	Ⓐ
	Construction waste dumping	kg	6.05×10^{-2}	8.52×10^{-5}	1.31×10^{-5}	1.23×10^{-11}	2.21×10^{-5}	5.02×10^{-9}	Ⓒ

Ⓐ: Korean life-cycle inventory database; Ⓑ: National Database on Environmental Information of Building Materials; Ⓒ: Oekobaudat.

3.3.2. Application of KOLID

To calculate direct impacts on humans and ecosystems using the EEI assessment results derived for each EI category, the end-point-level LCIA methodology, which systematizes the damage index for each safety guard using results from natural science research, is required.

In this study, KOLID [38] was applied. KOLID is an end-point-level damage-calculation LCEI assessment methodology developed by the Korean ME in 2009 to better understand the damage caused by environmental issues and to expand the distribution of environmentally friendly products. This methodology quantifies 16 end-point damages, including cancer, infectious disease, and cataract, attributable to the six EI categories (GWP, AP, EP, ODP, POCP, and ADP) triggered by products and services, and it evaluates the four safety guards (human health, social assets, biodiversity, and primary production) (refer to Figure 1). Regional correlations were considered, and the damage index for safety guard objects was quantitatively calculated using the LCEEIs of the apartment buildings. Table 7 shows the safety guards and damage indexes of KOLID, and Equation (3) represents the damage-index calculation formula for each safety guard using KOLID:

$$SI_i = \sum_{j=1}^{n} \left(EI_j \times DF_{i,j}\right), \quad (3)$$

where SI_i is the damage index of safety guard (i), EI_j are the EEIs of EI category (j), and $DF_{i,j}$ is the damage factor of safety guard (i) for EI category (j).

Table 7. Safety guard and damage index of Korean life-cycle impact assessment method based on damage-oriented modeling (KOLID).

Classification	Safety Guard	End Point	Indicator	Damage Factor
GWP	Human health	Mortality damages caused by heat/cold stress, infections, natural disaster damage, and malnutrition	Lost life	1.23×10^{-7} DALY/kg CO_2
	Social assets	Decreases in agricultural production output	Agricultural production output	2.54×10^{-3} USD/kg CO_2
		Changes in energy consumption due to increases in cooling and decreases in heating	Energy consumption quantity	
		Sea-level rising	Land prices	
AP	Human health	Damages caused by asthma and respiratory diseases	Lost life	2.38×10^{-4} DALY/kg SO_2
	Social assets	Decreases in wood production output	Wood production output	4.76×10^{0} USD/kg SO_2
	Primary production	Decreases in primary production output of land plants	Primary production output	2.27×10^{1} kg/kg SO_2

Table 7. *Cont.*

Classification	Safety Guard	End Point	Indicator	Damage Factor
EP	Social assets	Decreases in fishery production output	Fishery production output	2.16×10^{0} USD/kg PO_4^{3-}
ODP	Human health	Damages caused by malignant melanoma, basal cell carcinoma, and spinocellular carcinoma	Lost life	1.35×10^{-3} DALY/kg CFC-11
	Social assets	Decreases in agricultural and wood production output	Agricultural and wood production output	1.21×10^{0} USD/kg CFC-11
	Primary production	Decreases in primary production output of land plants and phytoplankton	Primary production output	2.79×10^{2} kg/kg CFC-11
POCP	Human health	Damages caused by sudden death, asthma, and respiratory diseases	Lost life	3.22×10^{-5} DALY/kg C_2H_4
	Social assets	Decreases in agricultural and wood production output	Agricultural and wood production output	0.77×10^{0} USD/kg C_2H_4
	Primary production	Decreases in primary production output of land plants	Primary production output	2.64×10^{1} kg/kg C_2H_4
ADP	Social assets	Decreases in resource deposits	Users' costs	1.42×10^{1} kg/kg Sb
	Biodiversity	Changes in the composition of plant species	Species changes	1.53×10^{-1} EINES/kg Sb
	Primary production	Land changes, and potential NPP decreases in land use	Primary production output	8.90×10^{-14} kg/kg Sb

4. Results and Discussion

This section describes the assessment of the LCEEIs of the apartment buildings with different structure types and plans, as well as the analysis of the assessment results and characteristics from the perspectives of total EIs, building life-cycle stages, major building materials, and safety guards.

4.1. Analysis of Total Environmental Impacts

Figure 3 shows the results of the LCEEI assessment of the apartments analyzed in this study. According to Figure 3, the EIs of tower-type apartment buildings with a flat plate structure were the lowest for all EI categories, while those of plate-type apartment buildings with a wall structure were the highest. If the reduction in EIs is considered during the apartment building design stage using such characteristics, planning only tower-type apartment buildings with a flat plate structure instead of plate-type buildings with wall structures will reduce the potential EIs of each EI category by between 10.74% and 21.67% (refer to Table 8).

Table 8. Reduction ratio of environmental impacts (EIs).

Classification	Wall Structure, Plate Type	Flat Plate Structure, Tower Type	Reduction Ratio
GWP (kg CO_{2eq}/m^2)	4.18×10^{2}	3.57×10^{2}	14.59%
AP (kg SO_{2eq}/m^2)	9.33×10^{-1}	8.32×10^{-1}	10.83%
EP (kg $PO_4{}^{3-}{}_{eq}/m^2$)	1.21×10^{-1}	1.08×10^{-1}	10.74%
ODP (kg $CFC11_{eq}/m^2$)	5.26×10^{-5}	4.12×10^{-5}	21.67%
POCP (kg C_2H_{4eq}/m^2)	1.01×10^{0}	7.96×10^{-1}	21.19%
ADP (kg Sb_{eq}/m^2)	2.26×10^{0}	1.96×10^{0}	13.27%

The increase or decrease in EIs according to the structure types and plans of the apartment buildings tended to vary relatively regularly for all EI categories. In other words, it was found that the EIs tended to decrease as the structure type changed from a wall structure to frame structures and flat plate structures. Within the same structure type, EIs also varied regularly according to the change in plan. In other words, in wall structures, the EIs of all EI categories decreased as the plan changed from plate to mixed and to tower type. In the flat plate structure, EIs decreased as the plan changed from mixed to plate and to tower type. In the frame structure, the tower type exhibited the lowest EIs despite that changes in some EIs depended on the EI category.

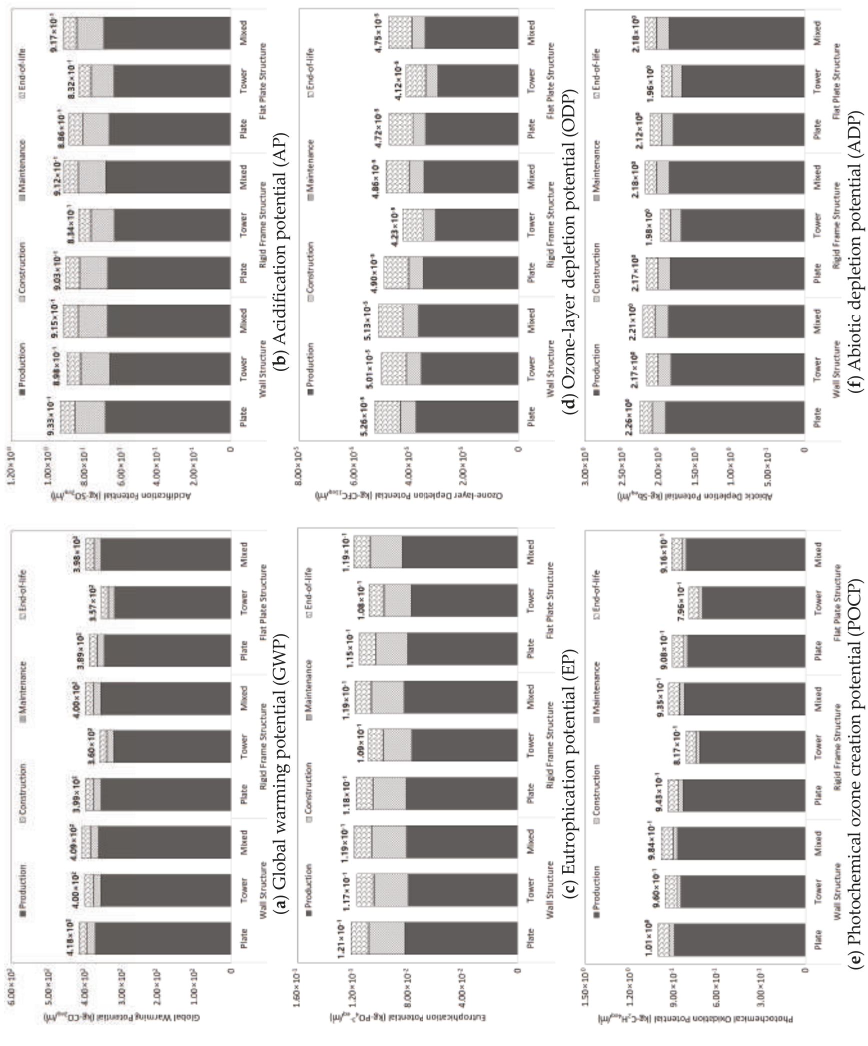


Figure 3. Results of life-cycle embodied environmental impacts (LCEEIs) by life-cycle stages.

4.2. Analysis by Life-Cycle Stage

According to Figure 3, among the LCEEIs of the apartment buildings, the impacts of the production stage were the highest for all EI categories, while those of the maintenance stage were the lowest. In particular, among the overall EEIs assessed in this study, the percentages of EEIs caused by the production stage ranged from 67.96% (EP, wall structure, plate type) to 90.04% (GWP, flat plate structure, tower type), indicating that reducing EEIs during the production stage is imperative for decreasing LCEEIs of apartment buildings.

The percentages of the EEIs caused by the construction stage ranged from 2.94% (POCP, flat plate structure, tower type) to 21.04% (EP, wall structure, plate type) depending on the EI category, and the percentages caused by the end-of-life stage ranged from 5.23% (GWP, flat plate structure, tower type) to 18.29% (ODP, flat plate structure, tower type). In particular, the proportions of EEIs caused by the construction and end-of-life stages were generally higher for the ODP, AP, and EP impact categories. This indicates that the GWP analysis focused on the production stage, which was mainly performed in previous studies, as well as that the EEI analysis, which considers various EI categories, is necessary for reducing EEIs caused by buildings. This confirms that EI reduction strategies in terms of a building's entire life cycle, including production, construction, and end-of-life stages, are indispensable.

4.3. Analysis by Major Building Materials

Figure 4 shows the results of the LCEEI assessment for the major building materials. As shown in the figure, the impacts of ready-mixed concrete were the highest for all EI categories, while those of glass were the lowest. In particular, among the overall EEIs assessed in this study, the percentages of those caused by ready-mixed concrete ranged from 68.13% (EP, flat plate structure, tower type) to 94.75% (ODP, wall structure, plate type). This indicates that the development and application of concrete with reduced EIs, which considerably replaces conventional concrete with supplementary cementitious materials (SCMs), must be performed to reduce the LCEEIs of apartment buildings.

The percentages of EEIs caused by reinforcement steel ranged from 2.83% (ODP, wall structure, plate type) to 27.52% (AP, flat plate structure, tower type) depending on the EI category. In particular, the EEIs of reinforcement steel were inversely proportional to those of ready-mixed concrete. This is because reinforcement steel and ready-mixed concrete are materials that largely constitute the structures of buildings, and thus the input quantity of reinforcement steel relatively decreased as that of ready-mixed concrete increased, depending on the structure types and plans. As such, from the perspective of EI reduction for apartment buildings, it is necessary to design structural materials considering the balance between EEIs of ready-mixed concrete and reinforcement steel.

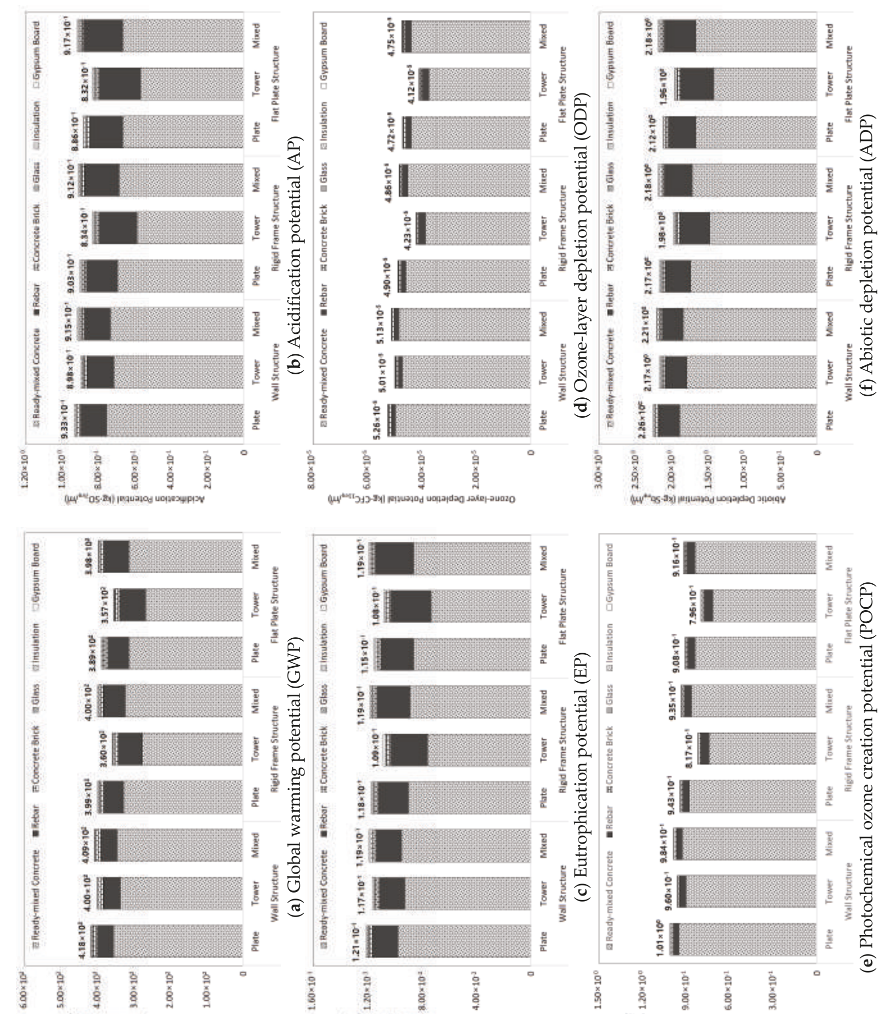


Figure 4. Results of life-cycle embodied environmental impacts (LCEEIs) by major building materials.

4.4. Analysis by Safety Guards

Table 9 shows the results of the damage index assessment by safety guards according to the structure types and plans of the apartment buildings. As can be seen from the figure, the tower-type buildings with a flat plate structure exhibited the lowest damage indexes for all safety guards, while the plate-type buildings with a wall structure showed the highest values. In addition, the increase or decrease in the damage indexes by safety guards tended to vary relatively similarly to how the structure types and plans of the apartment buildings changed regularly for all items. In other words, the damage index by safety guard tended to decrease as the structure type changed from wall structures to frame structures and flat plate structures in the same way as the characteristics of the EI categories changed, as mentioned earlier in Section 4.1: Analysis of Total Environmental Impacts. Furthermore, for wall structures, the damage indexes for all safety guards decreased as the plan changed from plate to mixed and to tower type. In flat plate structures, the damage indexes for safety guards tended to decrease as the plan changed from mixed to plate and to tower type.

Table 9. Results of damage index by safety guard.

Classification	Unit	Wall Structure			Rigid Frame Structure			Flat Plate Structure		
		Plate Type	Tower Type	Mixed Type	Plate Type	Tower Type	Mixed Type	Plate Type	Tower Type	Mixed Type
Human health	DALY/m^2	3.06×10^{-4}	2.94×10^{-4}	3.00×10^{-4}	2.94×10^{-4}	2.69×10^{-4}	2.96×10^{-4}	2.88×10^{-4}	2.68×10^{-4}	2.97×10^{-4}
Social assets	USD/m^2	6.11×10^{0}	5.87×10^{0}	5.99×10^{0}	5.88×10^{0}	5.38×10^{0}	5.92×10^{0}	5.75×10^{0}	5.34×10^{0}	5.93×10^{0}
Biodiversity	EINES/m^2	3.46×10^{-1}	3.32×10^{-1}	3.39×10^{-1}	3.32×10^{-1}	3.03×10^{-1}	3.34×10^{-1}	3.25×10^{-1}	3.01×10^{-1}	3.34×10^{-1}
Primary Production	kg/m^2	5.11×10^{-2}	4.89×10^{-2}	5.00×10^{-2}	4.86×10^{-2}	4.35×10^{-2}	4.86×10^{-2}	4.72×10^{-2}	4.29×10^{-2}	4.83×10^{-2}

4.5. Discussion

As the reduction in the LCEEIs of buildings has been emphasized recently, studies should be carried out to analyze the EEIs of building materials. This is because quantitative values of the LCEEIs of buildings and their major causes must be analyzed first in order to reduce these impacts.

This study provides a significant contribution towards this goal because it presents basic data for reducing the EEIs of buildings by selecting 443 Korean apartment buildings as samples and analyzing their EEIs in terms of six impact categories and damage indexes by safety guards. In particular, the EEIs analyzed in this study according to the structure types and plans of the apartment buildings can be used as factors for easily identifying the EEIs of apartment buildings in construction practice. Furthermore, it appears that the improvement in the environmental performance of ready-mixed concrete, which was found to be the main cause of EEIs, can be utilized as basic data for reducing the EEIs of apartment buildings.

On the other hand, plate-type apartment buildings with a wall structure produced the highest results for all EI categories within the scope of this study, because plate-type apartment buildings with a wall structure used the highest quantity of ready-mixed concrete, which was the most influential in all the EI categories compared to the apartment buildings with other structure types and plans. Therefore, in order to effectively reduce the EEIs of plate-type apartment buildings with a wall structure, it would be effective to apply high-strength concrete to the vertical structural member to reduce the input quantity of ready-mixed concrete and rebar by way of reducing the cross-section. In addition, it is necessary to actively use low-EI concrete that replaces cement, which causes high EIs, with industrial by-products such as fly ash (FA) and ground-granulated blast-furnace slag (GGBS) as a binder for concrete.

This study, however, conducted research only for apartment buildings, not considering various other building types, and the numbers of samples for each structure type and plan were not even a result of difficulty in data collection. In the future, it is necessary to extend the analysis to other building types and improve the reliability and significance of analysis results by securing additional sample data. Moreover, further studies are required to conduct deterministic analyses of EEIs of buildings in combination with probabilistic analysis methods. Research to facilitate the decision-making of stakeholders by integrating EEI assessment results composed of various impact categories and damage indexes for each safety guard into a single index is also required.

5. Conclusions

The purpose of this study was to analyze the EEIs of Korean apartment buildings on the basis of major building materials as part of research with the goal of reducing the LCEIs of buildings. The results are summarized as follows:

1. The LCEEIs of apartment buildings according to structure types and plans were assessed using 443 apartment buildings in South Korea, and the results were analyzed from the perspectives of total EIs, building life-cycle stages, major construction materials, and safety guards.
2. The analysis results showed that the tower-type apartment buildings with a flat plate structure exhibited the lowest EIs for all EI categories (GWP, AP, EP, ODP, POCP, and ADP) on the basis of total EIs, whereas the plate-type apartment buildings with a wall structure showed the highest EIs.
3. In particular, the percentage of EEIs caused by the production stage was the highest for all EI categories; for example, the maximum proportion of 90.04% was found for the tower-type apartment buildings with a flat plate structure for GWP. In addition, the percentages of EEIs of the construction and end-of-life stages reached 21.04% and 18.29%, respectively, depending on the EI category.
4. It was confirmed that ready-mixed concrete and reinforcement steel, both of which constitute the structures of apartment buildings, are major construction materials that cause such EEIs and that the EEIs of ready-mixed concrete are inversely proportional to those of reinforcement steel. In particular, the percentage of the EEIs caused by ready-mixed concrete reached 94.75% for ODP in plate-type apartment buildings with a wall structure, whereas that caused by reinforcement steel reached 27.52% for AP in tower-type apartment buildings with a flat plate structure.
5. The damage index by safety guard was the lowest in the tower-type apartment buildings with a flat plate structure, similarly to total EIs, and was the highest in the plate-type apartment buildings with a wall structure.

Author Contributions: All authors contributed substantially to all aspects of this article.

Acknowledgments: This research was supported by a grant (16CTAP-C114806-01) from the Technology Advancement Research Program (TARP), funded by the Ministry of Land, Infrastructure, and Transport of the Korean government.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript.

LCA	Life-cycle assessment
LCI	Life-cycle inventory analysis
LCIA	Life-cycle impact assessment
LCI DB	Life-cycle inventory database
KOLID	Korean life-cycle impact assessment method based on damage-oriented modeling
LCEI	Life-cycle environmental impact
LCEEI	Life-cycle embodied environmental impact
EI	Environmental impact
EEI	Embodied environmental impact
OEI	Operational environmental impact
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
ODP	Ozone-layer depletion potential

POCP	Photochemical ozone creation potential
ADP	Abiotic depletion potential
DALY	Disability-adjusted life years
EINES	Expected increase in number of extinct species
NPP	Net primary production
SCM	Supplementary cementitious material
FA	Fly ash
GGBS	Ground-granulated blast-furnace slag

References

1. Simpson, N.P.; Basta, C. Sufficiently capable for effective participation in environmental impact assessment? *Environ. Impact Assess. Rev.* **2018**, *70*, 57–70. [CrossRef]
2. Gorobets, A. Eco-centric policy for sustainable development. *J. Clean. Prod.* **2014**, *64*, 654–655. [CrossRef]
3. Vrieze, R.; Moll, H. An analytical approach towards sustainability-centered guidelines for Dutch primary school building design. *Int. J. Sustain. Build. Technol. Urban Dev.* **2017**, *8*, 93–124.
4. Vonka, M.; Hajek, P.; Lupisek, A. SBToolCZ: Sustainability rating system in the Czech Republic. *Int. J. Sustain. Build. Technol. Urban Dev.* **2013**, *1*, 46–52. [CrossRef]
5. Braganca, L.; Mateus, R.; Koukkari, H. Building Sustainability Assessment. *Sustainability* **2010**, *2*, 2010–2023. [CrossRef]
6. Simona, P.L.; Spiru, P.; Ion, I.V. Increasing the energy efficiency of buildings by thermal insulation. *Energy Procedia* **2017**, *128*, 393–399. [CrossRef]
7. Li, J.; Colombier, M. Managing carbon emissions in China through building energy efficiency. *J. Environ. Manag.* **2009**, *90*, 2436–2447. [CrossRef] [PubMed]
8. Pierucci, A.; Cannavale, A.; Martellotta, F.; Fiorito, F. Smart windows for carbon neutral buildings: A life cycle approach. *Energy Build.* **2018**, *165*, 160–171. [CrossRef]
9. Dong, L.; Wang, Y.; Li, H.X.; Jiang, B.; Al-Hussein, M. Carbon Reduction Measures-Based LCA of Prefabricated Temporary Housing with Renewable Energy Systems. *Sustainability* **2018**, *10*, 718. [CrossRef]
10. Huedo, P.; Mulet, E.; Lopez-Mesa, B. A model for the sustainable selection of building envelope assemblies. *Environ. Impact Assess. Rev.* **2016**, *57*, 63–77. [CrossRef]
11. Cellura, M.; Guarino, F.; Longo, S.; Mistretta, M. Different energy balances for the redesign of nearly net zero energy buildings: An Italian case study. *Renew. Sustain. Energy Rev.* **2015**, *45*, 100–112. [CrossRef]
12. Haase, M.; Andresen, I.; Gustavsen, A.; Dokka, T.H.; Hestnes, A.G. Zero Emission Building Concepts in Office Buildings in Norway. *Int. J. Sustain. Build. Technol. Urban Dev.* **2011**, *2*, 150–156. [CrossRef]
13. Ferrante, A.; Mochi, G.; Predari, G.; Badini, L.; Fotopoulou, A.; Gulli, R.; Semprini, G. A European Project for Safer and Energy Efficient Buildings: Pro-GET-onE (Proactive Synergy of inteGrated Efficient Technologies on Buildings' Envelopes). *Sustainability* **2018**, *10*, 812. [CrossRef]
14. Harkouss, F.; Fardoun, F.; Biwole, F.H. Multi-objective optimization methodology for net zero energy buildings. *J. Build. Eng.* **2018**, *16*, 57–71. [CrossRef]
15. Annunziata, E.; Frey, M.; Rizzi, F. Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe. *Energy* **2013**, *57*, 125–133. [CrossRef]
16. AIA. *AIA Guide to Building Life Cycle Assessment in Practice*; AIA: Washington, DC, USA, 2010.
17. Zuo, J.; Zhao, Z.Y. Green building research–Current status and future agenda: A review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 271–281. [CrossRef]
18. Oliveira, Z.L.; David, V.L.; Serra, S.M.B.; Barreto, D. Decision making process assisted by life cycle assessment: Greenhouse gas emission. *Int. J. Sustain. Build. Technol. Urban Dev.* **2017**, *8*, 244–253.
19. Roh, S.; Tae, S. Building Simplified Life Cycle CO_2 Emissions Assessment Tool (B-SCAT) to Support Low-Carbon Building Design in South Korea. *Sustainability* **2016**, *8*, 567. [CrossRef]
20. Rovers, R. Material-Neutral Building: Closed Cycle Accounting for Buildings Construction a new practical way to measure improvements in creating a balanced resource use for construction. *Int. J. Sustain. Build. Technol. Urban Dev.* **2010**, *1*, 152–159. [CrossRef]
21. Geng, S.; Wang, Y.; Zuo, J.; Zhou, Z.; Du, H.; Mao, G. Building life cycle assessment research: A review by bibliometric analysis. *Renew. Sustain. Energy Rev.* **2017**, *76*, 176–184. [CrossRef]

22. Rashid, A.F.A.; Yusoff, S. A review of life cycle assessment method for building industry. *Renew. Sustain. Energy Rev.* **2015**, *45*, 244–248. [CrossRef]
23. Iban-Mohammed, T.; Greenough, R.; Taylor, S.; Ozawa-Meida, L.; Acquaye, A. Operational vs. embodied emissions in buildings—A review of current trends. *Energy Build.* **2013**, *66*, 232–245. [CrossRef]
24. Chastas, P.; Theodosiou, T.; Bikas, D.; Kontoleon, K. Embodied Energy and Nearly Zero Energy Buildings: A Review in Residential Buildings. *Procedia Environ. Sci.* **2017**, *38*, 554–561. [CrossRef]
25. Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]
26. Luo, Z.; Yang, L.; Liu, J. Embodied carbon emissions of office building: A case study of China's 78 office buildings. *Build. Environ.* **2016**, *95*, 365–371. [CrossRef]
27. Roh, S.; Tae, S.; Shin, S. Development of building materials embodied greenhouse gases assessment criteria and system (BEGAS) in the newly revised Korea Green Building Certification System (G-SEED). *Renew. Sustain. Energy Rev.* **2014**, *35*, 410–421. [CrossRef]
28. Li, X.; Yang, F.; Zhu, Y.; Gao, Y. An assessment framework for analyzing the embodied carbon impacts of residential buildings in China. *Energy Build.* **2014**, *85*, 400–409. [CrossRef]
29. Moncaster, A.M.; Song, J.Y. A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *Int. J. Sustain. Build. Technol. Urban Dev.* **2012**, *1*, 26–36. [CrossRef]
30. Zeng, R.; Chini, A. A review of research on embodied energy of buildings using bibliometric analysis. *Energy Build.* **2017**, *155*, 172–184. [CrossRef]
31. Shi, Q.; Yu, T.; Zuo, J. What leads to low-carbon buildings? A China study. Renew. *Sustain. Energy Rev.* **2015**, *50*, 726–734. [CrossRef]
32. Wen, T.J.; Siong, H.C.; Noor, Z.Z. Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. *Energy Build.* **2015**, *93*, 295–302. [CrossRef]
33. Roh, S.; Tae, S.; Shin, S.; Woo, J. Development of an optimum design program (SUSB-OPTIMUM) for the life cycle CO_2 assessment of an apartment house in Korea. *Build. Environ.* **2014**, *73*, 40–54. [CrossRef]
34. Heinonen, J.; Säynäjoki, A.; Junnonen, J.; Pöyry, A.; Junnila, S. Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator? *Build. Environ.* **2016**, *95*, 116–125. [CrossRef]
35. Dixit, M.K. Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renew. Sustain. Energy Rev.* **2017**, *79*, 390–413. [CrossRef]
36. Guinee, J.B. *Handbook on Life Cycle Assessment Operational Guide to the ISO Standards, CML*; Leiden University: Leiden, The Netherlands, 2002.
37. ISO. *ISO 14025: Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures*; ISO: Geneva, Switzerland, 2006.
38. Korea Environmental Industry & Technology Institute. *Development of Integrated Evaluation Technology on Product Value for Dissemination of Environmentally Preferable Products*; Korea Ministry of Environment: Sejong, Korea, 2009.
39. Roh, S.; Tae, S.; Suk, S.J.; Ford, G. Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea. *Renew. Sustain. Energy Rev.* **2017**, *73*, 135–144. [CrossRef]
40. Roh, S.; Tae, S.; Suk, S.J.; Ford, G.; Shin, S. Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system. *Renew. Sustain. Energy Rev.* **2016**, *53*, 954–965. [CrossRef]
41. Korea Institute of Civil Engineering and Building Technology (KICT). *Standard Estimating System of the Construction Work*; KICT: Goyang, Korea, 2017.
42. Korea Legislation Research Institute (KLRI). Korea Corporate Tax Act: Korea Ministry of Strategy and Finance. 2013. Available online: http://elaw.klri.re.kr/kor_service/lawView.do?hseq=28577&lang=ENG (accessed on 31 March 2018).
43. Korea Environmental Industry & Technology Institute (KEITI). *Waste Statistics*; KEITI: Seoul, Korea, 2017.
44. Korea Environmental Industry & Technology Institute (KEITI). Korea Life Cycle Inventory Database. 2004. Available online: http://www.edp.or.kr/lci/lci_db.asp (accessed on 12 March 2018).

45. Korea Institute of Civil Engineering and Building Technology (KICT). *The Final Report of National DB on Environmental Information of Building Materials*; KICT: Goyang, Korea, 2008.
46. Germany Federal Ministry of the Interior, Building and Community. Oekobaudat. 2017. Available online: http://www.oekobaudat.de/en/database/database-oekobaudat.html (accessed on 31 March 2018).

sustainability

MDPI

Article

Building Ownership, Renovation Investments, and Energy Performance—A Study of Multi-Family Dwellings in Gothenburg

Mikael Mangold [1,*], Magnus Österbring [2], Conny Overland [3], Tim Johansson [4] and Holger Wallbaum [2]

1 City Development, Research Institutes of Sweden, 41261 Gothenburg, Sweden
2 Architecture and Civil Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden; magost@chalmers.se (M.Ö.); holger.wallbaum@chalmers.se (H.W.)
3 Department of Business Administration, University of Gothenburg, 40530 Gothenburg, Sweden; conny.overland@handels.gu.se
4 Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 97187 Luleå, Sweden; tim.johansson@ltu.se
* Correspondence: mikael.mangold@ri.se; Tel.: +46-70-297-9778

Received: 28 March 2018; Accepted: 17 May 2018; Published: 22 May 2018

Abstract: The European building stock was renewed at a rapid pace during the period 1950–1975. In many European countries, the building stock from this time needs to be renovated, and there are opportunities to introduce energy efficiency measures in the renovation process. Information availability and increasingly available analysis tools make it possible to assess the impact of policy and regulation. This article describes methods developed for analyzing investments in renovation and energy performance based on building ownership and inhabitant socio-economic information developed for Swedish authorities, to be used for the Swedish national renovations strategy in 2019. This was done by analyzing measured energy usage and renovation investments made during the last 30 years, coupled with building specific official information of buildings and resident area characteristics, for multi-family dwellings in Gothenburg (N = 6319). The statistical analyses show that more costly renovations lead to decreasing energy usage for heating, but buildings that have been renovated during the last decades have a higher energy usage when accounting for current heating system, ownership, and resident socio-economic background. It is appropriate to include an affordability aspect in larger renovation projects since economically disadvantaged groups are over-represented in buildings with poorer energy performance.

Keywords: renovation extent; energy retrofitting; rent affordability; tenure; energy performance certificate; decision support

1. Introduction

In 2010, buildings accounted for 32% of total global final energy usage [1]. The European Directive 2012/27/EU [2] requires member states to have a strategy for renovation of the building stock with the target of reducing energy usage by 20% by 2020 compared with 1990. In many European countries, the building stock increased at a rapid pace during the period 1950–1975 [3]. This aging building stock needs to be renovated, and there is a possibility to introduce energy efficiency measures in the renovation process [4,5].

Building condition, building ownership, and rent affordability determine what kind of renovation measures are possible and optimal [6]. Furthermore, tenure types, building regulations, construction practices etc. vary between different contexts, which increases the need for country-specific studies on renovation investments and energy performance [7–9]. The authors have developed methods for analyzing investments in renovation and building energy performance based on comprehensive building-specific information that can be used to analyze subgroups of building owners and specific socio-economic inhabitant groups. This was done for the Swedish case and to be used by the Swedish authorities. The paper tries to answer the question how can merged official comprehensive building specific information be used to describe the developments in the multi-family dwelling stock?

There are several studies on how ownership and socio-economic area conditions affect investment and energy performance. For rental multi-family dwellings, the landlord–tenant problem can be a barrier to energy retrofitting and renovation [10–14]. The multi-family dwellings that are resident-owned also have internal barriers to larger investments in energy retrofitting [15–17]. There is also not a consensus on which parameters should be included in an optimization of renovation projects. For instance, renovations financed by increased rents in socio-economically disadvantaged areas risk aggravating societal inequities [18–20].

The purpose of this article is to describe quantitative methods developed for analyzing how overall renovation progress and improved energy performance of buildings is related to ownership structures. The methods were developed for the multi-family dwellings in Gothenburg, Sweden, with the intention of being applicable for the entire national building stock in the update of the national strategy of energy efficient renovation in 2019. This article also contributes within the field of analysis of building specific information coupled with *measured* energy usage, also presented as Building Energy Epidemiology by the International Energy Agency, Annex 70. Countries have different registers and specific ways of storing and working with information. This article presents the Swedish case and methods developed for working with Swedish building specific information.

Building specific energy usage for all Gothenburg multi-family dwellings was gathered from Swedish Energy Performance Certificates (EPC). In most other counties in Europe the EPCs contain estimated energy usage, while in Sweden the EPCs should be issued by an certified energy expert that registers measured energy for heating from the 13 most commonly used heating sources, heating for tap water, and domestic electricity usage [21,22]. Renovation investments were deduced from official property taxation records. By aligning these datasets with building-specific information on ownership, tenure, and living-area socio-economic information, it is possible to analyze the progress toward the goals of reduced energy usage and decreased segregation. Michelsen et al. [23] also used measured energy usage from EPC data for German the building stock and made similar analyses focusing mainly on the difference between smaller and larger real estate owners. Michelsen et al. [23] found that larger real estate companies outperform smaller companies in terms of extensive renovations, but smaller companies can be better at continuous maintenance. This article compares real estate companies with other types of ownership. Albatici et al. [24] and Šijanec Zavrl et al. [25] merged mainly energy-related databases for the Italian and Slovenian building stock to model scenarios of developments toward energy efficiency. Our additional contribution is to work toward the development of methods that also include socio-economic parameters of building stock development.

Matschoss et al. [17] made a larger European summary of renovation policy that include tenure and found that incentives for condominium owners to energy retrofit buildings are needed in Europe to reach the 20-20-20 targets. This article sheds light on the renovation activities of multi-family dwellings in Sweden in two main ways. First, it describes methods developed for analyzing energy usage and investment in renovation in different ownership groups intended to be applied future analysis of impact of building regulations and subsidies. Second, we add to the literature on decision-making by presenting an empirical analysis of a large sample of homogeneous organizations, where one can distinguish between individual and social decision making.

Real-Estate Ownership in Sweden

To analyze the impact of regulations and subsidy schemes, it is necessary to distinguish between different ownership for which decision-making structures, taxation rules, subsidies, and the availability of funds are different. In addition, there is a variation between the ownership types in living area per person and in the resident profit or increased cost from improved living standards and energy performance.

Swedish multi-family dwellings are primarily of two tenure types: rental apartments or resident owned apartments, which is a type of tenure comparable with condominiums. Residents own a tradable share in a resident's organization that gives them the right to inhabit a specific apartment of the building. Member of the resident's organization are required to pay a membership fee toward maintenance and capital costs.

The rental apartments can be divided in two larger groups: municipally owned and privately owned [26]. From 1960 to 1975, a national initiative was initiated with the aim to build one million dwellings to cover an urgent housing need in Sweden [26,27]. The multi-family dwellings constructed during this period were constructed as privately owned rental apartments (20%), municipal rental apartments (50%), and resident-owned apartments (30%) [26]. Details about the building age typology can be found in Table A1. The main construction types in the Gothenburg multi-family building stock are slab block, enclosed block, point block, and gallery access block.

Private real estate firms are for-profit organizations that typically are family controlled, though investment funds are growing in importance within this group. Private real estate firms span from private individuals that own one building to large firms that own properties nationally as well as internationally. The modus operandi of private building owners is expected to be that of for-profits in general—to maximize asset value over time. For this reason, renovation as investments in general by private building owners are more likely to take place in attractive areas where risk is lower. With lower risk, the value added to money invested is higher. Some variation should also be found between different private tenants in how they make decisions. For instance, large firms possess superior organizational capacity and have better access to external finance. This means that they are likely to be better equipped to make investments in general and thereby are more inclined to follow through with investments [23].

Municipality owned multi-family dwellings in Gothenburg consist of four large companies. Municipally owned apartments are located in both areas with higher and lower income. They differ from private firms as they, historically, have not had profits as an organizational goal. In fact, they have not even been allowed to make profits. Instead, their focus has been to provide sufficient and affordable housing. The pro-social goal of these firms indicates that they are more inclined to make investments in lower income areas. Renovation can also be more common in municipally owned building due the fact that these companies have had access to cheaper finance through municipal bails.

Resident-owned apartments differ from both private and municipal housing companies. To start with, they are not subject to rental regulation. That means that they can increase their member fees for supplying value-adding features to their members in ways that rental housing companies cannot. For instance, if a private real estate company invests in reduced energy usage and improved indoor climate, this investment has to be carried by the cost reductions from the lower energy usage only. They are not allowed to charge a higher rent for the improved indoor climate and area branding. The group of resident-owned apartments, by contrast, can internalize such features in their member fees. This should increase the scope for more far-reaching renovation.

However, investments in resident-owned buildings are dampened by obstacles associated with social choice. In particular, if the membership fee is increased, the market value of the apartment decreases, making it difficult for all tenants to agree on a time when renovation should happen. Mastschoss et al. [17] studied barriers to energy retrofitting of owner-occupied multi-family dwellings in nine European countries, not including Sweden, finding that collective decision problems is a challenge in every country and that lack of professional experience of real estate management is another challenge. Indeed, suboptimal decisions in co-ops can be costly [28].

As part of the strategy to tackle the housing need that existed before the 1960–1975 era, two cooperatives for groups of resident owned apartments were founded, HSB and Riksbyggen.

These cooperatives constructed buildings that were sold to their member groups. The cooperatives also manage and maintain the resident-owned buildings. The cooperatives promote maintenance plans and certain types of renovations. The economic model may include a larger maintenance plan with more frequent visits and thus require less renovation projects.

After the Swedish bank crisis in 1991, privately owned rental apartments were converted into resident-owned apartments at an increased pace. It is more common with resident-owned buildings in attractive parts of the city, and the price increase of apartments in resident owned buildings has had a strong positive development during the past 20 years. During the same period, municipally owned multi-family dwellings have been sold to private capital funds in order to finance renovation and maintenance [29].

2. Materials

In this chapter, the materials from several Swedish authorities and institutions are described. Sampling was not necessary because 82% of the Gothenburg multi-family dwellings are covered by all matched datasets. Buildings were grouped based on the described ownership types and conversions.

2.1. Matched Datasets

Some datasets used for the analyses in this article were previously described in an article on the data quality of Swedish EPC data [30] and an article describing the renovation and energy retrofitting need in Gothenburg [31]. In these articles analyses of aspects related to the work behind this article such as data uncertainties can be found. Data on real-estate ownership was extracted from the Swedish National Land Survey and Retriever Business was matched with the EPC and base area socio-economic information. Base areas are the smallest demographical statistics area in Sweden containing 50 to 4000 residents. The combined geocoded datasets that describe the Gothenburg building stock are presented in Table 1.

Table 1. Details on datasets and data providers for multi-family dwellings in Gothenburg.

	The National Board of Housing Building and Planning	**Swedish Land Survey**	**Gothenburg City Executive Office**	**Retriever Business**
Aggregation level	Building	Building	Base area [1]	Organization
N	6320	64,600	434	1140
Information used in this article	Heating and energy usage, identified energy saving measures, number of apartments, heated floor area [3]	Construction year, renovation year, value year [2],building owner, corporate form	Average income, number of inhabitants	Organization establishment year

[1] Base areas are the smallest demographical statistics area in Sweden containing 50 to 4000 residents; [2] Value year is further explained in 3.1 Renovation extent; [3] Heated floor area is a measure specifically developed for EPC in Sweden (A_{temp}). Heated floor area is defined as the heated floor space including shared spaces and footprints of walls but not including garages.

The Swedish Land Survey information contains the corporate form under which the building is owned. This makes it possible to separate the resident-owned buildings and the municipal housing companies. Due to legal limitations, socio-economic data had to be aggregated to base area level. For studies in 2019, it is recommended to aggregate sensitive socio-economic inhabitant information to the multi-family dwelling level.

2.2. Characteristics of Building Ownership Groups

The three tenure types are described in 1.1. Real estate ownership in Sweden was further subdivided to reflect differences in regard to the distinction between individual and social decision-making and area attractivity. The privately owned group was further subdivided into buildings owned by: private persons, private companies, or owned by foundations based on the distinction between individual and social decision making. To be noted is that student housing with a total heated floor area of 200,000 m^2 is owned by foundations.

Income was previously used as an indicator to geographically separate the city into more and less attractive areas in Gothenburg by Mangold et al. [31]. The threshold of average income of 200,000 SEK/year before tax was used to divide the ownership groups municipally owned and private company owned into dummy groups of more disadvantaged suburban areas or more attractive rental areas (1$ = 8.26 SEK as of 1 March 2018). It should be noted that this separation does not reflect the official low-income definition, which is 60% of median income, 148,000 SEK/year. The resident-owned buildings were divided into buildings that were built by the cooperatives for resident owned-buildings (HSB and Riksbyggen) and buildings that have been converted into resident-owned buildings. The details for the ownership groups can be seen in Table A2.

2.3. Buildings Converted into Resident-Owned Buildings

Retriever Business is a register of all companies in Sweden including organizations of resident-owned buildings, which contains establishment year. Most of the buildings registered as resident-owned in Retriever Business are registered as resident-owned in the Swedish National Land Survey—see Table A3—but there are overlaps with other ownership groups due to a few different verified reasons: change of ownership between the records were made, split ownership of the building, and a company can own a share of a resident owned building. From 2000 to 2009 the buildings registered as resident owned increased from 901,000 to 2,280,000 m^2 heated floor area. During the same time the group "private company owned, higher income" decreased from 3,380,000 to 2,550,000 m^2 heated floor area. This made it possible to identify under which tenure renovations have taken place by comparing establishment year and reconstruction year.

3. Methods

The regressions were made to find and compare patterns of renovation investments and energy usage. The intention is to use these types of regressions for the assessment of building regulations and subsidy schemes in 2019. However, there are several other data analysis methods and visualization tools that are needed to communicate results with decision makers. The categorization of the building owners in this paper is an illustration of how to make the comprehensive building specific information more understandable. Timelines is another way to illustrate development that make it easy for practitioners, academics and decision makers to work together in the development of policy.

Regressions were made in R to explain variance in renovation investments and energy performance, see Table 2. Renovation investments and energy performance were derived from value year and renovation year in the register of the Swedish National Land Survey and from the Energy Performance Certificates (EPC). The value year is initially the year of construction, but as the building is renovated, the value year will be changed depending on the cost of the renovation. This is further described in Table A4. The purpose of recording a value year is to have an official record of anticipated remaining service life of buildings [32].

Table 2. Description of models in the regression analyses.

	Type	Dependent	Unit/Value	*N*
Model 1	Ordinal	Renovation group	0, 1, 2, 3	6244
Model 2	Linear	Renovation extent	%	6244
Model 3	Linear	Energy performance	kWh/m^2.year	5725
Model 4	Linear	Energy performance excluding energy for heating domestic hot water	kWh/m^2.year	5697

3.1. Renovation Investments

In Sweden, renovations are registered on a municipal level. The Swedish Tax Office require that a renovation is registered as a change in value year depending on the cost of the renovation in relation to new building cost as described in Table A4 and Equation (1). New building cost is revised yearly by the Swedish tax authority to reflect inflation and changes in construction costs.

$$\text{Renovation extent} = \frac{\text{Renovation cost}}{\text{New building cost}} = \frac{\text{Value year} - \text{Construction year}}{\text{Renovation year} - \text{Construction year}} \quad (1)$$

The groups in Table A4 were used in the ordinal (logit) regression in model 1. The groups are further described in Table A5. Using Equation (1), it was possible to calculate the renovation extent and equivalent cost of previous renovation projects from the value year and reconstruction year for group 2. The renovation extent was used as a dependent in model 2.

3.2. Energy Performance

Most EPCs for multi-family dwellings in Gothenburg were issued in 2008 and 2009 [30]. Since only one measurement of energy use is available from the EPC the statistical analysis for the relationship between building energy performance and investment in renovation the buildings were divided using renovation year of 2009 as a watershed. Energy performance of buildings renovated before 2009 include the impact of renovations. Only these buildings were used to analyze the importance of renovation investment for building energy performance, $N = 5697$. The buildings renovated after 2009 were used to analyze the importance of energy savings advice provided in the EPC for renovation investments.

The EPC will be renewed in 2019. This will make it possible to replace energy performance with change in energy performance as a dependent in the future analyses of success and impact of changed building regulations and subsidy schemes.

Energy for heating domestic hot water is included in the energy performance presented in the EPC. However, regression analyses have been made for both energy performance including and excluding energy for heating domestic hot water. There is a large difference in registered heating for domestic hot water between the building ownership groups in Gothenburg (see Figure 1). Removal of outliers was conducted with the criterion 2.5 standard deviation above average buildings energy performance (223 and 182 kWh/m^2.year for energy performance with and without energy for heating domestic hot water).

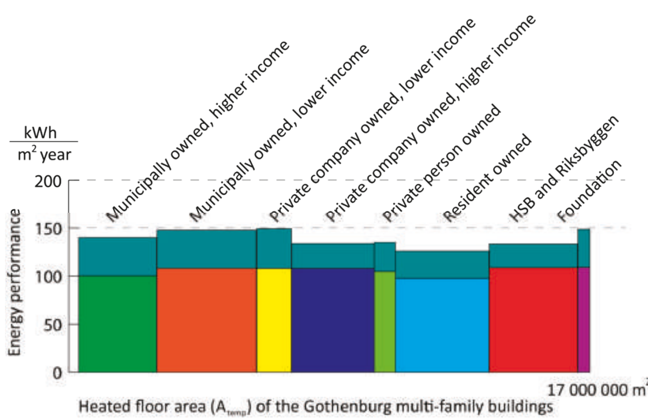


Figure 1. Energy usage in the Gothenburg multi-family dwellings separated into ownership groups. The energy for heating domestic hot water is teal.

Some studies suggest that water usage can be used as a proxy for number of inhabitants and time spent at home [33]. In Figure 1, the energy for heating of domestic hot water has been separated from the energy performance to illustrate the differences between the ownership groups. Living area per person has impact on both the need of renovation and on energy usage in buildings.

3.3. Independent Variables in Regression Analyses

Nominal, ordinal, and scalar variables were used in the regression analyses. The independent variables building age, heating system, and ownership group are nominal variables that were converted into nominal groups of variables for the linear regression analyses. One variable in each group was kept outside of the linear regression analyses as a reference category; these are indicated with asterisk in Table A6. In the regression analyses, it was also possible to use base area average income as an independent variable instead of separating private company and municipal ownership into subgroups. For the statistical analyses of building energy performance, the importance of the time period in which the renovation happened was studied by creation an ordinal variable in segments 1979–1989, 1990–1999, and 2000–2009. This variable was excluded in the analyses of renovation investment because of the strong interdependence of the two variables both derived from renovation year.

3.4. Robustness Checks

In order to estimate renovation investments made in the entire building stock and be able to make a linear regression for the renovation costs, costs for renovations for group 1 and group 3 in Table A4 were assumed. The robustness of these assumptions was checked through the comparison between model 1 and 2, as well as an additional linear regression for only group 2. The assumptions caused no larger differences in the predictions.

Data on building ownership from Swedish National Land Survey only describe the building ownership in 2014. The changes in ownership were included by the addition of conversions registered in Retriever Business. The analysis of investment in relation to conversion was done only for the buildings registered in Retriever Business.

4. Results

Analyses of total costs and estimates of future cost of renovations and energy retrofitting were conducted by Mangold et al. [31]. In Figure 2, past renovation costs have been separated further in the ownership groups. A difference in how consistently the members in ownership groups invest in renovations can be seen and the economic crises in 1991 and 2000 are observable.

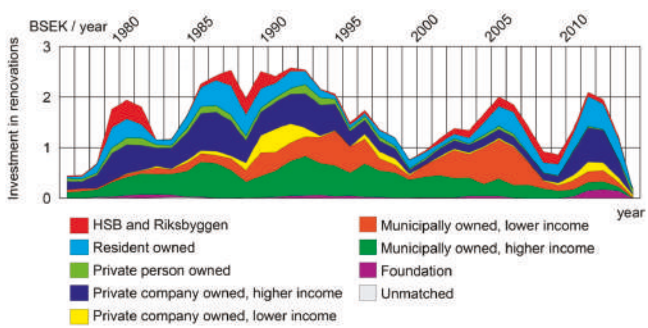


Figure 2. Costs of renovation registered for ownership groups.

The division of areas into higher and lower income is based on income statistics from 2015 which means that changes in income is not reflected in Figure 2. Some of the renovation costs in the municipally owned, higher income areas in the 1980ties and 1990ties were made in central areas that had a lower income level when they were renovated but are now higher income areas.

The renovation costs in Figure 2 include buildings from all construction periods. In the two largest ownership groups of multi-family dwellings constructed during 1960–1975—HSB and Riksbyggen and municipally owned, lower income—there is a considerable amount of multi-family dwellings that has not been renovated (see Table 3). The group resident-owned contain the most renovations that have been conducted with a cost of less than 20% of new building cost in Table 3. It is easier for resident that own their buildings to agree on and carry out smaller renovation investments than it is for other ownership groups.

For the discussion on municipal or private ownership of rental buildings in lower income areas, it is relevant to notice that private companies, and especially private persons, have registered fewer investments through renovations than municipal companies in Table 3.

Table 3. Share of heated floor area (10^3 m^2) in the renovation cost groups of the buildings built during 1960–1975.

	No Renovation	Less than 20%	20–70%	More than 70%	Grand Total
Municipally owned, higher income	44%	20%	9%	26%	398
Municipally owned, lower income	50%	23%	20%	6%	2390
Private company owned, lower income	50%	38%	9%	3%	745
Private company owned, higher income	37%	41%	18%	3%	1019
Private person owned	92%	8%	0%	0%	119
Resident owned	30%	55%	12%	2%	570
HSB and Riksbyggen	68%	26%	6%	0%	1358
Foundation owned	74%	12%	3%	12%	167
Unmatched	100%	0%	0%	0%	30

In Figure 3, the renovation costs in relation to conversion to resident ownership have been illustrated. Right after the conversion renovation projects are the most frequent. Fewer buildings were renovated and then converted. In connection with the analysis of shared ownership (such as resident owned buildings) it was hypothesized that larger multi-family dwellings would be less renovated. However, a separation of the building stock in regard to building heated floor area did not show any significant relationship between resident owned buildings' size and renovation cost.

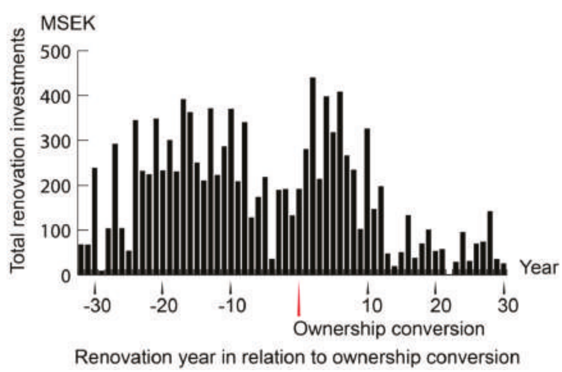


Figure 3. Costs of renovations of resident-owned building summed by the years between renovation year and the year the building tenure was converted into resident ownership, for only buildings registered as resident-owned in Retriever Business.

Regression Results

The coefficients in Table 4 mostly reflect expected patterns in the building stock of Gothenburg. This is a promising result for the later analysis of changes in energy usage connect using the same methods for the national building stock in 2019. However, there are also some important considerations to be made when applying these methods.

Table 4. Ordinal (logit) and linear regression results.

	Model 1		**Model 2**		**Model 3**		**Model 4**	
Variable	Estimate	Sig.	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
Constant			73.594 ***	0.000	167.775 ***	0.000	132.131 ***	0.000
Renovation extent [%]					−0.084 ***	0.000	−0.092 ***	0.000
Energy performance [kWh/m^2.year]	−0.007 ***	0.000	−0.156 ***	0.000				
Private company owned	0							
Municipality owned	0.335 ***	0.000	3.018 **	0.010	8.089 ***	0.000	−1.656	0.063
Private person owned	−1.080 ***	0.000	−16.991 ***	0.000	−0.116	0.935	−1.56	0.094
Resident owned	−0.475 ***	0.000	−11.061 ***	0.000	−1.129	0.264	1.8	0.079
HSB and Riksbyggen	−0.483 ***	0.000	−6.947 ***	0.000	−2.36 *	0.034	−0.222	0.866
Foundation owned	0.106	0.560	5.331	0.065	19.369 ***	0.000	13.48 ***	0.000
Base area share of university degree [%]	0.094	0.572	0.005	0.437	7.503 ***	0.000	11.803 ***	0.000
Base area average income [KSEK]	−0.001 **	0.005	−0.037 ***	0.000	−0.047 ***	0.000	−0.037 ***	0.000
Was recently renovated					1.86 ***	0.000	1.27 **	0.005
FTX or other heat recovery from ventilation	0.643 ***	0.000	6.041 ***	0.000	−2.865 **	0.007	−3.362 ***	0.001
District heating	0							
Heat pumps	−0.453 ***	0.000	1.521	0.502	−68.443 ***	0.000	−51.217 ***	0.000
Electricity	−1.187 ***	0.000	−9.632 **	0.003	−32.891 ***	0.000	−29.621 ***	0.000
Boiler	−0.335 ***	0.000	−7.85 *	0.028	5.982 *	0.028	6.413 *	0.010
Constructed before 1945	0							
Constructed 1945–1960	−0.754 ***	0.000	−16.415 ***	0.000	0.511	0.628	−1.049	0.279
Constructed 1960–1975	−1.631 ***	0.000	−35.937 ***	0.000	1.732	0.157	−1.424	0.206
Constructed after 1975	−3.583 ***	0.000	−49.154 ***	0.000	−27.724 ***	0.000	−26.676 ***	0.000
Heated floor area [10^3 m^2]	0.014	0.356	−0.039	0.868	−0.852 ***	0.000	−0.564 ***	0.001
Sides with other buildings	−0.085	0.033	−0.78	0.237	−5.325 ***	0.000	−4.3 ***	0.000
Number of floors	−0.026	0.107	−1.047 ***	0.000	−1.074 ***	0.000	−0.847 ***	0.000
Number of staircases	−0.006	0.559	−0.061	0.701	−0.301 *	0.015	−0.258 *	0.024
Heated basements	0.232 ***	0.000	0.463	0.621	−6.591 ***	0.000	−5.582 ***	0.000
Heated garage ratio to building [%]	−2.115 **	0.004	−31.77 **	0.001	1.096	0.832	6.279	0.191
N	6235		6235		5725		5697	
Unit			%		kWh/m^2.year		kWh/m^2.year	
R^2 adjusted			0.255		0.484		0.400	

* Coefficient is significant at the 0.05 level (2-tailed); ** Coefficient is significant at the 0.01 level (2-tailed); *** Coefficient is significant at the 0.001 level (2-tailed).

Models 3 and 4 explain variance in energy performance including and excluding heating for domestic hot water. This separation is important to make in order to understand why municipally owned multi-family dwellings have worse energy performance registered in the EPC than other ownership groups.

More costly renovations have resulted in lower energy usage, but buildings that have been renovated during the last decades have a higher energy usage when accounting for current heating system, ownership, and resident socio-economic background. As seen in Table 4, parts of the variance in energy performance are explainable by variables describing the energy systems of the buildings. The types of energy systems also differ between the ownership groups, as seen in Table 5. This should also be considered when comparing the energy performance of the different ownership groups. The group heat pump stands out in the regression analysis because the energy supplied to the heat pump is recorded in the EPC, and not the energy provided by the heat pump to the building. Installation of ventilation with heat recovery and changing heating systems from electricity or boilers to heat pumps or district heating have been registered as renovations. Buildings constructed after the 1975 and after the oil crises were built with better energy performance.

Table 5 also illustrates how different ownership results in different types of energy savings measures. Installing heat pumps have been a profitable energy savings measure for especially private persons and residents owning their buildings. The price of district heating is close to the price of electric heating directly which incentivizes building owners to install heat pump. However, for municipal housing companies, buying district heat from waste heat and more carbon-neutral heating distributed by the municipal energy company is the most prevalent solution. Other commonly used energy savings measures in Sweden have been roof insulation, ventilation heat recovery, wall insulation, replacement of windows, and balcony heat bridge mitigation.

Table 4 also illustrates that municipally owned real estate companies make most of the larger investments in renovations. Fewer renovations are registered for resident owned buildings. Contributing factors to this pattern are that: parts of the renovations cost are shifted from the building owner to the apartment owner, ownership of the apartment reduces needs of maintenance, it is more difficult to agree on larger investments in larger groups of owners, HSB and Riksbyggen sell maintenance services which reduce the need for more costly renovations, and finally one unverified interpretation is that buildings built by HSB and Riksbyggen are in larger need of renovations.

Multi-family dwellings in base areas inhabited by economically disadvantaged people have a worse energy performance and fewer renovations have been made in these areas. This emphasizes the importance of including affordability aspects in the sustainability analysis of renovations of multi-family dwellings.

Table 5. Multi-family dwellings with different heat sources and energy efficient ventilation (FTX or heat recovery) in building ownership groups.

	Boiler	District Heating	Electricity	Heat Pump	Total	Energy Efficient Ventilation
Municipally owned, high income	10	1020	13	26	**1069**	169
Municipally owned, low income	0	810	9	1	**820**	86
Private company owned, low income	1	293	2	8	**304**	40
Private company owned, high income	13	975	14	38	**1040**	111
Private person owned	5	368	9	26	**408**	15
Resident owned	40	1188	67	165	**1460**	204
HSB and Riksbyggen	18	908	0	65	**991**	104
Foundation owned	0	140	1	11	**152**	25
Unmatched	0	49	0	26	**75**	37
Grand Total	87	5751	115	366	**6319**	791

Separate statistical analyses were also made for the buildings renovated between 2009 and 2014 ($N = 485$). The EPCs were issued in 2009, so for this analysis, the recorded energy performance was instead seen as a predictor of renovation. It was found that buildings with a poor energy performance were prioritized for larger renovations after 2009. The average building energy performance (excluding heating for domestic hot water) was 161 kWh/m^2.year for renovation investment cost Group 3 ($N = 17$); compared with total average energy performance of 131 kWh/m^2.year. However, it was not possible to establish a significant relationship between suggested energy saving measures and renovation extent.

For the statistical analysis of the socio-economic information, we found that using base area as a level of aggregation for socio-economic information introduces error sources and limitations for the interpretation of results. Existence of other building types made it difficult to establish clear links between number of residents in multi-family dwellings and base areas. Analyses that explain socio-economic status of areas would need to include information aggregated to the multi-family dwelling level.

5. Discussion

In this article methods of analyzing building-specific investment and energy performance have been described. The methods are intended to be used to present decision makers with analyses of developments in the multi-family dwelling stock. The interpretation of results is highly context specific and is also a political matter. Different subsidy schemes apply for the separate ownership groups and priorities in housing policy are based on political decisions.

Hsu [34] also used comprehensive building energy usage and engineering audits and found that variance in energy performance of buildings is not sufficiently explained by building and heating system characteristics. In this article we demonstrate that variance in building energy performance can be further described when adding building ownership and area socio-economic information. Huber et al. [20] studied the challenges of renovating and energy retrofitting multi-family dwellings in socio-economically disadvantaged areas. In this article, we find that the municipally owned real estate companies in Gothenburg are most exposed to those challenges. Trade-offs need to be made between energy usage reductions, rent increases, and increased living standards. Curtis et al. [35] used EPC data matched with census data for the Irish building stock, and found building energy performance to be worse in buildings in socio-economically disadvantaged areas.

Michelsen et al. [23] found that larger real estate companies outperform smaller companies in terms of extensive renovations, but that smaller companies can be better at continuous maintenance. Company size was not part of the analysis in this article. However, we would like to add that the least number of renovations were registered for private person owned rental buildings. The municipally owned real estate companies are large, and they have executed most large renovation projects.

Matschoss et al. [17] compared energy efficiency renovations in multi-family dwellings in eight European countries with regard to building ownership, not including Sweden. They found that resident joint ownership may have internal barriers to making larger investments in energy retrofitting. In Sweden, the costs of renovating the interior of the resident owned apartments are not included in renovation cost of the entire building. Interior apartment renovations are frequent in resident owned buildings, due to the strong market development of resident owned apartments. Including these renovations costs and associated environmental impact would be necessary to make a more complete evaluation of multi-family dwelling resident ownership as a tenure type. Furthermore, other studies have shown that it is not possible to establish that energy usage cost calculations in the EPC affect the price of the resident owned apartments [36–39].

For rental apartments, the landlord–tenant problem can be a barrier to energy retrofitting and renovation [10,12–14]. It was difficult to isolate these aspects in the analysis of the Gothenburg multi-family dwellings. In Sweden, the real estate owner pays the heating cost. In the past decades, individual volumetric metering billing of electricity and water have been increasingly installed in rental apartments in Gothenburg [40].

Central for the regression analyses with building energy performance as dependent was the removal of domestic hot water heating. Only a minor share of the heat in domestic hot water remains in the building after usage. Most of the heat exits the building in the waste water [41]. Excluding heating for water usage from energy performance, which is most strongly predicted by living area per person [33,40], is one manner of separating the impact of user behavior. When excluding energy for heating domestic hot water, no significant association between energy performance and building ownership could be made. This finding is relevant in the context that European countries are reissuing EPCs in which more countries will include measured, instead of calculated, energy and water usage. Because of the differences in water usage between the ownership groups, there are risks that groups of multi-family dwellings that are more crowded appear as have comparatively poorer energy performances depending on how the energy performance certification with measured energy usage is implemented in European counties.

6. Conclusions

This article analyzed variance in investments in renovations and building energy performance of multi-family dwellings, based on building ownership, location and building characteristics. We found that both building ownership and socio-economic area characteristics are useful in explaining variance. Central findings are that energy used for heating domestic hot water and heating systems varies between ownership groups and that municipally owned real estate companies face challenges in the renovation of building in socio-economically disadvantaged areas. Including affordability aspects in the sustainability analyses of larger renovations in such areas is necessary since economically disadvantaged groups are overrepresented in multi-family dwellings with poor energy performance. Buildings which have had higher energy usage are overrepresented in the group of buildings having gone through larger renovations in recent years. Large renovation is a predictor of lower energy usage. However, when accounting for current heating system, ownership, and resident socio-economic background, buildings that have been renovated during the last decades have a higher energy usage.

Building ownership is context specific, but the overall renovation progress and energy performance of buildings in different types of ownership groups can be described using official and publicly accessible databases. Comprehensive building specific information, separated in ownership groups, made it possible to demonstrate the differences in renovations and building energy performance between ownership groups. Furthermore, statistical analyses of the data can be used to reinforce conclusions.

Future Studies

The EPCs were designed to be renewed every 10 years. This will make it possible to describe and explain the changes in energy usage in Sweden in 2019. These studies will investigate predictors of energy retrofitting projects and changes in socio-economic inhabitation characteristics. Ideally, casual relationships can be made between these changes and changes in building regulation and subsidy schemes. In this study, sensitive socio-economic inhabitant information should be aggregated to the multi-family dwelling level during the time of the two waves of EPCs.

In this article, information about the Gothenburg multi-family dwelling stock has been studied. Johansson et al. [42] also used the information sources described in this paper to develop methods for connecting the entire Swedish national databases. This will make it possible to provide decision support to the national authorities which are responsible for building regulation and subsidy schemes.

Adding building-specific energy models would enable comprehensive strategic advice for building owners [43,44]. Using the records of renovation cost and energy performance linked with scenarios will make it possible to point out which building owners should be in line for energy retrofitting.

Author Contributions: M.M. wrote the article and did the statistical data analysis. M.Ö. provided support in writing and analysis of data. C.O. provided support in real estate economics and wrote the segments on 1.1 Real estate ownership in Sweden. T.J. did the merging of different data sources and helped in the writing of the paper. H.W. supervised the project, provided support in the writing and framed the paper as part of the research field.

Acknowledgments: The authors would like to thank Martin Storm at the National Board of Housing Building and Planning for sharing EPC data, Lutz Ewert at Gothenburg CEO for all discussions and for sharing socio-economic data and Eric Jeansson at CPA for giving us access to the Gothenburg spatial city plan. This work was financially supported by Chalmers Infrastructure Engineering, SIRen, and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning-Formas. The Formas funds includes a budget post open access payment which will be used for this paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A Tables with Descriptions of Ownership Groups and Variables for the Regression Analyses

Table A1. Heated floor area of multi-family dwellings in Gothenburg divided by construction periods and ownership groups [10^3 m^2].

	Built before 1931	1931–1945	1946–1960	1961–1975	1976–1990	1991–2005	Built after 2005
Municipally owned, higher income	512	383	788	398	320	169	76
Municipally owned, lower income	34	31	746	2387	94	7	7
Private company owned, lower income	21	21	351	745	1	1	17
Private company owned, higher income	389	624	383	999	208	65	62
Private person owned	180	275	123	119	12	6	2
Resident owned	919	467	402	590	194	235	252
HSB and Riksbyggen	87	159	755	1358	346	183	51
Foundation owned	58	19	43	167	9	66	41
Unmatched	11	1	4	31	22	1	151
Total	**2211**	**1980**	**3595**	**3049**	**1206**	**733**	**659**

Table A2. Descriptions of the ownership groups. Geographical analyses were conducted to verify the validity of the groups.

	Number of Buildings	Heated Floor Area [10^3 m^2]	Average Income [SEK/Person.Year]	Higher Education [1]
Municipally owned, higher income	1069	2646	241,000	44%
Municipally owned, lower income	820	3305	153,000	27%
Private company owned, lower income	304	1156	156,000	30%
Private company owned, higher income	1040	2729	263,000	48%
Private person owned	408	717	264,000	54%
Resident owned	1460	3059	283,000	52%
HSB and Riksbyggen	991	2939	243,000	38%
Foundation owned	152	403	238,000	68%
Unmatched	75	223	286,000	19%

Table A3. Retriever Business data description and overlap with data from Swedish National Land Survey.

	Buildings Registered as Resident Owned	Heated Floor Area in Retriever Business [10^3 m^2]	Overlap of the Datasets	Average Construction Year	Average Organization Registration Year
Municipally owned, higher income	53	147	6%	1944	2004
Municipally owned, lower income	1	1	0%	1977	2005
Private company owned, lower income	5	20	2%	1931	2006
Private company owned, higher income	185	578	21%	1941	2004
Private person owned	98	214	30%	1937	2005
Resident owned	696	1561	51%	1944	1990
HSB and Riksbyggen	94	481	16%	1957	1956
Foundation owned	7	10	3%	1958	2006

Table A4. Methods for setting a value year based on renovation costs according to Swedish Tax Agency [32].

	Renovation Cost	Method of Setting the Value Year
Group 1	Less than 20% of the new building cost [1]. Assumed to be 10% in the linear regression model.	No change in Value year
Group 2	20–70% of the new building cost [1]	The value year is set based on the cost of the renovation compared with the cost of constructing a comparable building using Equation (1).
Group 3	More than 70% of the new building cost [1]. Assumed to be 90% in the linear regression model.	Value year is set to the year of the renovation

[1] New building cost is set and updated by the Swedish tax authorities. In order to calculate and compare renovation costs between years New building cost of 2012 [32] is be used in this article, which was 15,300 SEK/m^2 (1$ = 8.26 SEK as of 1 March 2018). The new building cost is increasing based on Inflation, changes in construction costs and property value.

Table A5. Description of renovation cost groups. Renovation cost is presented as a percentage of New building cost as specified by the Swedish Tax Agency [32].

	Number of Buildings	Heated Floor Area [10^3 m^2]	Average Building Size [m^2]	Average Construction Year
No renovation	3090	8050	2610	1966
Group 1	984	3770	3830	1958
Group 2	1040	2750	2640	1943
Group 3	1210	2610	2160	1937

Table A6. Independents in the regression analyses.

Type	Variable	Unit	Average	Std. dev.
Nominal	Private company owned [1]	Yes/no	0.198	-
Nominal	Municipality owned	Yes/no	0.308	-
Nominal	Private person owned	Yes/no	0.068	-
Nominal	Resident owned	Yes/no	0.219	-
Nominal	HSB and Riksbyggen	Yes/no	0.170	-
Nominal	Foundation owned/student housing	Yes/no	0.025	-
Scalar	Base area share of university degree	%	0.433	0.196
Scalar	Base area average income	KSEK	238	64.7
Ordinal	Was recently renovated (decades from 1988)	Ordinal	0.924	1.18
Nominal	FTX or other heat recovery from ventilation	Yes/no	0.123	-
Nominal	District heating [1]	Yes/no	0.903	-
Nominal	Heat pumps	Yes/no	0.062	-
Nominal	Electricity	Yes/no	0.020	-
Nominal	Boiler	Yes/no	0.015	-
Nominal	Constructed before 1945 [1]	Yes/no	0.353	-
Nominal	Constructed 1945–1960	Yes/no	0.215	-
Nominal	Constructed 1960–1975	Yes/no	0.224	-
Nominal	Constructed after 1975	Yes/no	0.208	-
Scalar	Heated floor area	10^3 m^2	2.63	2.97
Ordinal	Sides shared with other buildings	Integer	0.500	0.807
Ordinal	Number of floors	Integer	4.17	2.26
Ordinal	Number of staircases	Integer	3.58	3.89
Ordinal	Number of heated basements	Integer	0.700	0.494
Scalar	Heated garage ratio to building	%	0.090	0.044

[1] Variable used as reference category in the regression analyses.

References

1. IPCC. Working Group III—Mitigation of Climate Change, Chapter 9 Buildings. 2014. Available online: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_frontmatter.pdf (accessed on 28 April 2018).
2. EU (The European Union). *Directive 2012/27/EU on Energy Efficiency*; EU: Brussels, Belgium, 2012.
3. Meijer, F.; Itard, L.; Sunikka-Blank, M. Comparing European residential building stocks: Performance, renovation and policy opportunities. *Build. Res. Inf.* **2009**, *37*, 533–551. [CrossRef]
4. Ball, E. Holistic strategies for energy efficient refurbishment of the housing stock and renewal of the related energy supply system. In *WP Transnational Manual*; German Association for Housing, Urban and Spatial Development (DV): Berlin, Germany, 2011.
5. Heeren, N.; Jakob, M.; Martius, G.; Gross, N.; Wallbaum, H. A component based bottom-up building stock model for comprehensive environmental impact assessment and target control. *Renew. Sustain. Energy Rev.* **2013**, *20*, 45–56. [CrossRef]
6. Ostermeyer, Y.; Wallbaum, H.; Reuter, F. Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 1762–1779. [CrossRef]
7. Pombo, O.; Rivela, B.; Neila, J. The challenge of sustainable building renovation: Assessment of current criteria and future outlook. *J. Clean. Prod.* **2016**, *123*, 88–100. [CrossRef]
8. Grossmann, K.; Kabisch, N.; Kabisch, S. Understanding the social development of a post-socialist large housing estate: The case of Leipzig-Grünau in eastern Germany in long-term perspective. *Eur. Urban Reg. Stud.* **2017**, *24*, 142–161. [CrossRef]
9. Corvacho, H.; Alves, F.B.; Rocha, C. A Reflection on Low Energy Renovation of Residential Complexes in Southern Europe. *Sustainability* **2016**, *8*, 987. [CrossRef]
10. Charlier, D. Energy efficiency investments in the context of split incentives among French households. *Energy Policy* **2015**, *87*, 465–479. [CrossRef]
11. Deng, Y.; Wu, J. Economic returns to residential green building investment: The developers' perspective. *Reg. Sci. Urban Econ.* **2014**, *47*, 35–44. [CrossRef]
12. Hope, A.J.; Booth, A. Attitudes and behaviours of private sector landlords towards the energy efficiency of tenanted homes. *Energy Policy* **2014**, *75*, 369–378. [CrossRef]

13. Kholodilin, K.A.; Michelsen, C. The Market Value of Energy Efficiency in Buildings and the Mode of Tenure. *Urban Stud.* **2017**, *54*, 3218–3238. [CrossRef]
14. Pivo, G. Unequal access to energy efficiency in US multifamily rental housing: Opportunities to improve. *Build. Res. Inf.* **2014**, *42*, 551–573. [CrossRef]
15. Bardhan, A.; Jaffee, D.; Kroll, C.; Wallace, N. Energy efficiency retrofits for U.S. housing: Removing the bottlenecks. *Reg. Sci. Urban Econ.* **2014**, *47*, 45–60. [CrossRef]
16. Genus, A.; Theobald, K. Creating low-carbon neighbourhoods: A critical discourse analysis. *Eur. Urban Reg. Stud.* **2016**, *23*, 782–797. [CrossRef]
17. Matschoss, K.; Heiskanen, E.; Atanasiu, B.; Kranzl, L. Energy renovations of EU multifamily buildings: Do current policies target the real problems. In *Rethink, Renew, Restart*; IEEE: Piscataway Township, NJ, USA, 2013.
18. Ahlfeldt, G.M. Blessing or curse? Appreciation, amenities and resistance to urban renewal. *Reg. Sci. Urban Econ.* **2011**, *41*, 32–45. [CrossRef]
19. Arbaci, S.; Tapada-Berteli, T. Social inequality and urban regeneration in Barcelona city centre: Reconsidering success. *Eur. Urban Reg. Stud.* **2012**, *19*, 287–311. [CrossRef]
20. Huber, A.; Mayer, I.; Beillan, V.; Goater, A.; Trotignon, R.; Battaglini, E. Refurbishing residential buildings: A socio-economic analysis of retrofitting projects in five European countries. In Proceedings of the World Sustainable Energy Days, Wels, Austria, 2–4 March 2011; pp. 2–4.
21. Pagliaro, F.; Cellucci, L.; Burattini, C.; Bisegna, F.; Gugliermetti, F.; de Lieto Vollaro, A.; Salata, F.; Golasi, I. A methodological comparison between energy and environmental performance evaluation. *Sustainability* **2015**, *7*, 10324–10342. [CrossRef]
22. Hjortling, C.; Björk, F.; Berg, M.; Af Klintberg, T. Energy mapping of existing building stock in Sweden-Analysis of data from Energy Performance Certificates. *Energy Build.* **2017**, *153*, 341–355. [CrossRef]
23. Michelsen, C.; Rosenschon, S.; Schulz, C. Small might be beautiful, but bigger performs better: Scale economies in "green" refurbishments of apartment housing. *Energy Econ.* **2015**, *50*, 240–250. [CrossRef]
24. Albatici, R.; Gadotti, A.; Baldessari, C.; Chiogna, M. A decision making tool for a comprehensive evaluation of building retrofitting actions at the regional scale. *Sustainability* **2016**, *8*, 990. [CrossRef]
25. Šijanec Zavrl, M.; Stegnar, G.; Rakušček, A.; Gjerkeš, H. A bottom-up building stock model for tracking regional energy targets—A case study of kočevje. *Sustainability* **2016**, *8*, 1063. [CrossRef]
26. Hall, T.; Vidén, S. The Million Homes Programme: A review of the great Swedish planning project. *Plan. Perspect.* **2005**, *20*, 301–328. [CrossRef]
27. Castell, P. *The Swedish Suburb as Myth and Reality*; Chalmers University of Technology: Göteborg, Sweden, 2010.
28. Almenberg, J.; Karapetyan, A. Hidden costs of hidden debt. *Rev. Financ.* **2013**, *18*, 2247–2281. [CrossRef]
29. Lind, H. Does the Law on Rental Appartments Lead to Correct Renovations? (Leder Hyreslagens Regler Till Rätt Renoveringar: Analys Och Förslag). Available online: http://www.renoveringscentrum.lth.se/fileadmin/renoveringscentrum/SIRen/Publikationer/Leder_hyreslagens_regler_till_ratt_renovering.pdf (accessed on 28 April 2018).
30. Mangold, M.; Österbring, M.; Wallbaum, H. Handling data uncertainties when using Swedish energy performance certificate data to describe energy usage in the building stock. *Energy Build.* **2015**, *102*, 328–336. [CrossRef]
31. Mangold, M.; Österbring, M.; Wallbaum, H.; Thuvander, L.; Femenias, P. Socio-economic impact of renovation and energy retrofitting of the Gothenburg building stock. *Energy Build.* **2016**, *123*, 41–49. [CrossRef]
32. Swedish Tax Agency. *The Tax Office General Advice (Skatteverkets Allmänna Råd)*; Swedish Tax Agency: Solna, Sweden, 2015.
33. Pullinger, M.; Browne, A.; Anderson, B.; Medd, W. *Patterns of Water: The Water Related Practices of Households in Southern England, and Their Influence on Water Consumption and Demand Management*; Lancaster University: Lancaster, UK, 2013; Available online: https://www.escholar.manchester.ac.uk/uk-ac-man-scw:187780 (accessed on 28 April 2018).
34. Hsu, D. How much information disclosure of building energy performance is necessary? *Energy Policy* **2014**, *64*, 263–272. [CrossRef]

35. Curtis, J.; Devitt, N.; Whelan, A. Using census and administrative records to identify the location and occupancy type of energy inefficient residential properties. *Sustain. Cities Soc.* **2015**, *18*, 56–65. [CrossRef]
36. Bonde, M.; Song, H.-S. Is energy performance capitalized in office building appraisals? *Prop. Manag.* **2013**, *31*, 200–215. [CrossRef]
37. Bruegge, C.; Carrión-Flores, C.; Pope, J.C. Does the housing market value energy efficient homes? Evidence from the energy star program. *Reg. Sci. Urban Econ.* **2016**, *57*, 63–76. [CrossRef]
38. Cerin, P.; Hassel, L.; Semenova, N. Energy performance and housing prices. *Sustain. Dev.* **2012**, *22*, 404–419. [CrossRef]
39. Fuerst, F.; McAllister, P.; Nanda, A.; Wyatt, P. Energy performance ratings and house prices in Wales: An empirical study. *Energy Policy* **2016**, *92*, 20–33. [CrossRef]
40. Mangold, M.; Morrison, G.; Harder, R.; Hagbert, P.; Rauch, S. The transformative effect of the introduction of water volumetric billing in a disadvantaged housing area in Sweden. *Water Policy* **2014**, *16*, 973–990. [CrossRef]
41. McNabola, A.; Shields, K. Efficient drain water heat recovery in horizontal domestic shower drains. *Energy Build.* **2013**, *59*, 44–49. [CrossRef]
42. Johansson, T.; Olofsson, T.; Mangold, M. Development of an energy atlas for renovation of the multifamily building stock in Sweden. *Appl. Energy* **2017**, *203*, 723–736. [CrossRef]
43. Österbring, M.; Mata, É.; Thuvander, L.; Mangold, M.; Johnsson, F.; Wallbaum, H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. *Energy Build.* **2016**, *120*, 78–84. [CrossRef]
44. Mastrucci, A.; Baume, O.; Stazi, F.; Leopold, U. Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to Rotterdam. *Energy Build.* **2014**, *75*, 358–367. [CrossRef]

sustainability

MDPI

Article

How does the Ecological Well-Being of Urban and Rural Residents Change with Rural-Urban Land Conversion? The Case of Hubei, China

Min Song [1,2,*], Lynn Huntsinger [2] and Manman Han [3]

[1] School of Business Administration, Zhongnan University of Ecomomics and Law, Wuhan 430073, China
[2] Department of Environmental Science, Policy and Management, University of California at Berkeley, Berkeley, CA 94720-3110, USA; huntsinger@berkeley.edu
[3] Department of Land Management, Zhejiang University, Hangzhou 310058, China; hanman1016@163.com
* Correspondence: songmin0211@hotmail.com; Tel.: +86-189-862-43230

Received: 4 January 2018; Accepted: 14 February 2018; Published: 15 February 2018

Abstract: Human well-being can be affected by the loss of ecosystem services from conversion of agricultural lands. Uncovering negative ecological consequences of rural-urban conversion is important for regulating rural-urban land conversion. This paper evaluates the impacts of rural-urban land conversion on the ecological well-being of different interest groups in China and makes policy recommendations for mitigating them. This research empirically quantifies and compares changes in the ecological well-being of rural and urban residents due to rural-urban land conversion and examines how transformation factors affect such changes in Hubei, China using the Fuzzy Synthetic Evaluation Model. Results show that compared with urban residents, rural resident ecological well-being level declines more obviously with rural-urban land conversion. Two socio-demographic characteristics, age and education level, as well as zoning characteristics, influence both rural and urban resident well-being changes. It is argued that there is a need for quantitative measurement of agricultural ecosystem services changes and that the construction of ecological compensation policies in areas undergoing rural-urban land conversion is essential for regulating rural-urban land conversion and for maintaining resident ecological well-being.

Keywords: ecological well-being changes; rural-urban land conversion; transformation factors; urban residents; rural residents; China

1. Introduction

Humans are dependent upon the services provided by nature and unless we effectively account for the range of values from ecosystems in our efforts to protect the environment, we cannot sustain human well-being [1,2]. Land use and land cover change (LUCC) is a driver of global change that directly influent the status and integrity of ecosystems and in last term its capacity to supply ecosystem services [3]. While human well-being, as an endpoint and central yardstick for sustainability, is widely recognized as an important issue but is difficult to be studied empirically [4–6]. One of the outcomes of urbanization in China, "rural-urban land conversion" is the change from agricultural land in rural areas to developed urban land which is a kind of LUCC [7,8]. Rural-urban land conversion provides land element for urban sprawl, industrial development and economic growth. But it also presents a challenge to the ecological system because many ecosystem services provided by agricultural land are lost in the process of conversion, which can be described as the negative external ecological effects of rural-urban land conversion [9–13]. Fortunately, such losses in human well-being have received increasing attention in economic analysis and public policy making, based on the ecosystem services functions as well as human well-being indicators made in the Millennium Ecosystem Assessment

(MA) [14–17]. Currently, some empirical studies aimed to uncover the relationship between land use change or ecosystem services and human well-being have been reported in many countries, including the U.S. [18], Brazil [19], South Africa [20], China [6], Spanish [3] and the U.K. [21]. However, the issue of how to quantify the changes in ecological well-being of rural and urban residents due to rural-urban land conversion and how conversion factors affect such changes has not been adequately studied [22–24]. In view of this, this paper constructs an ecological well-being index for residents, quantifies the changes in ecological well-being of residents caused by rural-urban land conversion and examines the impact of transformation factors (socio-demographic characteristics and zoning characteristics) on these changes for rural and urban residents.

The agricultural social-ecological system includes agricultural land, the natural environment and human interventions. It is commonly characterized as semi-natural and semi-artificial [25–27]. The agroecosystem provides not only agricultural products including grain, fiber, vegetable, wood and fishery products but also multiple ecological services such as air purification, climate regulation, soil stability and eco-landscapes [14,28,29]. With the acceleration of land-based urbanization in China since the 1980s, the population has been migrating to urban areas triggering unprecedented, fierce land competition and tremendous land use changes. The character of rural-urban land conversion in China in the last 30 years has been described as 'accelerating urban expansion, establishing the eastern part of China as the center of gravity and extending out to the Midwest of China' [16]. Rural-urban land conversion transfers the semi-natural landscapes to a landscape of buildings and roads. The biological community, soils, water flow and surface structure of agricultural lands is destroyed in this process which means that the land's original ecosystem degrades [30–32]. The capability of agricultural land to providing various ecological services is diminishing and declining accordingly [33]. Therefore, rural-urban land conversion which is a common social-economic phenomenon in developing countries has significant negative externalities from the ecological point of view [13,31,34,35]. Such land use transitions had negative effects on local ecological systems and human well-being may decline when these negative externalities are ignored and incorrectly treated [3,36,37]. In 2005, the MA presented a conceptual framework which revealed the interactions between ecosystem services, human well-being and the driving forces of change and it pointed out that ecosystem services (including provision services, regulating services, cultural services and supporting services) are closely related to human well-being. Human well-being was explained as the basic material for a good life, health, good social relations, security and freedom of choice and action [38,39]. In view of these, the human well-being discussed in this paper is limited to those factors closely associated with ecosystem services and termed "human ecological well-being".

The existing research usually focuses on the evaluation of a certain kind of ecological service from the agricultural ecosystem, such as supply services that underpin basic livelihood capacity [40], coordinating services that can prevent extreme weather, conserve water and purify the air [31,41], support services that provide habitat for plants and animals and maintain the potential for sustainable use of agricultural land resources in the future [42,43], as well as cultural services that include educational opportunities, inspiration, entertainment and local identity [44–46]. Scholars in China have paid close attention to the changes in the overall welfare of some stakeholders in the process of rural-urban land conversion [11,47,48], especially the overall welfare of farmers [49–51]. Most of these papers used the theories and methods of welfare economics to calculate the economic or material welfare changes caused by rural-urban land conversion, while neglecting the impact of ecosystem change on human well-being from the externalities of land use change [40]. In recent years, some scholars have begun to link human ecological well-being loss with ecosystem change from the perspective of the relationship between ecosystem services and human well-being, based on the framework for ecosystem services as well as human well-being constituents from the MA [15,17,52]. Such research calls for the investigation of resident ecological well-being changes in the process of rural-urban land conversion. Of quantitative measurement methods, the most commonly used methods are stated-preference methods including the Contingent Valuation Method (CVM), Choice

Experiment Method (CE), etc. [44–46]. However, these methods have some inherent defects, to be more specific, CVM can only estimate a well-being change caused by one certain state of environmental change and the accuracy of its result is affected by more than ten kinds of inherent latent deviations such as hypothetical deviation, partial-global deviation, strategic deviation, etc. [53,54]. Although CE is able to calculate the economic value of different attributes of resources, its estimation accuracy depends on the authenticity and reliability of the survey data and is influenced by embedding bias, hypothetical deviation, etc. [55]. Therefore, the systematic research on the relationship between agroecosystem services and human well-being needs to be further advanced in terms of content and method.

Moreover, for the sake of protecting limited agricultural land, China implemented the world's most stringent Land Use Control System starting in the 1980s, upgrading to Land Use Spatial Control in recent ten years. It can be seen as a conversion from reserving the quantity of agricultural land to regulating agricultural land protection spatially [13,56,57]. Specifically, Land Use Spatial Control in China divides the entire land space into four major function oriented zones including the Optimizing Development Zone, Key Development Zone, Restricted Development Zone as well as the Forbidden Development Zone according to resource and environment carrying capacity, existing development density and development potential, natural environmental constituents, the level of socio-economic development, ecosystem characteristics and the spatial differentiation of human activities in different areas. This raises some questions, notably, when rural-urban land conversion occurs in the different zones, are there different changes in the ecological well-being of residents? Investigation of this question can provide a basis for the implementation of spatially heterogeneous ecological compensation mechanisms for agricultural land protection.

The goal of this paper, therefore, is to examine the specific human well-being constituents that closely relate to the ecological services from agricultural lands and which foster "human ecological well-being". We construct an evaluation index for resident ecological well-being, quantify the changes in ecological well-being of residents due to rural-urban land conversion and analyze the effect of individual and zoning transformation factors. We examine impacts on both rural and urban residents: we hypothesize that both are affected by the agroecosystem because of spillover effects but that they are affected differently owing to their different relationship with and distance from agricultural lands. The research findings from this study provide a foundation for evaluating impacts of conversion on the ecological well-being of different interest groups, for regulating rural-urban land conversion by zoning and for establishing an efficient ecological compensation mechanism for rural-urban land conversion.

2. Constituents of Resident Ecological Well-Being

The Millennium Ecosystem Assessment (MA) was called for by United Nations Secretary-General Kofi Annan in 2000 and had lasted for 4 years since it was initiated in 2001. The objective of the MA was to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being. Two of the four core questions of MA are "Who caused the ecosystem and their services change and how these changes affected human well-being?" In 2005, the MA presented a conceptual framework which revealed the interactions between ecosystem services and human well-being and it pointed out that ecosystem services (including provision services, regulating services, cultural services and supporting services) are closely related to human well-being (including the basic material needs for a good life, health, good social relations, security and freedom of choice and action) [38]. On this basis, series indices are selected in this paper to set up the evaluation index system for resident ecological well-being based on the classification for human well-being constituents of MA, combined with the characteristics of agroecosystem and the existing literature about human well-being (Figure 1 and Table 1). In view of the different ecological impacts on rural and urban residents from rural-urban land conversion, the specific indices of ecological well-being for the two groups are slightly different (Table 1).

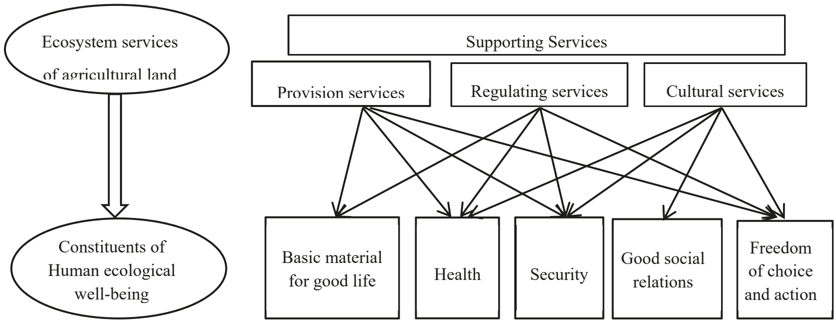


Figure 1. Relationship between agro ecosystem services and human ecological well-being.

Table 1. Index system of resident ecological well-being.

Constituents of Ecological Well-Being	Criterion	Indices: Rural residents	Indices: Urban residents
Security X_1	Access to clean and secure living spaces	Waste recycling capability X_{11}	
	Reduction of environmental attack and threats	Frequency of agroecosystem-related meteorological disasters (such as drought, floods, soil erosion and desertification) X_{12}	
Basic material for a good life X_2	Access to resources for income and livelihood	Obtain daily staple food X_{21} Obtain daily vegetables X_{22} Obtain daily meat X_{23}	
Health X_3	Access to clean air	Satisfaction with air quality X_{31}	
	Access to adequate and clean water	Satisfaction with water quality X_{32}	
	Obtain adequate nutrition	Safety of food, vegetables and meat consumption X_{33}	
	Avoidance of preventable diseases	Pollution-related diseases X_{34}	
Good social relations X_4	Opportunities to express cultural and spiritual values associated with the ecosystem	Rural life nostalgia X_{41} Children's rural experiences X_{42}	
	Opportunities to experience the aesthetic and recreational values associated with the ecosystem		Frequency of ecotourism X_{43} Satisfaction with the natural landscape X_{44}
Freedom of choice and action X_5	Achieving the status of valuable survival state	Livelihood choices X_{51}	

2.1. Security

The MA recognizes that the security refer to safety of person and possessions, secure access to necessary resources and security from natural and human-made disasters [38]. Rural-urban land conversion weakens the land's capacity for water conservation, weather moderation and waste recycling [31,40]. The recycling of surface runoff and flood regulation are significantly affected [31]. This paper selects the indices of waste recycling and the frequency of meteorological disasters (such as drought, floods, soil erosion and desertification etc.), which are related to the agricultural ecosystem, to characterize resident well-being level for the security constituent. What needs to be explained is that the index of waste recycling capability is only for rural resident survey and analysis, because waste needs ecosystems to degrade in many rural areas where still short of complete waste disposal system.

2.2. Basic Materials for a Good Life

Basic material for a good life refers to the ability to have a secure and adequate livelihood, including income and assets, enough food and water at all times, shelter, ability to have energy to keep warm and cool and access to goods [38]. Agroecosystem synthesize organic compounds by solar energy and artificial auxiliary energy, providing the fundamental materials for human life [58]. Rural-urban land conversion changes the basic material conditions of rural residents as the direct users of agricultural land. Therefore, the existing compensation institutions for agricultural land acquisition should not only take economic compensation into account but also compensation for degradation of access to ecosystem resources [40]. In the assessment's conceptual framework of interactions between ecosystem services and human well-being constructed by MA, one of the services—the provisioning service—refers to the products obtained from the ecosystem. Changes in provisioning services such as food, water and fuelwood have very strong influences on the adequacy of material for a good life. And it is also stated that the access to these materials is heavily mediated by socioeconomic circumstances [38]. This research focuses on agroecosystem which produce food mainly. Besides, in many underdeveloped rural areas in China, farming is still the main way for farmers to get food to meet the basic need of life. Therefore, this paper uses changes in the way that rural residents obtain daily ingredients (staple food, vegetables and meat) to represent the change in basic materials for a good life. It should be noted that the relationship between an urban resident's basic materials for a good life and the agroecosystem is not significant, because on the one hand, they have no direct connection with the agricultural land (they do not farm), on the other hand, as a relatively wealthy group, local changes in ecosystems may not cause a significant change in their access to necessary material goods [38]. Accordingly, this paper considers that the basic materials for an urban resident's good life remain unchanged in rural-urban land conversion. So the indices of obtained daily staple food, obtained daily vegetables and obtained daily meat, which are employed to characterize the constituents of basic materials for a good life, are only used for the rural resident survey and analysis.

2.3. Health

The MA states that the constituent of health is the ability of an individual to feel well and be strong, or in other words to be adequately nourished and free from disease, to have access to adequate and clean drinking water and clean air and to have the ability to have energy to keep warm and cool [38]. Rural-urban conversion destroys the nutrient recycling capacity of agroecosystem [59–62]. Therefore, this paper investigates the satisfaction of rural and urban residents with their daily consumption of staple food, vegetables and meat to measure the change in their capability of obtaining enough nutrition. Existing studies also suggest that agroecosystem have the function of blocking and absorbing a certain amount of particulate waste [63], preventing the deterioration of river water [64] and controlling the spread of epidemic diseases [58]. In view of these, in this paper, the capability of avoiding preventable diseases is measured by the indices of number of ecological pollution-related diseases. Access to adequate and clean water as well as clean air is measured by the indices of resident satisfaction with water quality and air quality separately.

2.4. Good Social Relations

Good social relations can be explained as the presence of social cohesion, mutual respect and the ability to help others and provide for children [38]. The capability of providing aesthetic values and interactions between human and the ecological environment offered by agricultural lands have been recognized as vital service functions [17,65]. Rural-urban land conversion typically triggers aesthetic damage [66]. For urban residents, the decline of agricultural land reduces their opportunities for rural tourism, agritainment, etc. In this paper, the constituents of good social relations for urban residents are measured by indices of frequency of ecotourism and satisfaction with the natural landscape. Agroecosystem fosters specific agricultural cultures which include agricultural production activities and rural lifestyles [67] and also the link between humans and nature as well as humans and society [44]. In China, farmers are strongly attached to their agricultural land. A deep and irreversible ruin of the cultural and spiritual heritage of rural areas takes place when rural-urban land conversion proceeds [68].Therefore, the constituent of good social relations for rural residents is characterized by indices of rural life nostalgia and children's rural experiences.

2.5. Freedom of Choice and Action

Freedom of choice and action refers to the ability of individuals to control what happens to them and to be able to achieve what they value doing or being [38]. The basic livelihood of rural populations depends mainly on the services provided by agroecosystem [40]. Agricultural populations who live in poor areas are influenced by land use change more directly and profoundly [69].

Before rural-urban land conversion, rural residents have the freedom to make choices between farming and working in urban areas. However, after the rural-urban land conversion, their livelihood choices are more limited because they have no other choice but to work in urban areas. Their low level of education and inadequate non-agricultural labor skills exacerbate this limitation. While for urban residents, rural residents entering urban areas to work compete for the available jobs. Therefore, this paper uses livelihood choices as an index to measure changes in resident freedom of choice and action.

3. Materials and Methods

3.1. Study Area

Wuhan City and Shiyan City in Hubei Province were selected as the study area (Figure 2). Wuhan City which is located in a Key Development Zone according to the Main Function Oriented Division (MFOD) is a megalopolis in middle of China. Wuhan City, with an urbanization rate of 71.7% at the end of 2016, significantly higher than any other city in Hubei province, is developing at soaring speed in recent years. It is in the phase of accelerated urbanization which accompanies rapid urban expansion. Wuhan City has 13 districts, including 7 central districts and 6 suburban districts. The latter is composed of Jiaxia district, Caidian district, Huangpi district and so on and the area with the highest rate of rural-urban land conversion in the last few years. However, Shiyan City, located in the northwest border of Hubei Province, is in a Restricted Development Zone. It is not only a poor region of the Qin-ba mountain area but also the Core Water Source Area of the Middle Route of the South-to-North Water Diversion Project. This city, which has adopted a "focus on ecology externally and focus on humanities internally" as its development strategy is now facing the dilemma of balancing ecological protection and economic development.

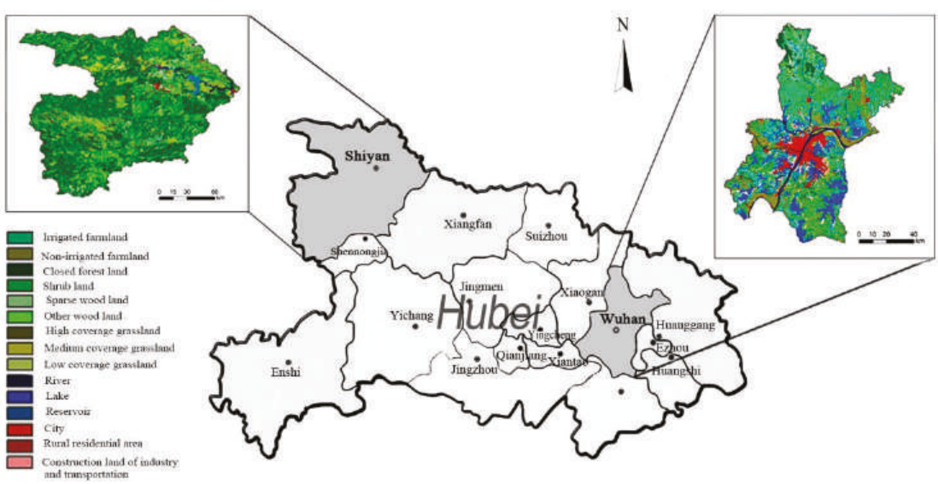


Figure 2. Study areas (Color should be used).

3.2. Questionnaire Design and Data Collection

In general, the questionnaire collected information regarding (1) a brief description about the multifunction of agricultural land and agricultural land loss in the process of rapid urbanization in China (2) respondents' perception of the ecosystem services changes caused by rural-urban land conversion. Questions are designed according to the indices showed in Table 1 (i.e. "Do you think the Frequency of drought/floods/soil erosion/desertification increased?" If "yes," "Do you think it is related to rural-urban land conversion?" The five-point Likert scale (i.e. strongly disagree, mildly disagree, unsure, mildly agree and strongly agree) was used for respondents to choose (3) the socio-demographic information of area residents. It must be noted that, considering the specific indices of ecological well-being for the rural residents and urban residents are slightly different (Table 1), two different questionnaires were developed for these two groups of respondents. Specifically, rural residents were asked to compare the state of each kind of agroecosystem services before and after they lost their agricultural land (either positive or negative). If they think there were changes, they needed to indicate their opinion about whether those changes were related to rural-urban land conversion as well as the degree of relevance. Urban residents were asked to clarify their perception of the changes of each kind of agroecosystem services in the last fifteen years and also needed to indicate their views on whether those changes were related to rural-urban land conversion as well as the degree of relevance. To avoid investigators deviation in survey, we made no effort to force respondents to provide arguments; they were given the option to not provide an argument if they did not recognize any change [3,70].

In this research, respondents are composed of two groups, rural residents and urban residents, defined according to the census registration system in China. "Rural residents" refers to people who are registered in a village and are generally eligible to be assigned agricultural land to work and make a living from. "Urban residents" are those who are registered as urban permanent residents and live in urban areas. Major Function Oriented Zoning Division (MFOZD) of China which is the guideline for optimizing the spatial pattern of regional development in China is put forward in 2011. Based on comprehensive analysis on regional resources and environment capacity, existing development density and potential, MFOZD divides the land space of China into a series of regional units according to a specified major function for each area. Some regions are planned as urbanizing regions (develop functional regions) whose major function is providing industrial products and services. Such areas are named "Priority Development Zone" or "Key Development Zone". Other regions are planned as agricultural regions (ecology functional areas) whose major function is providing ecological services. Such areas are named "Restricted Development Zone" or "Forbidden Development Zone". In order to investigate the impact of location on resident ecological well-being changes, Wuhan City and Shiyan City of Hubei Province are selected as study areas in this study. The two cities belong to a Key Development Zone and a Restricted Development Zone, respectively, according to the MFOZD of China.

Specifically, survey sites for rural residents were selected in the suburbs, where rural-urban land conversion has been frequent in recent years, while for urban residents the sites selected were open spaces or parks with a large flow of people. Ultimately, rural residents were surveyed in five administrative villages including Xingfu Village, Xiangyang Village, Fangliang Village, Liuhe Village and Chunhe Village in the Jiangxia District of Wuhan City, as well as in five administrative villages including Erdaopo Village, Caijialing Village, Wolonggang Village, Qinglongshan Village and Changping Village in Yunyang District of Shiyan City. Urban residents were surveyed in two central districts including the Hongshan District and Hangjiang District in Wuhan City as well as the Zhangwan District in Shiyan City. Sample size was estimated using the following sampling formula proposed by Scheaffer [71].

$$N^* = N/\left[(N-1)\sigma^2\right] + 1$$

where N^* is the needed theoretical sample size, N is the population of study area, σ is the sampling error ($\sigma = 5\%$) [71]. By the end of 2015, the population of Wuhan and Shiyan were 1166.24×10^4 obtained from Wuhan Statistical Yearbook (2016) and Wuhan Statistical Yearbook (2016), including 729.57×10^4 urban residents and 436.67×10^4 rural residents. Accordingly, the sample size required for our research should be at least 402. Considering the possible unresponsive or invalid samples, a total of 500 interviewees including 220 rural residents and 280 urban residents were randomly selected to be surveyed in the study areas mentioned above. Our research team which was composed of 8 postgraduates majoring in land resource management took face-to-face interviews to obtain data throughout the entire data collection periods in May 2015 and May 2016. Interviewers were asked to learn the contents of the questionnaire, especially the key issues and questions, through pre-training and pre-research to avoid investigators deviation. Besides, each interview was limited to 20–25 min to avoid length of residence time bias. After a brief description of the purpose of our research and obtaining permissions, we explained meaning of each index embedded in the questions of the questionnaire. And their answers were faithfully recorded by the interviewers. Ultimately, valid questionnaires were obtained from 209 rural residents and 266 urban residents after discarding invalid samples that included illogical or incomplete information.

3.3. Methods

3.3.1. Fuzzy Synthetic Evaluation Model

The core essence of Fuzzy Mathematics is regarding fuzzy concepts as study objects, employing fuzzy sets to determine imprecise or complex things and adopting the value of membership function to describe the degree to which a certain constituent belongs to a fuzzy set, which is employed to describe imprecision or vagueness [49]. The 'human ecological well-being' which is studied in this paper is one aspect of the concept of 'human well-being.' Researching the impacts of changes in life status and the subjective feelings and psychological characteristics of rural residents and urban residents as they are related to the ecosystem of agricultural land is essential to exploring this issue. Since most of these constituents are subjective and vague, the Fuzzy Synthetic Evaluation Model has a significant advantage for dealing with the subjective evaluation indexes is appropriate for this study.

X is defined as the fuzzy set of resident state of ecological well-being. W is a subset of X which represents the possible change in ecological well-being as a result of rural-urban land conversion. Then, the ecological well-being function $W^{(n)}$ of the nth rural dweller or urban dweller can be expressed as follows:

$$W^{(n)} = \{x, \mu_w(x)\}$$

where $\mu_w(x)$ is the membership value function for x belonging to W, $\mu_w(x) \in [0,1]$ and $x \in$ X. It is well accepted that the higher the membership value is, the higher the ecological well-being level is. When the membership value is 1, the ecological well-being of residents is the best; when it is 0 it is the worst and 0.5 is the medium state, neither good nor bad.

3.3.2. Forms of Membership Function

The membership function is one of the critical points of the fuzzy synthetic evaluation method and the membership function is different according to the different types of variables used. Variables are usually divided into three types: virtual dichotomous variables, virtual continuous variables and virtual qualitative variables. Let x_{ij} represent the value of the jth evaluation index of the ith constituent of the resident's ecological well-being. x_i is the ith constituent subset of resident ecological well-being which is determined by the primary index x_{ij}. The initial index of ecological well-being is $x = [x_{11}, \cdots, x_{ij}, \cdots]$.

There are only two cases of virtual dichotomous variables which are commonly described by "true" or "false". For example, the question "Whether you and your family have had diseases that are related to ecosystem?" applies to the virtual dichotomous variable whose membership function can be expressed as follows:

$$\mu(x_{ij}) = \begin{cases} 0 & X_{ij} = 0 \\ 1 & X_{ij} = 1 \end{cases} \quad (1)$$

When the respondent has diseases due to ecological environmental pollution, X_{ij} is 0, otherwise X_{ij} is 1.

Virtual continuous variables are the indices that have continuous values. Their membership function can be expressed as follows. Equation (2) describes the positive relationship between X_{ij} and the state of ecological well-being, while Equation (3) describes the negative relationship between them.

$$\mu(x_{ij}) = \begin{cases} 0 & 0 \le x_{ij} \le x_{ij}^{min} \\ \frac{x_{ij} - x_{ij}^{min}}{x_{ij}^{max} - x_{ij}^{min}}, & x_{ij}^{min} \le x_{ij} \le x_{ij}^{max} \\ 1 & x_{ij} \ge x_{ij}^{max} \end{cases} \quad (2)$$

$$\mu(x_{ij}) = \begin{cases} 0 & 0 \le x_{ij} \le x_{ij}^{min} \\ \frac{x_{ij}^{max} - x_{ij}}{x_{ij}^{max} - x_{ij}^{min}}, & x_{ij}^{min} \le x_{ij} \le x_{ij}^{max} \\ 1 & x_{ij} \ge x_{ij}^{max} \end{cases} \quad (3)$$

where x_{ij}^{min} and x_{ij}^{max} represent the minimum and maximum value of X_{ij} respectively.

Quantitative data are generally not available for some ecological well-being indices as some can be described by qualitative words only. Examples like this including the respondents' answers about "How satisfied are you with the air quality," "How about your nostalgia about rural life?" etc. These kinds of indexes are dealt with by a Likert scale which assigns the range of agroecosystem services from 1 through 5 at equidistant intervals. When satisfaction is measured, a larger value indicates a better ecological well-being state. On the contrary, when a negative indicator such as the frequency of agroecosystem-related meteorological disasters is measured, a larger value indicates a worse state. The membership function $\mu(x_{ij})$ of the virtual qualitative variable is as follows:

$$\mu(x_{ij}) = \begin{cases} 0 & 0 \le x_{ij} \le x_{ij}^{min} \\ \frac{x_{ij} - x_{ij}^{min}}{x_{ij}^{max} - x_{ij}^{min}}, & x_{ij}^{min} \le x_{ij} \le x_{ij}^{max} \\ 1 & x_{ij} \ge x_{ij}^{max} \end{cases} \quad (4)$$

$$\mu(x_{ij}) = \begin{cases} 0 & 0 \le x_{ij} \le x_{ij}^{min} \\ \frac{x_{ij}^{max} - x_{ij}}{x_{ij}^{max} - x_{ij}^{min}}, & x_{ij}^{min} \le x_{ij} \le x_{ij}^{max} \\ 1 & x_{ij} \ge x_{ij}^{max} \end{cases} \quad (5)$$

where x_{ij}^{min} and x_{ij}^{max} represent the minimum and maximum value of X_{ij} respectively.

3.3.3. Weight Determination

The Delphi method and the Analytic Hierarchy Process are commonly used in the calculation of weights but these are questioned due to the subjectivity of their results. This paper uses the weight definition proposed by [72] and employs the weight function as modified by [49,73].

$$\omega_{ij} = ln\left[1/\overline{\mu(x_{ij})}\right] \quad (6)$$

3.3.4. Aggregate the Membership Values of Indices

According to the different types of the constituents described above in Section 3.3.2, corresponding membership functions are selected to calculate the indices membership value. And then the constituents' membership value is calculated according to the weight function. Therefore, the membership value of resident ecological well-being is as follows:

$$W^{(n)} = \sum_{i=1}^{I} \mu\left(x_{ij}\right)^{n} \cdot \omega_{ij}^{(n)'} \;/ \sum_{i=1}^{I} \omega_i \tag{7}$$

3.3.5. Transformation Factors

Well-being can be described as an individual's satisfaction with some aspects of his/her life as determined by his/her individual life states, physiological conditions and psychological factors [74]. It is recognized as the freedom and capability to choose different kinds of lifestyles in order to get access to a beautiful life, a healthy state, rich experiences, good social relations, cultural identity, a deep sense of belonging, respect and self-realization etc. in the process of natural ecosystem utilization and development [75,76]. Capability approach was put forward by Sen and he discussed the relationship between an individual's functioning, capability and values (or utilities which are defined in the usual terms of pleasures, happiness, or desire fulfillment) [77–79]. On this basis, the changes of farmers' economic and non-economic well-being in the process of rural-urban land conversion have been researched [49,51,73]. It figured out that the conversion degree and efficiency by which the goods or service changing to well-being are significantly different for each individual due to the differences in personal, social and environmental conditions which are conceptualized as "transformation factors". For example, different age groups have different anticipations when facing same environmental changes, more highly educated groups have better ability for livelihood selection and further environmental cognition [51,80]. In addition, an individual's preference for ecosystem services is affected by local environmental resources endowments to some extent [29]. Transformation factors could explain that why different people in same state have different levels of well-being. Sen (1999) studied five categories of conversion factors including the heterogeneity of individual, the diversity of the environment, the difference of social atmosphere, the difference of interpersonal relationship and the distribution of the family. Considering that the social atmosphere is stable in certain period of time in China, interpersonal relationship mainly reflect different social differences and ecological well-being is closely related to personal perception not the family internal distribution, this paper uses 'transformation factors' which influence the impact of rural-urban land conversion on an individual's ecological well-being to further investigate the effects of rural-urban land conversion. Socio-demographic characteristics including gender (T_1), age (T_2) and education level (T_3), as well as zoning characteristic which is represented by location (T_4) are selected as transformation factors which are employed to analyze the differences of ecological well-being change between rural residents and urban residents.

4. Results

4.1. Changes in Resident Ecological Well-Being

According to the actual situation obtained through the survey, the membership values of rural resident ecological well-being indices including satisfaction with air quality, satisfaction with water quality, rural life nostalgia and children's rural experiences are all set as 0.5 which means that the state of rural resident ecological well-being mentioned above is neither good nor bad before rural-urban land conversion and the membership values of their ecological pollution-related diseases is set as 1 which means they did not get diseases due to ecological environment pollution. The membership values of urban residents' each ecological well-being index and overall ecological well-being are all set as 0.5 which means that the state of their ecological well-being is neither good nor bad before rural-urban land conversion. Resident ecological well-being changes are displayed in Table 2.

Table 2. Fuzzy evaluation results of resident ecological well-being change due to urban-rural land conversion.

Ecological Well-Being Constituents	Rural Residents				Urban Residents			
	Membership Value		Weight		Membership Value		Weight	
	Before	After	Before	After	Before	After	Before	After
X_1	0.553	0.509	0.593	0.676	0.500	0.437	0.657	0.828
X_{11}	0.542	0.518	0.565	0.487	—	—	—	—
X_{12}	0.564	0.500	0.573	0.693	0.500	0.437	0.657	0.828
X_2	0.677	0.417	0.390	0.876	—	—	—	—
X_{21}	0.770	0.397	0.261	0.924	—	—	—	—
X_{22}	0.692	0.417	0.368	0.875	—	—	—	—
X_{23}	0.615	0.438	0.486	0.826	—	—	—	—
X_3	0.500	0.456	0.693	0.786	0.500	0.377	0.739	0.976
X_{31}	0.500	0.420	0.693	0.868	0.500	0.373	0.739	0.986
X_{32}	0.500	0.479	0.693	0.736	0.500	0.389	0.747	0.944
X_{33}	0.500	0.380	0.693	0.968	0.500	0.437	0.715	0.828
X_{34}	1.000	0.708	0.000	0.345	0.500	0.325	0.627	0.724
X_4	0.500	0.250	0.693	1.385	0.500	0.520	0.723	0.654
X_{41}	0.500	0.211	0.693	1.556	—	—	—	—
X_{42}	0.500	0.301	0.693	1.201	—	—	—	—
X_{43}	—	—	—	—	0.500	0.585	0.615	0.536
X_{44}	—	—	—	—	0.500	0.473	0.763	0.749
X_5	0.413	0.202	0.884	1.599	0.500	0.487	0.597	0.719
X_{51}	0.413	0.202	0.884	1.599	0.500	0.487	0.597	0.719
Overall	0.507	0.326			0.500	0.447		

4.1.1. Changes in the Ecological Well-Being of Rural Residents

Rural resident overall level of ecological well-being in Wuhan City and Shiyan City declines from 0.507 to 0.326 with urban-rural land conversion, a decrease of 35.67% (Table 2; Figure 3). In fact, levels of all the five well-being constituents decline.

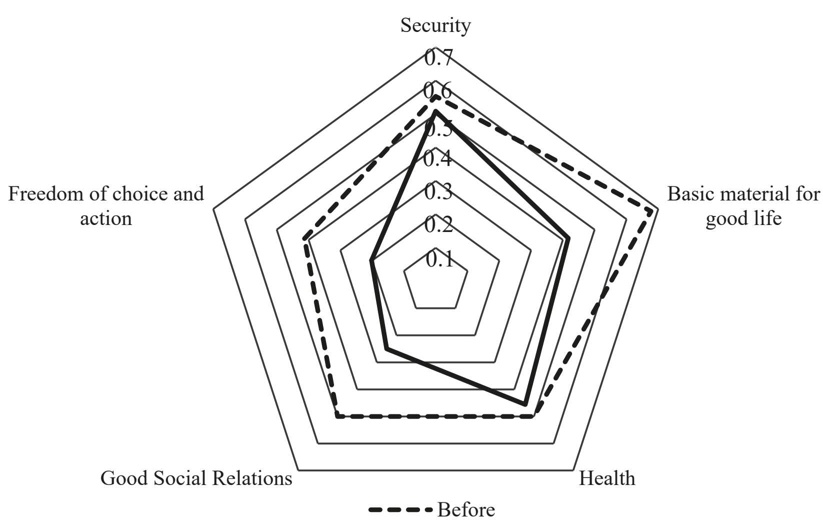


Figure 3. Membership value changes with the constituents of rural resident ecological well-being due to rural-urban land conversion.

- Security

Before rural-urban land conversion, waste in rural areas was normally disposed of using traditional methods (landfill, incineration, natural piling, etc.). Most livestock manure, litter, food waste and other production and household waste can be degraded by agroecosystem automatically. The survey found that although garbage collection boxes were provided in the study area after rural-urban land conversion, the inadequate infrastructure of garbage disposal and untimely recycling of garbage made the environment worse and some of the wastes that are still disposed of using traditional methods cannot actually be degraded by the environment any more. Consequently, the level of rural resident ecological well-being due to recycling capacities declines (from 0.542 to 0.518). In addition, rural-urban land conversion promotes the transfer of a huge amount of agricultural land to urban construction land in China. Changes in the surface environment trigger off declines in soil water holding capacity, which further weakens the local environment's capacity for moderating floods, droughts and other extreme weather. Results show that the level of rural resident ecological well-being about the frequency of agroecosystem-related meteorological disasters declines by more than 10% (from 0.564 to 0.500). In general, the overall level of the rural resident ecological well-being as related to security declines by 7.96% (from 0.553 to 0.509).

- Basic materials for a good life

With the rural-urban land conversion, the ability to have a secure and adequate livelihood of rural resident turns from a good status (0.677) in a negative direction (0.417), which breaks through the fuzzy state of neither good nor bad (0.500) and changes toward a bad direction (Table 2). The way that rural residents get access to daily necessities is changed directly by rural-urban land conversion. Before rural-urban land conversion, rural residents basically obtain daily staple food (rice, flour and beans), vegetables and meats from their own farms. A small amount of supplementary vegetables and meat products are purchased from the market. When farmers lose their agricultural land after rural-urban land conversion, they are forced to buy daily foods in the market. Our survey reveals that this change greatly increases their living expenses and makes their lives difficult.

- Health

Due to rural-urban land conversion, agricultural land's original ecosystem services such as atmospheric regulation and air purification are weakened. In addition, air pollution, construction dust and sewage disposal soar early in land development. The two effects are superimposed so that the indices of air quality satisfaction and water quality satisfaction fall by 16.00% (from 0.500 to 0.420) and 4.20% (from 0.500 to 0.479) separately. Further, rural residents have to purchase for the original materials of food from the market which was previously acquired from farming. This raises the risk of food safety issues. The index of safety satisfaction with staples, vegetables and meat falls by 24.00% (from 0.500 to 0.380). Moreover, the membership value for the index of ecological pollution-related diseases rises (0.708 > 0.500) after rural-urban land conversion but still has a certain degree of decline (from 1.000 to 0.708). On the whole, rural resident ecological well-being for the constituent of health is declines by 8.86% (from 0.500 to 0.456).

- Good social relations

This constituent is greatly influenced by rural-urban land conversion. Agricultural land is the material carrier of farming culture. Rural residents in China have a strong sense of dependence on agricultural land which is the basis of maintaining good social relations. Rural-urban land conversion cuts off their access to agroecosystem and cultures, which makes the indices of rural life nostalgia and children's rural experiences fall by 57.8% (from 0.500 to 0.211) and 39.8% (from 0.500 to 0.301) separately. As a whole, the membership value of the constituent of good social relations declines by 50.00% (from 0.500 to 0.250).

- Freedom of choice and action

Rural residents' freedom of choice and action is constrained by their lower ability to make a living, so it is at a low level before the rural-urban land conversion (0.413 < 0.500). With the loss of agricultural land, this constituent appears to be the constituent that declines most significantly, by 51.09% (from 0.413 to 0.202). The reason is that rural-urban land conversion directly reduces the natural capital of rural residents, which has a critical impact on their livelihoods [81]. In the surveyed area, the young landless rural residents have to work in township enterprises nearby or work in cities but their inadequate vocational skills make them poor. While older residents basically lose their way to make a living by farming and most of them can only stay at home. Considering the irreversibility of rural-urban land conversion, the decline of their freedom of choice and action is permanent.

4.1.2. Changes in the Ecological Well-Being of Urban Residents

Similar to the analysis of changes in rural resident ecological well-being, changes in the ecological well-being of urban residents can be summarized as follows briefly. Table 2 and Figure 4 show that the rural-urban land conversion makes the overall ecological well-being level drop from 0.500 to 0.447, 10.64%. Specifically, the three constituents of urban resident ecosystem well-being including security, health and freedom of choice and action all declines after the rural-urban land conversion. The constituent of health declines most significantly by 24.67% (from 0.500 to 0.377), within which the two indices including satisfaction with water quality and experience of ecological pollution-related diseases drop strikingly. The constituent of security declines by 12.60% (from 0.500 to 0.437) which reveals that urban residents approve of agricultural land's ecosystem services functions to a certain degree. Different from the rural residents, urban residents' freedom of choice and action is not affected by rural-urban land conversion significantly, it only drops by 2.60% (from 0.500 to 0.487) because urban residents are not closely linked with agricultural land and they have pluralistic livelihoods. It should be noted that the membership value of the constituent of good social relations rose slightly (from 0.500 to 0.520). Although the frequency of ecotourism reflects good social relations and has positive impact on resident ecological well-being, we discovered in the survey that the rise in this index's membership value is mainly due to improvement in people's living standards, allowing them to participate in ecological recreational activities more frequently. In other words, it is not closely related to the increase or decrease of agricultural land.

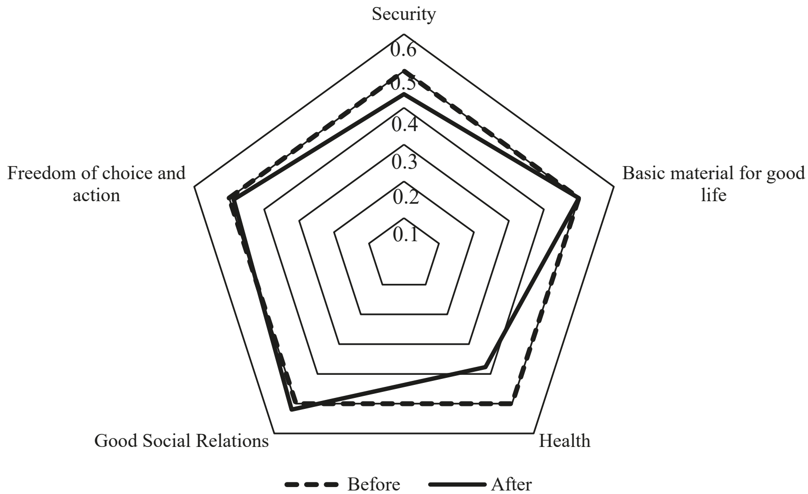


Figure 4. Membership value changes with the constituents of urban resident ecological well-being due to rural-urban land conversion.

4.1.3. Comparison

Comparing the ecological well-being of rural and urban residents, it can be observed that there are obvious differences between these two major stakeholder groups. The changes in rural residents overall ecological well-being and in each constituent of ecological well-being, are all greater than in urban residents. As direct users of agricultural land, rural residents are more closely and complexly interact with the agroecosystem than urban residents [82]. Owing to their high dependence on the agroecosystem, rural residents' ecological well-being unavoidably suffers from rural-urban land conversion. Rural residents are forced to move away from their original residence, lose their agricultural land and directly experience ecological deterioration, etc. Different than for rural residents, the link between urban residents and the agroecosystem is indirect, regardless of the spatial distance to the agricultural land or the intensity of interactions with the ecosystem.

4.2. Impact of Transformation Factors on the Changes in Resident Ecological Well-Being

4.2.1. Rural Residents

Table 3 displays the impact of transformation factors on the changes in rural resident ecological well-being.

- Impact of socio-demographic characteristics

Results show that the ecological well-being of the oldest sample group is the most affected, declining by 37.54%, followed by the least educated sample group, declining by 37.11%. Observing the impact of transformation factors on each constituent of rural resident ecological well-being, it is obvious that their age and education level have a momentous impact on both the ecological well-being constituents of good social relations and freedom of choice and action. The survey which reveals that the older and the less educated the interviewees are, the greater the dependence on their original way of life and the more difficult it is for them to find jobs after rural-urban land conversion. In other words, older and less educated rural residents have less opportunity to express cultural and spiritual values associated with the ecosystem and have less livelihood choices after losing their agricultural land.

- Impact of zoning characteristics

As described above, there are fundamental differences between Wuhan City and Shiyan City in terms of zoning. Specifically, the former is mountainous, while the latter is plains; in view of the MFOZD of China, the former is in a Key Development Zone, while the latter is located in China's Restricted Development Zone; from the ecological perspective, the latter's ecological vulnerability is higher than the former's. The overall change in the rural resident ecological well-being in Shiyan City (declines by 38.19%) is much greater than in Wuhan City (declines by 31.27%) (Table 3). Zoning characteristics have greatest impact on the ecological well-being constituents of freedom of choice and action (declines from 0.426 to 0.211 for Wuhan City and from 0.413 to 0.198 for Shiyan City, both of which declines more than 50%). The decline in the overall ecological well-being levels of rural residents in Wuhan City is mainly due to the decline in two constituents including basic material for a good life and freedom of choice and action. However, in Shiyan City, the dominant constituent in addition to the two above is the constituent of good social relations.

4.2.2. Urban Residents

Table 4 displays the impact of transformation factors on the changes in urban resident ecological well-being.

- Impact of socio-demographic characteristics

There are no significant differences in the impacts of socio-demographic characteristics on the overall levels of ecological well-being for urban residents. This field survey found urban residents' perceptions of changes in the ecological environment is more diverse and that they also have more diverse capabilities for adapting to the changes in the ecological environment brought about by rural-urban land conversion. In comparison, women's ecological well-being declines more than men's when rural-urban land conversion occurs and in the meantime, the older and the less educated the interviewees are, the greater their overall ecological well-being declines.

- Impact of zoning characteristics

Compared with Wuhan City with a higher level of urbanization and higher frequency of rural-urban land conversion, Shiyan City with its rich ecological resources endowment is part of China's key ecological function area and has higher environmental sensitivity. In other words, in comparison with Wuhan City, rural-urban land conversion occurring in Shiyan City will make the marginal benefit of ecosystem services decrease much more, resulting in the fact that urban residents in Shiyan City have more intense perceptions about ecological environment changes.

Table 3. Fuzzy evaluation of rural resident ecological well-being changes using transformation factors.

Transformation Factors			X_1		X_2		X_3		X_4		X_5		Overall		
			Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Change (%)
Socio-demographic characteristics	T_1	Male	0.556	0.511	0.678	0.415	0.500	0.459	0.500	0.255	0.416	0.208	0.509	0.331	−35.04
		Female	0.552	0.508	0.675	0.421	0.500	0.452	0.500	0.248	0.409	0.196	0.506	0.323	−36.08
	T_2	20–30	0.563	0.512	0.685	0.412	0.500	0.457	0.500	0.292	0.419	0.221	0.511	0.346	−32.25
		31–40	0.565	0.508	0.702	0.421	0.500	0.461	0.500	0.286	0.422	0.223	0.513	0.347	−32.40
		41–50	0.557	0.517	0.674	0.409	0.500	0.452	0.500	0.249	0.414	0.205	0.508	0.326	−35.78
		51–65	0.548	0.499	0.659	0.420	0.500	0.449	0.500	0.231	0.405	0.198	0.503	0.318	−36.85
		≥66	0.550	0.506	0.679	0.416	0.500	0.459	0.500	0.233	0.403	0.187	0.503	0.314	−37.54
	T_3	Elementary school graduate and below	0.561	0.507	0.693	0.422	0.500	0.451	0.500	0.246	0.408	0.188	0.507	0.319	−37.11
		Middle school graduate	0.547	0.512	0.665	0.416	0.500	0.457	0.500	0.253	0.413	0.206	0.506	0.329	−34.93
		High school graduate and above	0.554	0.508	0.681	0.417	0.500	0.462	0.500	0.261	0.421	0.211	0.510	0.334	−34.55
Zoning characteristics	T_4	Wuhan	0.548	0.503	0.667	0.439	0.500	0.445	0.500	0.329	0.426	0.211	0.510	0.351	−31.27
		Shiyan	0.557	0.514	0.691	0.412	0.500	0.469	0.500	0.217	0.413	0.198	0.508	0.314	−38.19

Table 4. Fuzzy evaluation result of urban resident ecological well-being changes using transformation factors.

Transformation Factors			X_1		X_3		X_4		X_5		Overall		
			Before	After	Before	After	Before	After	Before	After	Before	After	Change (%)
Socio-demographic characteristics	T_1	Male	0.500	0.456	0.500	0.379	0.500	0.523	0.500	0.491	0.500	0.454	−9.21
		Female	0.500	0.435	0.500	0.374	0.500	0.532	0.500	0.483	0.500	0.446	−10.72
	T_2	20–30	0.500	0.445	0.500	0.386	0.500	0. 522	0.500	0.501	0.500	0.456	−8.90
		31–40	0.500	0.451	0.500	0.389	0.500	0. 505	0.500	0.499	0.500	0.455	−9.00
		41–50	0.500	0.442	0.500	0.375	0.500	0.534	0.500	0.486	0.500	0.450	−10.09
		51–65	0.500	0.434	0.500	0.369	0.500	0.528	0.500	0.481	0.500	0.443	−11.35
		≥66	0.500	0.429	0.500	0.367	0.500	0.531	0.500	0.482	0.500	0.442	−11.64
	T_3	Elementary school graduate and below	0.500	0.503	0.500	0.388	0.500	0.516	0.500	0.423	0.500	0.435	−12.92
		Middle school graduate	0.500	0.466	0.500	0.376	0.500	0.533	0.500	0.486	0.500	0.448	−10.42
		High school graduate and above	0.500	0.429	0.500	0.383	0.500	0.512	0.500	0.500	0.500	0.450	−10.05
Zoning characteristics	T_4	Wuhan	0.500	0.421	0.500	0.373	0.500	0.527	0.500	0.509	0.500	0.450	−9.91
		Shiyan	0.500	0.443	0.500	0.384	0.500	0.522	0.500	0.489	0.500	0.452	−9.63

5. Discussion

This study investigated changes in the ecological well-being of rural and urban residents due to rural-urban land conversion, as well as the impact of transformation factors. It confirms what previous studies have indicated: Changes in rural resident overall ecological well-being and in each constituent of ecological well-being are all greater than those of urban resident [29,49,51,80,83]. And transformation factors including age, education level as well as location have significant influence on both rural and urban resident ecological well-being but the degree of influence is different. Rural residents and urban residents have different perception of the ecological services provided by agricultural land because they have a different degree of linkage with agricultural land and different knowledge of agroecosystem functions [60,84,85]. Rural resident ecological well-being experiences greater decline compared to urban residents, because they have closer and more direct contact with agricultural land [82]. Therefore, it is of great practical significance to analyze the ecological well-being changes brought out by rural-urban land conversion from the perspective of different interest groups. In addition, this is the first time location has been used in this way, representing zoning characteristics as a transformation factor for analyzing the effects of rural-urban land conversion on the ecological well-being changes in residents living in different areas with different ecological resources endowments. It could provide a theoretical foundation for regulating rural-urban land conversion by zoning.

This paper reveals the change amplitudes in ecological well-being brought out by rural-urban land conversion using a fuzzy synthetic evaluation model. How to quantify the currency value of the loss of resident ecological well-being is still a big challenge for researchers. The key point is how to transfer natural science field variables employed to quantify ecosystem services change into social science field variables which can be employed to quantify the human ecological well-being and measure changes. An effective linkage in needed. Additionally, different preferences for ecosystem services among interest groups should be identified in decision making and policy formulation, such that the response of interest groups and the priorities for ecosystem services compensation should be set up and decided both based on the revealed preference difference.

Previous studies have fully explained the significant effect of rural-urban land conversion on water, soil, climate and other aspects of ecosystem [38,55,69]. Combining the assessment of ecosystems by MA with the findings in this paper, it is found that the ecosystem functions of agricultural land including supply services, regulatory services, cultural services and support services are degraded or limited due to agricultural land loss which is a result of rural-urban land conversion. Consequently, resident ecological well-being, consisting of security, basic material for a good life, health, good social relations and freedom of choice and action declines. In China, this loss of ecological well-being ca not be compensated due to the lack of an eco-compensation mechanism. In other words, the loss of ecological well-being brought about by rural-urban land conversion exists in the form of a negative externality which has not been accounted for as a part of the cost of rural-urban land conversion. It can be recognized as one of the explanations for why the loss agricultural land in China is excessive. Therefore, it is necessary to establish efficient eco-compensation policies for rural-urban land conversion from the perspective of ecological well-being.

6. Conclusions and Future Work

Rural-urban land conversion in the process of urbanization in China causes a sharp decrease in agricultural land, resulting in the loss of its original ecosystem services. Consequently, people's opportunities for accessing various ecological services from agro-ecosystems are reduced and their freedom of choice and actions is limited. The ecological consequences in the form of negative externalities lead to a decline in people's ecological well-being. This paper constructs ecological well-being indices for rural and urban residents and then estimates the changes in resident ecological well-being caused by rural-urban land conversion using the Fuzzy Synthetic Evaluation Model. In addition, the differences of ecological well-being changes and the impact of transformation factors for ecological well-being changes between rural and urban residents are analyzed. Compared to urban residents, rural resident ecological well-being declines more due to rural-urban land conversion, because of the more serious ecological damage. For rural residents, all the five ecological well-being constituents including security, basic material for a good life, health, good social relations and freedom of choice and action show varying degrees of deterioration and the constituent of freedom of choice and action deteriorates most seriously. For urban residents, after rural-urban land conversion, all the ecological well-being constituents except the constituent of good social relations shows varying degrees of deterioration and the constituent of health deteriorates most seriously. The impact of transformation factors are also investigated in this paper. Two socio-demographic characteristics including age and education level as well as zoning characteristics have influence on both rural and urban resident well-being. Moreover, we argue that there is a need for quantitative measurement of agroecosystem services and for the construction of an ecological compensation mechanism for the process of rural-urban land conversion in China, as it is essential for regulating rural-urban land conversion and maintaining ecological well-being.

Our research is a starting point for quantifying the changes in ecological well-being of residents caused by rural-urban land conversion and examining the impact of transformation factors in this process. Since it was conducted at a provincial level, further research in a larger study area in future research is needed.

Acknowledgments: The authors acknowledge the funding received from the projects "Regulation of rural-urban land conversion based on negative externalities governance (No. 71303260)" and "Differential Eco-Compensation Mechanism for Farmland Protection under the Spatial Control of Land Use: Scale Dependence and Spatial difference (No. 71774174)" of the National Natural Science Foundation of China (NSFC).

Author Contributions: Min Song and Manman Han conceived and designed this research; Manman Han performed the field survey; Min Song and Manman Han analyzed the data; Min Song and Lynn Huntsinger wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Smith, L.M.; Case, J.L.; Smith, H.M.; Harwell, L.C.; Summers, J.K. Relating ecoystem services to domains of human well-being: Foundation for a U.S. index. *Ecol. Indic.* **2013**, *28*, 79–90. [CrossRef]
2. Leisher, C.; Samberg, L.H.; Buekering, P.V.; Sanjayan, M. Focal Areas for Measuring the Human Well-Being Impacts of a Conservation Initiative. *Sustainability* **2013**, *5*, 997–1010. [CrossRef]
3. Quintas-Soriano, C.; Castro, A.J.; Castro, H.; García-Llorente, M. Impacts of land use change on ecosystem services and implications for human well-being in Spanish drylands. *Land Use Policy* **2016**, *54*, 534–548. [CrossRef]
4. Kazana, V.; Kazaklis, A. Exploring quality of life concerns in the context of sustainable rural development at the local level: A Greek case study. *Reg. Environ. Chang.* **2009**, *9*, 209–219. [CrossRef]
5. Summers, J.K.; Smith, L.M. The Role of Social and Intergenerational Equity in Making Changes in Human Well-Being Sustainable. *Ambio* **2014**, *43*, 718–728. [CrossRef] [PubMed]
6. Wang, B.; Tang, H.; Xu, Y. Perceptions of human well-being across diverse respondents and landscapes in a mountain-basin system, China. *Appl. Geogr.* **2017**, *85*, 176–183. [CrossRef]
7. Zhang, A.; Yang, G.; Lu, H. The influence of rural-urban land conversion on the sustainable development of agriculture. *Theory Mon.* **1999**, *12*, 7–11.
8. Liu, Y.; Tang, W.; He, J.; Liu, Y.; Ai, T.; Liu, D. A land-use spatial optimization model based on genetic optimization and game theory. *Comput. Environ. Urban Syst.* **2015**, *49* (Suppl. C), 1–14. [CrossRef]
9. Stobbe, T. The Economics and Externalities of Agricultural Land in the Urban Fringe. Ph.D. Thesis, University of Victoria, Victoria, BC, Canada, 2008.
10. Eagle, A.J. Threats to Agriculture at the Extensive and Intensive Margins: Economic Analyses of Selected Land-Use Issues in the US West and British Columbia. Ph.D. Thesis, Wageningen University, Wageninge, The Netherlands, 2009.
11. Chen, Z.; Ju, D.; Zhang, A. Measuring external benefits of agricultural land preservation: An application of choice experiment in Wuhan, China. *Acta Ecol. Sin.* **2013**, *33*, 3213–3221. [CrossRef]

12. Racevskis, L.; Ahearn, M.; Alberini, A.; Bergstrom, J.; Boyle, K.B.; Libby, L.; Paterson, R.; Welsch, M. Improved information in support of a national strategy for open land policies: A review of literature and report on research in progress. In Proceedings of the 24th International Conference of Agricultural Economists, Berlin, Germany, 13–18 August 2000; pp. 1–16.
13. Song, M.; Han, M. Compensation mechanism of rural-urban land conversion in the perspective of ecological well-being: Literature review and framework construction. *Issues Agric. Econ.* **2016**, *11*, 94–102.
14. Smith, H.F.; Sullivan, C.A. Ecosystem services within agricultural landscapes—Farmers' perceptions. *Ecol. Econ.* **2014**, *98*, 72–80. [CrossRef]
15. Dai, G.; Na, R.; Dong, X.; Yu, B. The dynamic change of herdsmen well-being and ecosystem services in grassland of Inner Mongolia: Take Xilinguole League as example. *Acta Ecol. Sin.* **2014**, *34*, 2422–2430.
16. Liu, J.; Kuang, W.; Zhang, Z.; Xu, X.; Qin, Y.; Ning, J.; Zhou, W.; Zhang, S.; Li, R.; Yan, C.; et al. Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. *J. Geogr. Sci.* **2014**, *24*, 195–210. [CrossRef]
17. Yang, L.; Zhen, L.; Li, F.; Wei, Y.; Jiang, L.; Cao, X.; Long, X. Impacts of ecosystem services change on human well-being in the Loess Plateau. *Resour. Sci.* **2010**, *32*, 849–855.
18. Poor, P.J.; Brule, R. An Investigation of the Socio-Economic Aspects of Open Space and Agricultural Land Preservation. *J. Sustain. Agric.* **2007**, *30*, 165–176. [CrossRef]
19. Da Silva, J.M.C.; Prasad, S.; Diniz-Filho, J.A.F. The impact of deforestation, urbanization, public investments, and agriculture on human welfare in the Brazilian Amazonia. *Land Use Policy* **2017**, *65*, 135–142. [CrossRef]
20. Hamann, M. Exploring Connections in Social-Ecological Systems: The Links between Biodiversity, Ecosystem Services, and Human Well-Being in South Africa. Ph.D. Thesis, Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden, 2016.
21. Fischer, A.; Eastwood, A. Coproduction of ecosystem services as human–nature interactions—An analytical framework. *Land Use Policy* **2016**, *52*, 41–50. [CrossRef]
22. Offiong, R.A.; Eteng, O.E. Effect of urbanization on greenareas in Calabar metropolis. *Int. J. Eng. Sci.* **2014**, *3*, 71–75.
23. Sallustio, L.; Quatrini, V.; Geneletti, D.; Corona, P.; Marchetti, M. Assessing land take by urban development and its impact on carbon storage: Findings from two case studies in Italy. *Environ. Impact Assess. Rev.* **2015**, *54*, 80–90. [CrossRef]
24. Song, M.; Lei, Y. Negative externalities from different directions of rural-urban land conversion using CE Method. *China Popul. Resour. Environ.* **2017**, *27*, 28–39.
25. Liang, M.; Yang, Z. Research on ecological well-being loss and compensation of non-agricultural land transference. *J. Gansu Sci.* **2014**, *26*, 35–38.
26. Reyers, B.; Biggs, R.; Cumming, G.S.; Elmqvist, T.; Hejnowicz, A.P.; Polasky, S. Getting the measure of ecosystem services: A social–ecological approach. *Front. Ecol. Environ.* **2013**, *11*, 268–273. [CrossRef]
27. Fischer, J.; Hartel, T.; Kuemmerle, T. Conservation policy in traditional farming landscapes. *Conserv. Lett.* **2012**, *5*, 167–175. [CrossRef]
28. Zhang, W.; Ricketts, T.H.; Kremen, C.; Carney, K.; Swinton, S.M. Ecosystem services and dis-services to agriculture. *Ecol. Econ.* **2007**, *64*, 253–260. [CrossRef]
29. Soy-Massoni, E.; Langemeyer, J.; Varga, D.; Sáez, M.; Pintó, J. The importance of ecosystem services in coastal agricultural landscapes: Case study from the Costa Brava, Catalonia. *Ecosyst. Serv.* **2016**, *17*, 43–52. [CrossRef]
30. Qu, F.; Lu, N.; Feng, S. Effects of land use change on carbon emissions. *China Popul. Resour. Environ.* **2011**, *10*, 76–83.
31. Lee, Y.C.; Ahern, J.; Yeh, C.T. Ecosystem services in peri-urban landscapes: The effects of agricultural landscape change on ecosystem services in Taiwan's western coastal plain. *Landsca. Urban Plan.* **2015**, *139*, 137–148. [CrossRef]
32. Kroeger, T.; Casey, F. An assessment of market-based approaches to providing ecosystem services on agricultural lands. *Ecol. Econ.* **2007**, *64*, 321–332. [CrossRef]
33. Plieninger, T.; Bieling, C. *Resilience and the Cultural Landscape: Understanding and Managing Change in Human-Shaped Environments*; Cambridge University Press: Cambridge, UK, 2012; pp. 1–366.
34. Li, S.; Zhang, A. Research of rural-urban land conversion and social loss based on the demonstration study of Wuhan city circle. *Resour. Sci.* **2014**, *36*, 303–310.

35. Chen, Z.; Zhang, A.; Zhang, X.; Song, M. Measurement of external costs in rural-urban land conversion processes. *Resour. Sci.* **2010**, *32*, 1141–1147.
36. Long, H.; Liu, Y.; Hou, X.; Li, T.; Li, Y. Effects of land use transitions due to rapid urbanization on ecosystem services: Implications for urban planning in the new developing area of China. *Habitat Int.* **2014**, *44* (Suppl. C), 536–544. [CrossRef]
37. Chuai, X.; Huang, X.; Wu, C.; Li, J.; Lu, Q.; Qi, X.; Zhang, M.; Zuo, T.; Lu, J. Land use and ecosystems services value changes and ecological land management in coastal Jiangsu, China. *Habitat Int.* **2016**, *57*, 164–174. [CrossRef]
38. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Synthesis*; Island Press: Washington, DC, USA, 2005.
39. Singh, R.; Singh, G. Ecosystem services: A bridging concept of ecology and economics. *Ecol. Quest.* **2017**, *25*. [CrossRef]
40. Sinare, H.; Gordon, L.J.; Enfors Kautsky, E. Assessment of ecosystem services and benefits in village landscapes—A case study from Burkina Faso. *Ecosyst. Serv.* **2016**, *21*, 141–152. [CrossRef]
41. Brander, L.; Brouwer, R.; Wagtendonk, A. Economic valuation of regulating services provided by wetlands in agricultural landscapes: A meta-analysis. *Ecol. Eng.* **2013**, *56* (Suppl. C), 89–96. [CrossRef]
42. Omer, A.; Pascual, U.; Russell, N. A theoretical model of agrobiodiversity as a supporting service for sustainable agricultural intensification. *Ecol. Econ.* **2010**, *69*, 1926–1933. [CrossRef]
43. Landis, D.A. Designing Agricultural Landscapes for Biodiversity-Based Ecosystem Services. *Basic Appl. Ecol.* **2017**, *18*, 1–12. [CrossRef]
44. Barrena, J.; Nahuelhual, L.; Báez, A.; Schiappacasse, I.; Cerda, C. Valuing cultural ecosystem services: Agricultural heritage in Chiloé island, southern Chile. *Ecosyst. Serv.* **2014**, *7* (Suppl. C), 66–75. [CrossRef]
45. Van Zanten, B.T.; Zasada, I.; Koetse, M.J.; Ungaro, F.; Häfner, K.; Verburg, P.H. A comparative approach to assess the contribution of landscape features to aesthetic and recreational values in agricultural landscapes. *Ecosyst. Serv.* **2016**, *17*, 87–98. [CrossRef]
46. Van Berkel, D.B.; Verburg, P.H. Spatial quantification and valuation of cultural ecosystem services in an agricultural landscape. *Ecol. Indic.* **2014**, *37*, 163–174. [CrossRef]
47. Li, H.; Huang, X.; Kwan, M.P.; Bao, H.X. H.; Jefferson, S. Changes in farmers' welfare from land requisition in the process of rapid urbanization. *Land Use Policy* **2015**, *42*, 635–641. [CrossRef]
48. Huang, Y. Study on Estimating the Value of Cultivated Land Ecosystem Services and Economic Compensation of Cultivated Land Protection in Zhuzhou Area. Master Thesis, Hunan Normal University, Changsha, China, 2015.
49. Gao, J.; Qiao, R.; Zhang, A. Fuzzy evaluation of farmers' well-being in rural-urban land conversion based on Sen's capability approach. *Manag. World* **2007**, *6*, 45–56.
50. Peng, K.; Zhang, P.; Zhang, A. Welfare balance of different interest groups during rural-urban land conversion. *Chin. J. Popul. Resour. Environ.* **2009**, *7*, 57–64.
51. Peng, K.; Zhu, H. The Impacts of Rural-Urban Land Conversion on the Welfare of Different Aged Land-lost Farmers. *China Land Sci.* **2015**, *29*, 71–78.
52. Wang, B.; Tang, H. Human well-being and its applications and prospects in Ecology. *J. Ecol. Rural Environ.* **2016**, *32*, 697–702.
53. Venkatachalam, L. The contingent valuation method: A review. *Environ. Impact Assess. Rev.* **2004**, *24*, 89–124. [CrossRef]
54. Freeman, A.M., III; Herriges, J.A.; Kling, C.L. *The Measurement of Environmental and Resource Values: Theory and Methods*, 3rd ed.; RFF Press: New York, NY, USA, 2014.
55. Yang, X.; Burton, M.; Zhang, A. Estimation of farmland eco-compensation criteria based on latent class model: A case of discrete choice experiment. *China Popul. Resour. Environ.* **2016**, *7*, 27–36.
56. Cai, Y.; Zhang, A. Researching progress and trends of agricultural land's ecological compensation under land use planning control. *J. Nat. Resour.* **2010**, *25*, 868–880.
57. Guo, Z. The Farmland Protection System of China: Implementation Performance Evaluation, Implementation Deviation and Optimization Methods. *J. Zhengzhou Univ.* **2017**, *50*, 64–68.
58. Liu, Y. Study on the Level of China Agricultural Ecological Welfare and Promotion Strategy: Case of Hubei Province. Ph.D. Thesis, Huazhong Agricultural University, Wuhan, China, 2014.

59. Zhang, L. The breaking and reconstruction of nutrient recycling chains in agro-ecosystem in China. *Ecol. Econ.* **2006**, *2*, 103–105.
60. Peng, J.; Tian, L.; Liu, Y.; Zhao, M.; Hu, Y.; Wu, J. Ecosystem services response to urbanization in metropolitan areas: Thresholds identification. *Sci. Total Environ.* **2017**, *607–608*, 706–714. [CrossRef] [PubMed]
61. Francis, C.A.; Hansen, T.E.; Fox, A.A.; Hesje, P.J.; Nelson, H.E.; Lawseth, A.E.; English, A. Farmland conversion to non-agricultural uses in the US and Canada: Current impacts and concerns for the future. *Int. J. Agric. Sustain.* **2012**, *10*, 8–24. [CrossRef]
62. Chen, Z.; Zhang, A.; Song, M.; Zhang, Z. Measuring external costs of rural–urban land conversion: An empirical study in Wuhan, China. *Acta Ecol. Sin.* **2016**, *36*, 30–35. [CrossRef]
63. Glenk, K.; Colombo, S. Modelling outcome-related risk in choice experiments. *Aust. J. Agric. Resour. Econ.* **2013**, *57*, 559–578. [CrossRef]
64. Garcia, X. The value of rehabilitating urban rivers: The Yarqon River (Israel). *J. Environ. Econ. Policy* **2014**, *3*, 323–339. [CrossRef]
65. Baró, F.; Palomo, I.; Zulian, G.; Vizcaino, P.; Haase, D.; Gómez-Baggethun, E. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region. *Land Use Policy* **2016**, *57*, 405–417. [CrossRef]
66. Hart, J.F. Urban Encroachment on Rural Areas. *Geogr. Rev.* **1976**, *66*, 1–17. [CrossRef]
67. Swinton, S.M.; Lupi, F.; Robertson, G.P.; Hamilton, S.K. Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecol. Econ.* **2007**, *64*, 245–252. [CrossRef]
68. Yu, K. Three proposals for preventing the potential damage by building the new countryside and protecting the local cultural landscape and the industrial heritage. *Chin. Landsc. Archit.* **2006**, *8*, 8–12.
69. Li, H.; Zhang, A. Ecological compensation boosted ecological protection and human well-being improvement. *Acta Ecol. Sin.* **2013**, *33*, 1065–1070.
70. Sherren, K.; Verstraten, C. What Can Photo-Elicitation Tell Us About How Maritime Farmers Perceive Wetlands as Climate Changes? *Wetlands* **2012**, *33*, 65–81. [CrossRef]
71. Scheaffer, R.L.; Mendenhall, W. *Elementary Survey Sampling*, 6th Revised ed.; Brooks Cole: Boston, MA, USA, 2005; p. 486.
72. Cheli, B.; Lemmi, A. A totally fuzzy and relative approach to the multidimensional analysis of poverty. *Econ. Notes* **1995**, *24*, 115–134.
73. Gao, J.; Qiao, R. Analysis on variation in farmers welfare after rural-urban land conversion. *China Popul. Resour. Environ.* **2011**, *21*, 99–105.
74. Schirmer, J.; Berry, H.L.; O'Brien, L.V. Healthier land, healthier farmers: Considering the potential of natural resource management as a place-focused farmer health intervention. *Health Place* **2013**, *24*, 97–109. [CrossRef] [PubMed]
75. Smith, C.L.; Clay, P.M. Measuring subjective and objective well-being: Analyses from five marine commercial fisheries. *Human Organ.* **2010**, *69*, 158–169. [CrossRef]
76. Qi, J.; Yang, Z. Global climate changes and human well-being and adaptability. *Acad. Mon.* **2014**, *46*, 21–26.
77. Sen, A.K. *Commodities and Capabilities*; North-Holland: Amsterdam, The Ntherlands, 1985; pp. 1–104.
78. Nussbaum, M.; Sen, A.K. *Capability and Well-Being*; Clarendon Press: Oxford, UK, 1993.
79. Sen, A. *Development as Freedom*; Oxford University Press: New York, NY, USA, 1999.
80. Erickson, J.J.; Martinengo, G.; Hill, E.J. Putting work and family experiences in context: Differences by family life stage. *Human Relat.* **2010**, *63*, 955–979. [CrossRef]
81. Ding, S.; Zhang, Y.; Ma, Z. Research on changes of livelihood capabilities of rural households encountered by land acquisition: Based on improvement of sustainable livelihood approach. *Issues Agric. Econ.* **2016**, *6*, 25–34.
82. Skandrani, Z.; Daniel, L.; Jacquelin, L.; Leboucher, G.; Bovet, D.; Prevot, A.C. On Public Influence on People's Interactions with Ordinary Biodiversity. *PLoS ONE* **2015**, *10*, e0130215. [CrossRef] [PubMed]
83. Peel, D.; Berry, H.L.; Schirmer, J. Farm exit intention and wellbeing: A study of Australian farmers. *J. Rural Stud.* **2016**, *47*, 41–51. [CrossRef]

84. Pan, Y.; Marshall, S.; Maltby, L. Prioritising ecosystem services in Chinese rural and urban communities. *Ecosyst. Serv.* **2016**, *21*, 1–5. [CrossRef]
85. Jiang, C.; Jin, J.; Li, L. Non-market valuation of cultivated land protection using cvm: A case study of Wenling City. *Resour. Sci.* **2011**, *33*, 1955–1961.

sustainability

MDPI

Article

Estimation of Carbon Dioxide Emissions Generated by Building and Traffic in Taichung City

Chou-Tsang Chang and Tzu-Ping Lin *

Department of Architecture, National Cheng Kung University, 1 University Road, Tainan 701, Taiwan; archcct@hotmail.com

* Correspondence: lin678@gmail.com

Received: 23 October 2017; Accepted: 27 December 2017; Published: 5 January 2018

Abstract: The emissions of carbon dioxide generated by urban traffic is generally reflected by urban size. In order to discuss the traffic volume generated in developed buildings and road crossings in a single urban block, with the metropolitan area in Taichung, Taiwan as an example, this study calculates the mutual relationship between the carbon dioxide generated by the traffic volume and building development scale, in order to research energy consumption and relevance. In this research, the entire-day traffic volume of an important road crossing is subject to statistical analysis to obtain the prediction formula of total passenger car units in the main road crossing within 24 h. Then, the total CO_2 emissions generated by the traffic volume in the entire year is calculated according to the investigation data of peak traffic hours within 16 blocks and the influential factors of the development scale of 95 buildings are counted. Finally, this research found that there is a passenger car unit of 4.72 generated in each square meter of land in the urban block every day, 0.99 in each square meter of floor area in the building and the average annual total CO_2 emissions of each passenger car unit is 41.4 $kgCO_2$/yr. In addition, the basic information of an integrated road system and traffic volume is used to present a readable urban traffic hot map, which can calculate a distribution map of passenger car units within one day in Taichung. This research unit can be used to forecast the development scale of various buildings in future urban blocks, in order to provide an effective approach to estimate the carbon dioxide generated by the traffic volume.

Keywords: CO_2 emissions; transport; urban block; urban design

1. Introduction

According to the statistical data of the International Energy Agency (IEA), the global CO_2 emissions increased by 88.7% from 1971 to 2004 and according to the energy consumption structure of the transportation department in Taiwan, the energy consumption of road transportation accounts for maximally 90% of the total energy consumption of the transportation department [1]. Prior to the Revolution, the content of CO_2 in the atmosphere was about 280 ppm and this concentration increased to 403.3 ppm in 2016 [2].

At present, the energy consumption of the transportation department and CO_2 emissions increase continuously and there are many factors influencing urban energy consumption [3]. The location of the housing and its size are the dominant factors determining energy use and greenhouse gas emissions [4]; however, in the future, research should be conducted regarding the relation between the large proportion of energy consumption in urban transportation and the development of buildings. In addition to the fact that urban areas have great influence due to land use control, zoning and building design scale, it is required to carry out overall research and analysis of the CO_2 emissions generated by traffic demand, in order to effectively and completely know the overall urban energy consumption.

1.1. Method of Research on the Energy Consumption of Urban Building Groups

Of the various energy consumptions in urban areas, electricity accounts for the most and urban energy consumption can be calculated from the urban electric energy consumption model or energy use intensity, in order to obtain the urban energy consumption amount.

There are many researches in Taiwan, which are used to count and investigate the power consumption regarding the usage category, scale, or total power consumption of various buildings, in order to discuss the future power use mode or energy consumption situation of various buildings and provide forecasts and simulations in the future. In terms of power use analysis of various buildings, the building shell energy consumption ENVLOAD simple algorithm [5] is taken as the 12 variable factors to simplify climate and building design and effectively evaluate the annual air conditioning load and usage as the energy saving design method of evaluating the building shell.

In another research, the total carbon dioxide generated by a building is calculated through the life cycle assessment (LCA) [6], where the fossil fuels and electricity consumed are calculated to obtain the total amount of building material, the total amount of electricity used by the buildings, in order to calculate the complex variable regression model of CO_2 emissions of RC buildings. In the current building specifications of Taiwan [5], the emissions of CO_2 in RC buildings are 331 kg/m^2, as obtained through the assessment of CO_2 reduction indicators in the green building evaluation system.

In addition, urban energy is analyzed with the total energy consumption relation of various buildings in the urban block and the mutual change relation with the scale and use form patterns of various buildings. For various buildings, the "dynamic Energy Use Intensity (EUI) indicator method" [7] is employed to calculate the energy consumption density standard EUI (kwh/(m^2·yr)) of various classified spaces and power consumption can be calculated after the summary. By calculating carbon emissions from buildings according to electricity emission factor released by the Bureau of Energy and energy usage intensity [8]; in this manner, the carbon dioxide emitted during the use of various buildings can be calculated.

Regarding the research literature of the total power consumption of all buildings in a block of a residential area [9], the site area is used as a single variable, where the floor area ratio, block shape and location, business factor, road and park area proportion, etc., are included as the variables, in order to forecast and master all power usage behaviors in the residential area. After conversion of the power consumption in the residential area, the annual power consumption is equivalent to the emissions of about 650 mt CO_2.

As stated above, there have been relevant researches for the simulation and forecast mode of the relation between a single building and the total power consumption and CO_2 emissions of a block and such achievements should be further used in the future.

1.2. Research Method of the Carbon Dioxide of Traffic Systems

In the exiting transportation planning forecast mode, regarding the analysis and forecast mode of travel demands, the overall procedure planning of traditional transportation planning is usually adopted, which is classified into trip generation, trip distribution, model split and traffic assignment processes [10] and after calculation by sequence, the trip generation in an area is forecasted or calculated for traffic planning.

Additionally, regarding the assignment of static traffic volume, it is assumed that the traffic flow and traveling time within a road section do not change with the time [11], thus, the user equilibrium and system equilibrium [12] of traffic assignments, as proposed by Wardrop [13], are applied for further simulation in order to calculate the traffic assignment mode under a mixed traffic flow. Then, the design reference of the highway capacity is considered to calculate and distribute the expected design vehicle speeds to complete the overall traffic planning of urban transportation planning.

The proposal and execution of a traffic project can promote urban land use and will influence land price in the future [14]. Regarding the influence of urban form on travel demand [15], the potential variables and measured variables of three aspects, "urban form", "travel demand" and "control factors" are used for inclusive empirical analysis on the influential relationship. The research results show that, in the urban form characteristics, while higher development density will increase the trip generation rate, it can reduce the opportunity of selecting private vehicles; meaning the higher equilibrium of mixed land use will reduce the trip generation rate but will increase the selection of private vehicles.

Analysis of the relation of local temperature to the land use, which residential areas, traffic areas and greenhouse agricultural areas all contributed to an increase in local temperatures [16].

In addition, in the research of the relation between measured CO_2 concentration and land use [17], the land use type is classified into buildings and built-up areas with impervious pavement and the urban environments are free city spaces [18]. Then the road service level and highway capacity of the original design are used to calculate the traffic volume of various roads and "vehicle mileage emission factor method" is used to calculate the CO_2 emissions. Therefore, the transportation system must estimate the passenger car units (PCU) per hour from different road service levels, or calculate the total CO_2 emissions according to the statistical data of the usage rate of different vehicle types, or with the calculated parameters, such as different vehicles, mileage, fuels and emission coefficient.

Urban spatial and statistical data for metropolitan Tainan in southwestern Taiwan are used to explore inside and outside of the CO_2 system of the city and estimate the amount of CO_2 emissions from road traffic. Therefore, CO_2 emissions are concentrated in over-urbanized areas, where the population density is higher than 5000 people/km^2 [19].

Road engineering designs, such as different road slopes, road widths, speed limitations and pavement types will also influence vehicle speed, traffic flow and fuel consumption rate [20]. Regarding urban roads with two-way 4 lanes without central dividing strip, the result of analysis on the influence of road width on vehicle speed shows that, during the off-peak period, with every reduction of 0.3 m for the lane width, the average vehicle speed will be reduced by 0.97 km/h [21].

According to the research of Ardekani and Sumitsawan (2010) on roads in Texas, upon comparison of fuel consumption rate changes of vehicles traveling on flexible payment materials, the result shows that rigid pavement can reduce the required fuel amount by 3–17%. Regarding CO_2 and fuel consumption tests aimed at special vehicles, the statistics show that slope has a present correlation trend with carbon dioxide, where the larger the slope, the greater the carbon dioxide [22].

As stated above, in the calculation of internationally emitted greenhouse gases, the "IPCC Guidelines for National Greenhouse Gas Inventories" rules are usually used and the estimation of CO_2 emissions by the transportation department can be classified into large-range estimation by considering the fuel type, fuel consumption and carbon emissions of various fuels, where priority calculate is the total amount of fuel, then calculate the types of the fuel consumption rate, namely the Top-down approach; while small-range estimation calculations are based on the Bottom-up principle, according to the activity strength with a fuel consumption rate and this applies to the assessment of the small-range traffic management strategy [23].

Whether applying the Top-down principle or Bottom-up principle, the total CO_2 emissions generated by traffic is calculated by multiplying the type of vehicles (such as passenger car, truck and bus) by the fuel type (diesel, gasoline, etc.) and then by the emission factor for the usage of unit fuel or the emission coefficient of unit mileage [17].

1.3. Existing Carbon Dioxide Issue

In this research, based on existing transportation planning and execution procedures and methods of urban planning, the following research topics are proposed upon review.

Issue 1: Transportation analysis was mainly based on large-scale networks, lacking the information from the urban blocks

Regarding the calculation method of existing transportation planning, the regional total traffic volume can be estimated only by large investigations of the urban road networks and numerical data of road facilities. Moreover, the investigation and statistical method of the existing urban transportation traffic volume is to conduct model splits and traffic assignments on the vehicle flows in various regions, in order to form large-scale transportation results in urban areas.

However, follow-up urban planning or regular overall inspections adopt zoning and cooperate with traffic road system planning to form various basic divided urban block units. Therefore, measured investigation on road vehicle flow is salutatory and there is a lack of research on the mutual influence between the usage characteristics of urban block units, building scales, road system, etc.

Issue 2: There is no effective permitted data for the buildings to integrate the overall forecast of urban energy consumption

During an application for a building permit, if it is required to assess the environmental impact or consider urban design, the traffic volume in that region must be evaluated and measured. However, in the current document application, under the condition of no integrated application, it is impossible to immediately and properly use the relevant legally considered data above, which reduces the added value after consideration, or requires further application by the government or folk practitioners.

Therefore, in the application of environmental impact assessment or urban design review, in addition to the stated measured traffic volume data for the region, it is possible to integrate and analyze traffic data and building permits, in order to evaluate the application in the overall urban development.

Issue 3: The design of transportation planning lacks mapping of urban traffic environment characteristics

In transportation system planning, set the model split according to the data collection and measured investigation, forecast trip generation and trip distribution in the future and then evaluate the optimal feasible plan. In the follow-up design of a road system, the road geometry, road slope, running speed, etc., are used for planning and alignment.

The transportation system above is planned according to the completion of the road geometrical design and only the numerical design and calculation are taken as the main achievements, which lack a map evaluation mode of integrating the urban form and transportation trunk into complete readability [24] and urban traffic hot spots.

1.4. Research Purpose and Improvement Countermeasures

In this research, the small-scale application mode is used to analyze the urban energy consumption of urban areas, thus, with a single urban block as the basic unit to estimate traffic volume, the research purpose and countermeasures are proposed as follows:

To completely analyze the overall energy consumption of entire urban areas and taking the urban block as the basic analysis unit, in combination with the vehicle flow generated at the junction of the road system, as the basic application unit, develop and analyze the overall energy consumption correlation of the urban areas and establish the forecast model.

To effectively integrate the legal application deliberation of the documentation of a building permit and be beneficial to the follow-up modification of urban planning, this research applies and analyzes the report of the urban design review in order to research the influential factors of block development and building design, conduct in-depth analysis of the mutual relation with the traffic carbon dioxide and evaluate the total CO_2 emissions generated by urban development in the future.

This study used the basic urban block units formed by an urban road system, where relevant road systems and road engineering are simplified into road design factors and upon this research, the simple forecast model of urban roads and urban planning configurations are analyzed and the basic information of the traffic volume is presented to obtain a readable traffic volume map of urban areas. In addition, the research results will be conveniently and rapidly used in the follow-up revisions of urban planning, or the periodical overall review of urban planning.

2. Research Method

The research area is located in Taichung, which is in the middle of Taiwan, with a land area of 2214.9 km^2 and a total of 29 administrative regions. The research scope is mainly the 8 administrative regions in the Taichung metropolitan area, with a land area of 163.4 km^2, population of 1,121,128 (March 2015) and population density of 6612 persons per square kilometer.

The Taichung metropolitan area is a metropolitan form of commercial service and commercial mixing, the west is an industrial zone and the east is the Dakeng Scenic area (Figure 1).

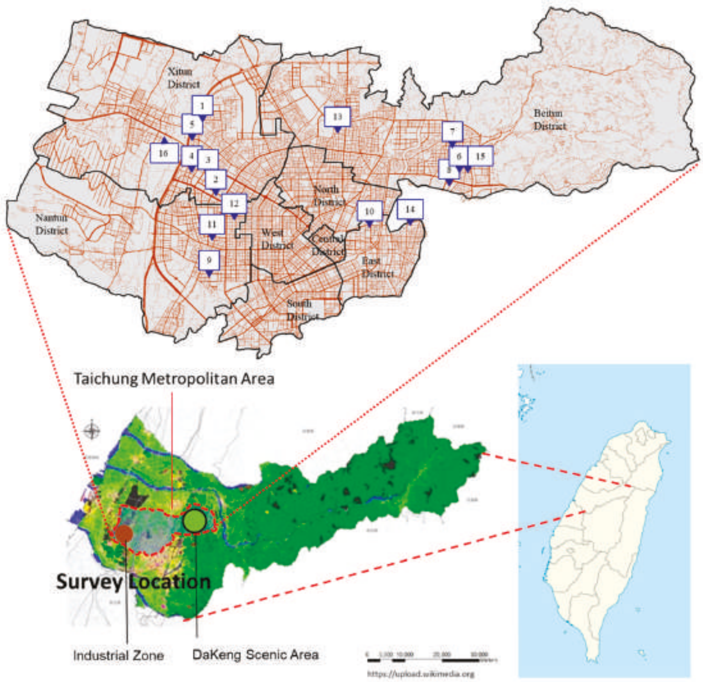


Figure 1. Location of Taichung city (Taiwan).

Due to the forecast mode of traffic volume, the investigation range of the traditional transportation planning method must often contain the regional characteristics formed by dozens of urban blocks and then, the measured traffic volume is used, thus, it belongs to large-range investigation and research. Regarding the mutual relation between land use control and building scale in urban areas, it is difficult to conduct in-depth research and analysis.

This research is aimed at the number of vehicles at four junctions in the urban blocks of Taichung's metropolitan area, as well as the applied development cases of various buildings in the urban blocks, in order to further calculate the total CO_2 emissions generated by the traffic volume and investigate and analyze the building development scale factors.

2.1. Estimation Model of Total Traffic Volume in the Urban Blocks

Regarding the main urban road crossings in this research, the number of vehicles within 24 h is measured and investigated. During an application for a building permit, the environmental impact evaluation case should be dominated by law. Due to the assessment contents of environmental impact, for the measuring of traffic volume generated by motorcycles, passenger cars and buses, it is required to calculate the passenger car unit (PCU) at the road crossings, as specified in the Taiwan Highway Capacity Manual [25], in order to obtain the traffic volume of the entire day as the basis of environmental impact assessment and design considerations.

First, this research analyzed the total number of vehicles of five main road crossings and then analyzed the forecasted regression formula of dependent variables during the morning peak and evening peak hours with the measured vehicle flow data of 07:30–08:30 in the morning and 17:30–18:30 in the evening.

In this research, the traffic investigation data of morning peak and evening peak hours in the urban design review cases are substituted into the forecasted regression formula of total number of vehicles in the five main road crossings, in order to respectively calculate the passenger car units in each junction of the block within one day.

Regarding the four road crossings in an urban block, the measured data of traffic volume are taken as the case and on the basis of practical cases, there is an extreme lack of hard-won cases, which are difficult to obtain. Therefore, in this research, hundreds of cases of urban design reviews over the years (2011–2013) are screened to determine the application of the site area of the blocks and those with road crossing investigation data are the preferred cases. Then, those with traffic volume in three crossings are taken as the minor cases.

Next, passenger car unit (PCU) at the road intersection in the city block was estimated and the Geographic Information System for metropolitan Taichung was used to calculate the length of each side road in the block as the travel distance of automobiles. The amount of fuel used by an automobile to travel an entire road was estimated on the basis of the travel distance per liter of fuel of the automobile in the city (9200 m), which was calculated using the research data published by the Industrial Technology Research Institute [26]. The carbon emission coefficient of gasoline was accordingly estimated to be 2.26 $kgCO_2/L$ [27]. The carbon emission coefficient of gasoline was multiplied by the total PCU and the travel distance of the automobile was subsequently estimated. In this way, the total CO_2 emissions from traffic were estimated using Equation (1).

$$\sum_{t=1}^{n} \mathrm{PCE_i} = \mathrm{N_i} \times \mathrm{FE} \times \mathrm{EC} \times \mathrm{D_i} \quad (1)$$

where, PCE_i is the CO_2 emissions generated by each passenger car unit ($kgCO_2/PCU$); N_i is the passenger car units (PCU) for each of the road, FE is the fuel consumption rate (0.000109 L/m), EC is the CO_2 emissions coefficient (2.26 $kgCO_2/L$), D_i is the length of the vehicle driving in the block (m). There are 64 data of the total traffic volume in each section, as well as the total CO_2 emissions generated by the vehicles.

2.2. Statistical Model of Building Development Factors

The building design case should be subject to the urban land use zoning and provisions of the Building Act to be convenient for the building design. Therefore, in this research, legal buildings are used as the main research targets. Upon reference to the "building cadastral mapping" system of the competent government building authority (Figure 2), after inquiry of construction permits in all buildings, the building permit data are referred and the design value is logged in.

Due to insufficient official government budget and in order to accelerate obtaining the public facility reserved land of urban areas, provisions on encouraging floor area for those who have obtained public facilities have been established, that is to say, after private practitioners obtain public facilities and give them to the government free of charge, the equivalent building floor area is obtained through private transformation and moved to the future development site area, in order to increase the actual floor area ratio of buildings in the future.

In addition, in order to award the private practitioners, the government increases the parking space to solve the urgent parking demand in urban areas; those private practitioners who have increased the parking space obtain the award of increased floor area. In addition, due to the insufficiency of green parkland space in urban areas, for example, a site area is reserved with a square up to a certain scale by law, which is connected for pedestrians and is opened to the public for passing or recreation; private practitioners also can obtain the award of increasing the floor area of the open space.

Figure 2. Study case reference to the "building permit data mapping" system of the competent government building authority.

Therefore, in order to reduce building development costs and consider increasing the value of building development products, private practitioners usually need to increase the building development scale and will often apply for the legal provisions applicable to the above three measures for awarding floor area. Thus, in addition to incorporating the general building plan of influential factors in this research, floor award area factors are also considered, in order that the research forecast result is pragmatic and broader in application.

As stated above, in this research, regarding the major analysis method of traffic volume and block-related factors, in addition to the site area, building coverage ratio, floor area ratio, etc. (Table 1), as stated in the building permit, the thirty-four factors of various buildings, green coverage areas, green coverage rate, etc. of the entire block are summarized. Therefore, the land use zoning in this research case is dominated by the residential area, for a total of 16 blocks, the building purpose is dominated by residential use; however, in some buildings, the first floor is used as shops, for a total of 95 buildings.

Table 1. Statistical for block-related factors.

Case	The Total Area of an Urban Block (m^2)	Site Area (m^2)	Building Development Land Ratio (%)
1	10,291.7	9971.5	96.9%
2	16,679.2	11,773.1	70.6%
3	13,554.5	10,047.6	74.1%
4	9747.7	6145.4	63.0%
5	3822.4	2944.5	77.0%
6	16,143.3	14,387.3	89.1%
7	6606.4	4843.9	73.3%
8	16,400.0	9739.2	59.4%
9	6856.0	6145.4	89.6%
10	3522.3	3127.7	88.8%
11	20,261.5	16,617.5	82.0%
12	7548.9	7548.9	100.0%
13	9813.0	8432.7	85.9%
14	9831.8	3767.8	38.3%
15	9264.0	9264.0	100.0%
16	26,498.8	10,548.6	39.8%

This research constructed a map of the total carbon budget of traffic, buildings and parks in metropolitan Taichung, central Taiwan [19]. Carbon emissions from buildings in the city were estimated according to electricity usage [28,29], e-Question results, a common building type in Taiwan (i.e., residential and commercial mixed-use building) and the energy consumption of low-story and high-story apartments, office buildings, hospitals, educational institutions and other building types. Therefore, the total CO_2 emissions from buildings in Taichung were measured according to 15 different building uses, EUI, land types as specified during urban planning and presented in grids of 100 × 100 m and the total floor area, with the estimation results shown in Table 2.

The forms of energy used in a building vary according to how the energy is used. For example, some residential buildings use fuel gas for cooking and heating bath water, whereas others use electricity in kitchens, industrial buildings have diverse use of energy, while other types of buildings use mainly electricity. Therefore, CO_2 emissions from buildings in grids were estimated as follows:

$$CO_2e_{\mathrm{Building}} = \left[EU_{\mathrm{elec}} + EU_{\mathrm{gas}}\right] \times C_{CO_2} \quad (2)$$

$$EU_{\mathrm{elec}} = \sum_{t=1}^{n} EUI_{\mathrm{i}} \times TFA_{\mathrm{i}} \quad (3)$$

where EU_{elec} (kWh/yr·grid) is the usage of electricity; EU_{gas} (kWh/yr·grid) is the usage of fuel gas (which is estimated to consume 0.23 times more domestic energy than does electricity, according to the CO_2 emissions data for residential buildings provided in [6]) and C_{CO_2} is the amount of CO_2 emissions per kWh of electricity generated in Taiwan in 2014. On the basis of the amount of CO_2 emissions per kWh of electricity generated in the year, the EEF was estimated to be 0.521 $kgCO_2$/kWh.

Table 2. Carbon budget coefficients of buildings and green spaces.

	Land use	CO_2 ($kgCO_2\ m^{-2}\ yr^{-1}$)	References
Building carbon dioxide emission	Residential I (House)	15.29	Lin [28]
	Residential II (Apartment without elevator)	13.09	Lin [28]
	Residential III (Apartment with elevator)	18.62	Lin [28]
	Commercial	111.33	Lin [28]
	University/High school	30.74	Lin [28]
	Junior high school	28.66	Lin [28]
	Elementary school	21.88	Lin [28]
	Traffic Station	184.96	Lin [28]
	Post office/Government agencies	63.04	Lin [28]
	Stadium	97.43	Lin [28]
	Industrial area	105.76	Lin [28]
	Hospital	136.03	Chen [29]
	Religious buildings	80.76	Lin [28]
	Traditional Market	42.71	Chen [29]
	Landfill	44.81	Lin [28]
Carbon dioxide absorption	Water	−0.02	Lin [28]
	Park	−2.24	Huang [30], Lin [28]
	Farmland	−4.59	Huang [30]

The CO_2 absorption of different land types (i.e., parks, soils and water bodies, as determined during urban planning) in metropolitan Taichung was analyzed and the carbon sink in each grid was estimated using the following equation:

$$CO_{2_{\mathrm{Sink}}} = \sum_{t=1}^{n} CS_{\mathrm{i}} \times A_{\mathrm{i}} \quad (4)$$

where $CO_{2_{\mathrm{Sink}}}$ ($-kgCO_2$/yr·grid) is the total amount of CO_2 absorbed in each grid, CS_{i} ($-kgCO_2/m^2$) is the CO_2 absorption coefficient of each land type and A_{i} (m^2) is the area of each land type.

Upon counting the design values of various buildings in the urban block, as well as the total number of traffic volume in each road section, as well as the respective calculations of the total CO_2 emissions generated by fuels, multiple regression analysis is applied on the relations of various relevant factors of overall urban energy consumption, in order to obtain the research results of the influence of changes in various dependent variables on the corresponding variables.

3. Results

3.1. Result of the Relation between Urban Blocks and Traffic CO_2 Emissions

In this research, regarding the forecast analysis model of the total traffic volume in each road crossing in the urban block, after counting the total number of vehicles within 24 h in the road crossing, linear regression analysis is conducted according to the morning peak and evening peak data (Figure 3).

In this research, the forecast of total traffic volume in the road crossings is obtained as shown in Equation (5) as follows:

$$y = 2261.52 + 2.36y_1 + 10.18y_2 \qquad R^2 = 0.99 \tag{5}$$

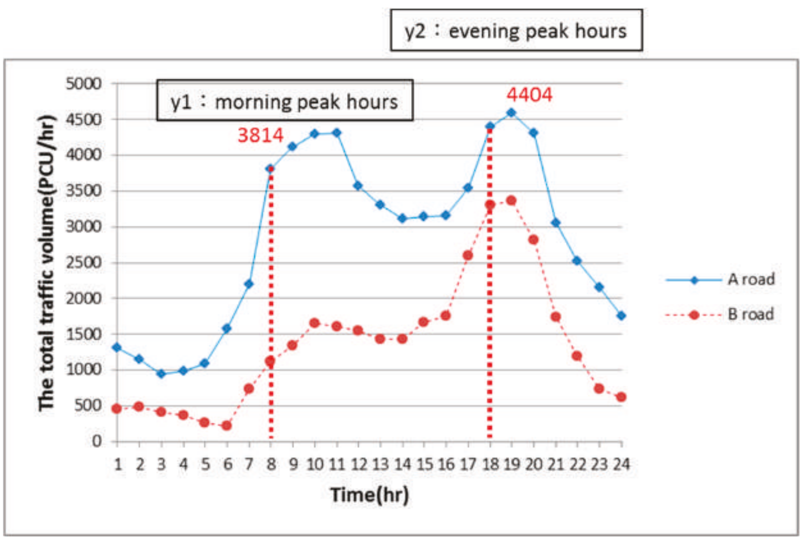


Figure 3. Relational diagram of the traffic volume at the morning peak and evening peak.

This formula is the passenger car unit (PCU/day) generated at the road crossings in an entire day, where y_1 is the morning peak hours (PCU/h) and y_2 is the evening peak hours (PCU/h).

In this research, the total area of an urban block, the total floor area of buildings, the total traffic volume generated at the four road crossings of the block and the total CO_2 emissions generated by the total number of vehicles (Table 3), are analyzed and counted (Figure 4) and the research results on the distribution of the total CO_2 emissions generated by total number of vehicles in each block is as follows (Figure 5):

Regarding the influential relation between the development scale of various buildings and the car traffic volume, through the analysis result in this research, each square meter area in the urban block generates a passenger car unit (PUC/day) of 4.72 every day. Each square meter of floor area of the building generates a passenger car unit (PCU/day) of 0.99 every day. Each passenger car unit (PCU) generates total CO_2 emissions of 41.4 kgCO_2/yr throughout the year.

Table 3. Statistical of the total traffic volume generated and the total CO_2 emissions generated by the total number of vehicles.

Case	The Total Area of an Urban Block (m^2)	The Total Floor Area (m^2)	The Total Traffic Volume (PCU/Day)	The Annual CO_2 Emissions by the Total Vehicles ($kgCO_2$/yr)
1	10,291.7	106,516.1	48,015	699,090.5
2	16,679.2	130,662.3	92,276	1,295,753.5
3	13,554.5	75,925.2	48,654	616,086.0
4	9747.7	26,305.0	47,321	455,057.5
5	3822.4	12,675.2	31,922	215,804.7
6	16,143.3	107,978.7	27,933	395,774.9
7	6606.4	42,656.7	10,945	98,181.4
8	16,400.0	47,283.0	94,676	1,511,754.3
9	6856.0	47,341.0	28,063	249,743.9
10	3522.3	18,860.2	81,547	616,230.2
11	20,261.5	62,957.3	63,484	1,028,001.9
12	7548.9	63,631.0	89,963	854,514.5
13	9813.0	44,720.1	24,158	245,017.3
14	9831.8	16,838.6	45,465	571,277.4
15	9264.0	38,424.3	16,007	160,771.2
16	26,498.8	40,730.6	130,807	2,441,902.1

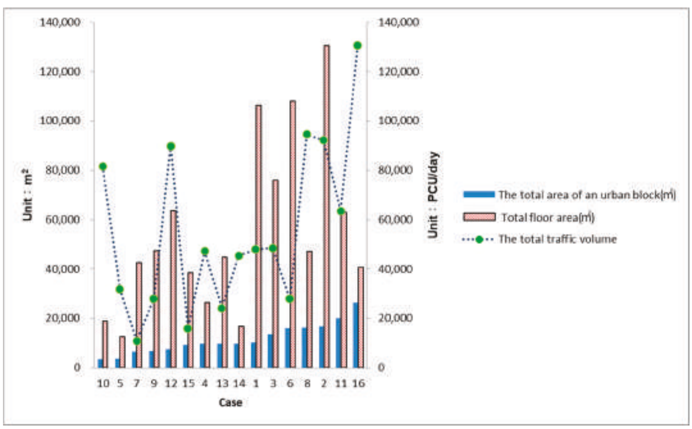


Figure 4. Relational diagram of street blocks and total traffic volume.

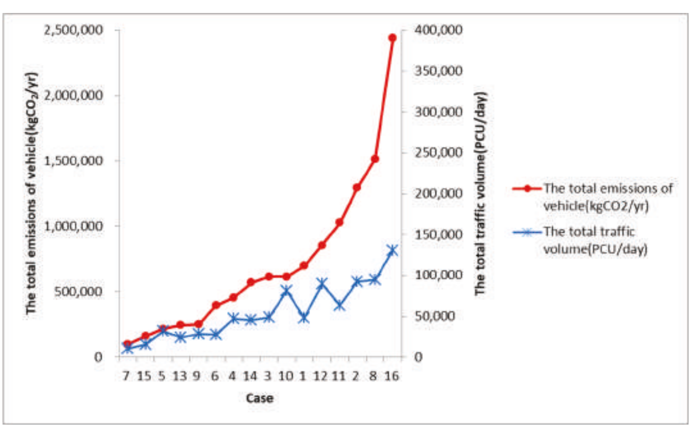


Figure 5. Relational diagram of total emissions and total traffic volume.

3.2. Results of Relation between an Urban Building Complex and Overall Traffic Energy Consumption

This study conducts in-depth analysis of the relation between traffic volume and building design scale. Regarding building design in this research, due to the applicable factors of award decrees of various floor areas, the ultimate design of the building scale is influenced, thus, this research incorporates the total area of the reward of building capacity with parking, total area of the reward of building capacity with open space and the urban building capacity transfer with floor area (Figure 6) and the result is shown as follows (Table 4).

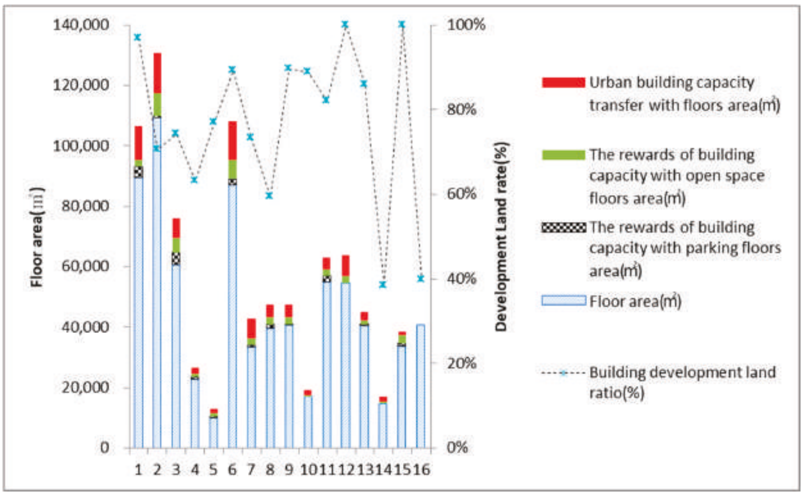


Figure 6. Relational diagram of applicable factors of award decrees of various floor areas.

In this research, an urban block is taken as the basic unit, the total traffic volume generated at the four road crossings of the block is analyzed in order to forecast the mutual relation and efficiently and conveniently estimate the overall urban energy consumption. The research result is as follows:

The relation between the total annual CO_2 emissions of urban blocks generated by vehicles and the total area of an urban blocks (Figure 7) is as follows:

$$y = 79.5 \times \text{TA} - 212{,}719 \qquad R^2 = 0.64 \tag{6}$$

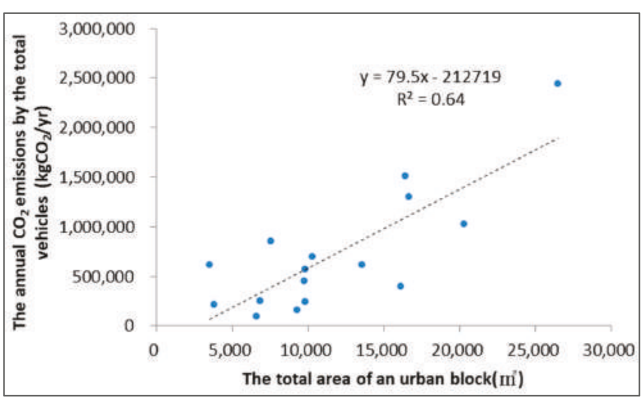


Figure 7. Relational diagram between the total area of an urban block and the total CO_2 emissions all year round.

Table 4. Statistical for the relation between traffic volume and building design scale in urban block.

Case	The Total Area of an Urban Block (m^2)	Site Area (m^2)	Building Area (m^2)	The Total Floor Area (m^2)	The Rewards of Building Capacity with Parking Floors Area (m^2)	The Rewards of Building Capacity with Open Space Floors Area (m^2)	Urban Building Capacity Transfer with Floors Area (m^2)	The Annual CO_2 Emissions by the Total Vehicles ($kgCO_2$/yr)
1	10,291.7	9971.53	5172.38	106,516.05	3566.66	2369.12	11,168.07	699,090.5
2	16,679.2	11,773.10	4905.56	130,662.31	533.33	7684.54	13,197.35	1,295,753.5
3	13,554.5	10,047.57	4631.52	75,925.21	4047.45	4753.48	6642.00	616,086.0
4	9747.7	6145.43	3503.77	26,305.03	833.33	1062.63	1928.18	455,057.5
5	3822.4	2944.46	809.45	12,675.17	433.33	903.44	1445.31	215,804.7
6	16,143.3	14,387.31	6831.72	107,978.68	1913.33	6401.51	12,615.63	395,774.9
7	6606.4	4843.89	2461.70	42,656.69	515.15	2320.36	6542.02	98,181.4
8	16,400.0	9739.19	4677.38	47,283.02	1350.00	2268.40	4203.50	1,511,754.3
9	6856.0	6145.35	2962.79	47,340.98	250.00	2470.84	4039.36	249,743.9
10	3522.3	3127.67	1510.91	18,860.16	0	483.23	1570.45	616,230.2
11	20,261.5	16,617.52	7571.38	62,957.32	2120.00	2115.73	4004.74	1,028,001.9
12	7548.9	7548.92	4252.06	63,631.02	0	2298.50	6895.75	854,514.5
13	9813.0	8432.73	4366.38	44,720.06	406.67	1115.10	2750.15	245,017.3
14	9831.8	3767.80	1706.17	16,838.64	0	571.17	1705.20	571,277.4
15	9264.0	9263.96	4527.37	38,424.30	963.33	2676.77	1255.83	160,771.2
16	26,498.8	10,548.63	4741.82	40,730.55	0	0	0	2,441,902.1

This formula is the total annual CO_2 emissions of vehicles in the blocks ($kgCO_2/yr$) and TA is the total area of an urban blocks (m^2).

The relation between the total annual CO_2 emissions of urban blocks generated by vehicles and the total floor area of buildings (Figure 8) is as follows:

$$y = 3.3 \times FA_{TA} + 532{,}167 \qquad R^2 = 0.04 \tag{7}$$

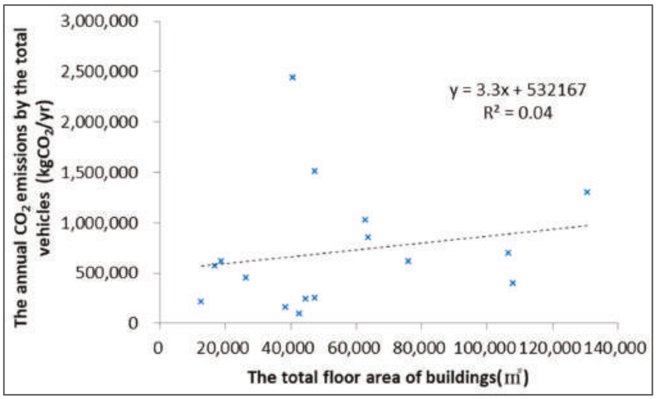


Figure 8. Relational diagram between the total floor area of buildings and the total CO_2 emissions all year round.

This formula is the total annual CO_2 emissions of vehicles in the urban blocks ($kgCO_2/yr$) and FA_{TA} is the total floor area of buildings (m^2).

After analysis of the 16 blocks, this research aimed at the seven important factors influencing building planning and the total CO_2 emissions of vehicles and the multiple regression forecast formula of the total annual CO_2 emissions of vehicles in the blocks is concluded as follows:

$$\begin{aligned} TVC = 14{,}359.71 + (109.94 \times TA) - (60.92 \times SA) - (88.17 \times BA) + (15.36 \times FA_{TA}) - (65.30 \times FA_P) \\ - (118.30 \times FA_O) - (39.60 \times FA_T) \qquad R^2 = 0.84 \end{aligned} \tag{8}$$

where, TVC is the annual CO_2 emissions generated by the total vehicles ($kgCO_2/yr$), TA is the total area of an urban blocks (m^2), SA is the site area (m^2), BA is the building area (m^2), FA_{TA} is the total floor area of buildings (m^2), FA_P is the total area of the reward of building capacity with parking (m^2), FA_O is the total area of the reward of building capacity with open space (m^2) and FA_T is urban building capacity transfer with floor area (m^2). In this research, the relation between seven important design factors of the building design and the daily passenger car unit is further analyzed and the forecast multiple regression formula of the total passenger car units of the blocks within one day is concluded as follows:

$$\begin{aligned} TV = 30{,}065 + (4.72 \times TA) - (4.99 \times SA) - (2.19 \times BA) + (1.09 \times FA_{TA}) - (6.47 \times FA_P) \\ - (6.38 \times FA_O) - (3.39 \times FA_T) \qquad R^2 = 0.57 \end{aligned} \tag{9}$$

where, TV (total vehicles) is the passenger car unit per day (PCU/day) and other symbols are the same as Equation (8).

Regarding the total floor area, new households and actual construction and development rate of blocks of building designs in an urban block, the forecast regression formula is concluded as follows:

$$TV = 94{,}042 - (59{,}234.2 \times BE) + (0.86 \times FA_{TA}) - (181.65 \times HH) \qquad R^2 = 0.66 \tag{10}$$

where, TV is the passenger car unit per day (PCU/day) and BE is the building development land ratio, which is the ratio of applied land for a building permit divided by the total block area, FA_{TA} is the total floor area of buildings (m^2) and HH is the number of households.

Regarding the relation with the total traffic volume, as generated by the urban traffic system within one day, the forecast regression formula in this research is concluded as follows:

$$TV_i = 8873.61 - (116.28 \times R_{di}) + (7.51 \times R_{ai}) \qquad R^2 = 0.83 \tag{11}$$

where, TV_i is the passenger car unit per day (PCU/day) generated on road i, R_{di} is the length of the road (m) at block i and R_{ai} is the area of road (m^2) at block i.

3.3. Result of the Distribution Map of One-Day Vehicle Volume in Urban Areas

According to the "Code for design of urban roads and auxiliary engineering" (1999) and the general practical application, the method to plan a lane usually depends on lane width. If the road is 15 m wide, planning is dominated by car lanes and motorcycle vehicle mixed lanes; if the road width is more than 20 m, the division of two lanes is taken as the principle.

In this research, in order to analyze the road width, as well as the mutual relation between the length of each road in the block and the amount of traveling vehicles generated in the road throughout the day, three road widths are classified (Type A: 8~12 m; Type B: 15~20 m; Type C: 23~60 m). This research found that the relation between the passenger car unit and road length in the three road widths is, the wider the road is, the longer the road and larger the traffic volume will be (Figure 9), thus, there is non-positive correlation for urban roads with a width less than 12 m.

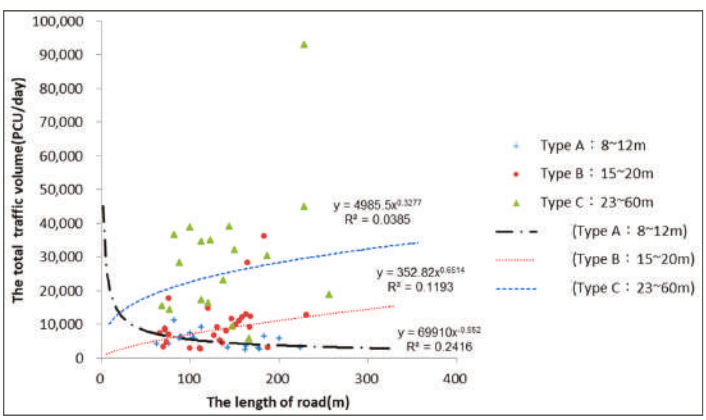


Figure 9. Relational diagram between the length of each road in the block and the amount of traveling vehicles generated in the road by three road widths.

This research takes the Geographic Information System data of Taichung in a scale of 100 × 100 m mesh, the urban planning road by law is taken as the main explanation target and the research result of Equation (11) is used to calculate the road length and road area; after calculation and layer analysis, the distribution map of passenger car units in Taichung within one day is presented (Figure 10) and amount of CO_2 emissions from traffic (Figure 11) and the urban traffic environmental characteristic map can effectively provide the basic information to judge traffic volume.

This figure presents a large distribution of traffic volume in the Taichung metropolitan area, which is dominated by linear distribution in the main external road, while a great characteristic is formed with the traffic flow on the ring road. In addition, for roads with higher traffic volume, a single hot spot is generated at the main road crossing.

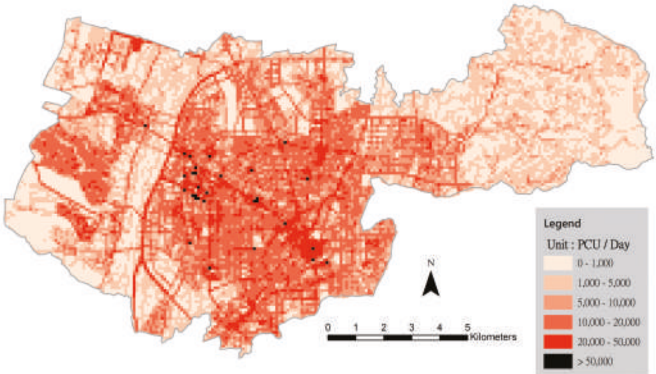


Figure 10. The distribution map of passenger car units in Taichung metropolitan area within one day.

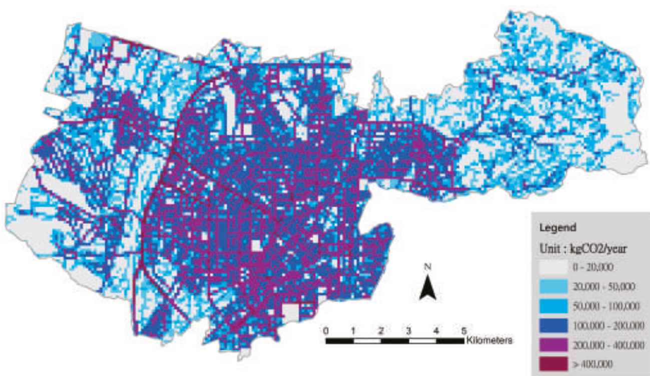


Figure 11. Amount of CO_2 emissions from traffic in Taichung metropolitan area.

Finally, the total CO_2 emissions from traffic and buildings in each 100×100 m grid in Taichung were estimated according to the type of land specified and the effects of the city's carbon sinks (e.g., rivers and parks) on that estimated volume of CO_2 emissions were analyzed. On the basis of these results, a carbon budget map for the city was constructed (Figure 12).

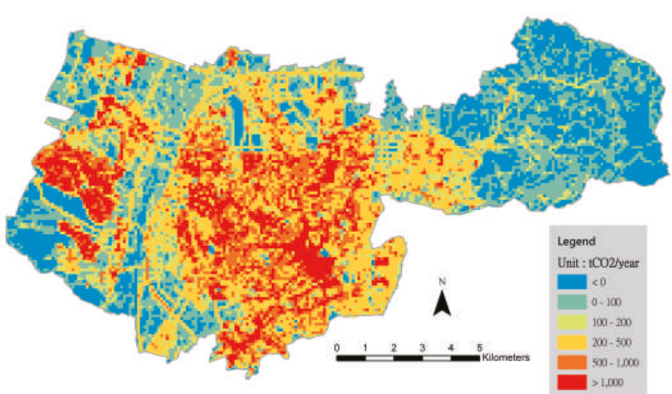


Figure 12. Annual total CO_2 emissions of Taichung metropolitan area.

4. Discussion

Due to climate change and the influence of the reduction of CO_2 emissions, in this research regarding the method and purpose of forecasting traffic volume and estimations of CO_2 emissions, the discussion and model application limitations are proposed as follows:

Daily traffic volumes were measured largely at thoroughfares; little such data were collected at typical roads. To increase the availability of traffic volume data at different types of roads, future studies can collect this data continuously and measure the traffic volume of both thoroughfares and common roads on a daily basis and analyze these data to improve the accuracy of prediction models. This research summed up hourly traffic volumes measured at thoroughfares and conducted a regression analysis of maximum traffic volumes at thoroughfares during morning and evening peak hours. Therefore, the CO_2 emissions from road traffic predicted by this research were characteristically large.

Regarding urban road travel distance, due to different forms of vehicles, different carbon emissions are generated; in terms of calculation, due to simplification and no consideration of types of fuels, driving speeds, road slopes and other fuel consumption influences, the research result belongs to the result of a larger forecast value. In the four road crossings in a single block in an urban area; regarding the case of measured data of existing traffic volume, practical data are difficult to obtain, thus, this research suggested that in order to increase the accuracy of the estimation formula, in the future, researchers can directly measure the road crossing traffic volume at the four road crossings of a single urban block and expand it for use.

The fuel usage and efficiency and CO_2 emissions of vehicles in use vary according to their types and road infrastructure planning. Therefore, future studies that analyze the amount of carbon emissions in an entire city can account for vehicle types and road infrastructure plans to inform their estimation of carbon emissions from road traffic. To estimate the amount of carbon emissions from buildings, future researchers can measure, on the basis of local EUI, the amount of CO_2 emissions from electricity used by different types of buildings. The carbon-sink effects of constructed landscapes such as trees or green spaces on the amount of CO_2 emissions from different types of buildings can also be measured to explicate how these effects on individual buildings help reduce CO_2 emissions on the scale of city blocks.

5. Conclusions

By simplifying the transportation demand mode in this research, the forecast formula of the total traffic volume at important road crossings throughout the day in Taichung is obtained and the relation between building complex development factors and traffic volume generated by the overall urban blocks is analyzed.

Regarding the relation between the development scale of various buildings and the influence of vehicle traffic flows, this research calculates the passenger car units generated by each square meter of area every day, as well as the result of the total annual CO_2 emissions. This research aimed at the relation between seven important design factors influencing building design, as well as the total traffic CO_2 emissions, in order to further obtain the multiple regression forecast estimation model of the total annual carbon dioxide of vehicles in the blocks.

Furthermore, it is possible to propose the integration of practical deliberation case information of building permits, such as urban planning laws and the Building Act, thus, when an architect designs the development factors, or when urban planners regularly conduct overall inspections of urban planning, it is possible to easily and effectively plan and evaluate urban areas and rapidly calculate the traffic volume in the future. Moreover, after proposing the cooperation of the conversion Geographic Information System information in urban areas, it is possible to clearly obtain the basic information of the traffic volume and present a map of urban traffic environmental characteristics.

Author Contributions: The author would like to thank the Urban Development Bureau of Taichung City Government in all the building permit data. Thanks to Building Permit Management Division for their document support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Liao, L.C. *The Assessment of the Energy Saving and the Carbon Dioxide Reduction Strategies for Road Transportation Sector*; Taipei University Institute of Natural Resourse and Environment Management: Taipei City, Taiwan, 2009; pp. 1–10.
2. Li, S.S. Method in Estimating CO_2 Emissions from Gasoline Vehicles in Taiwan. Master's Thesis, National Cheng Kung University, Tainan, Taiwan, 2007.
3. Henning, N.; Dagmar, H.; Martin, L.; Heidi, W. Environmental impact assessment of urban land use transitions—A context-sensitive approach. *Land Use Policy* **2009**, *26*, 233–248.
4. Fuller, R.J.; Crawford, R.H. Impact of past and future residential housing development patterns on energy demand and related emissions. *J. Hous. Built Environ.* **2011**, *26*, 165–183. [CrossRef]
5. Lin, H.T. *Green Building in Hot-Humid Climate*; Chan's Arch-Publishing Co., Ltd.: Taipei City, Taiwan, 2003.
6. Chang, Y.S. Life Cycle Assessment on the Reduction of Carbon Dioxide Emission of Buildings. Ph.D. Thesis, Department of Architecture, National Cheng Kung University, Tainan, Taiwan, June 2002; pp. 67–136.
7. Lin, H.T. *Footprint of Architecture Evaluation Theory*; Chan's Arch-Publishing Co., Ltd.: Taipei City, Taiwan, 2014; pp. 67–164.
8. Gan, J.J. A Study on the Electricity Consumption Prediction Method of City Blocks. Master's Thesis, Department of Architecture, National Cheng Kung University, Tainan, Taiwan, 2009; pp. 1–11.
9. Wang, R.J. A Study on Electricity Consumption Analysis of Residential Area. Ph.D. Thesis, Department of Architecture, National Cheng Kung University, Tainan, Taiwan, May 2005; pp. 107–126.
10. Po, C.S. Analysis of Energy Saving and Carbon Reduction by the Mode Choice and Trip Assignment Combined Model. Master's Thesis, Department of Civil and Ecological Engineering, I-Shou University, Kaohsiung, Taiwan, January 2011; pp. 8–40.
11. Hu, T.Y. Micro-simulation Based Dynamic Traffic Assignment. *Transp. Plan. J.* **2001**, *30*, 1–32.
12. Chen, J.N. A Study of Micro-simulation Based Dynamic Traffic Assignment Model under Mixed Traffic Flow Environment: The Principle of User Equilibrium. Master's Thesis, Department of Transportation Engineering and Management, Feng Chia University, Taichung, Taiwan, 2005; pp. 5–37.
13. Wardrop, J.G. *Some Theoretical Aspects of Road Traffic Research*; Institution of Civil Engineers: London, UK, 1952; pp. 325–378.
14. Doron, L. Land use for transport projects: Estimating land value. *Land Use Policy* **2015**, *42*, 594–601.
15. Yang, A.T. Structuralized Analysis of Urban Form Impacts on Travel Demand. *J. Chin. Inst. Transp.* **2006**, *18*, 391–416.
16. Jeong, Y.; Lee, G.; Kim, S. Analysis of the Relation of Local Temperature to the Natural Environment, Land Use and Land Coverage of Neighborhoods. *J. Asian Archit. Build. Eng.* **2015**, *14*, 33–40. [CrossRef]
17. Dai, G.F. The Research on the Interaction between Urban Land Use and Carbon Dioxide Concentration. Master's Thesis, Department of Urban Planning, National Cheng Kung University, Tainan, Taiwan, June 2010.
18. Hopkins, A.S.; Schellnhuber, H.J.; Pomaz, V.L. Urbanised territories as a specific component of the Global Carbon Cycle. *Ecol. Model.* **2004**, *173*, 295–312. [CrossRef]
19. Lin, T.P.; Lin, F.Y.; Wu, P.R. Multiscale analysis and reduction measures of urban carbon dioxide budget based on building energy consumption. *Energy Build.* **2017**, *153*, 356–367. [CrossRef]
20. She, P.C. A Study of the Influence of Highway Design Factors on Vehicle Carbon Emissions in Taiwan. Master's Thesis, Institute of Construction Engineering and Management, National Central University, Taoyuan, Taiwan, 2012; pp. 37–58.
21. Heimbach, C.L.; Cribbins, P.D.; Chang, M.S. Some partial consequences of reduced traffic lane widths on urban arterials. *Transp. Res. Rec.* **1983**, *923*, 69–72.
22. Chen, C.L.; Zhuang, Z.W.; Jiang, Y.H. Research energy consumption and pollution emissions by vehicle. In Proceedings of the Combustion Institute of R.O.C. 18th Symposium, Taiwan, 29 March 2008.

23. Huang, Y.K.; Tsao, S.M. An analysis of carbon dioxide emissions in transportation sector. *Urban Traffic Q.* **2003**, *18*, 1–14.
24. Ren, C.; Wu, E.N. *Urban Climatic Map—An Information Tool for Sustainable Urban Planning*; China Building Industry Publishing: Beijing, China, 2012; pp. 11–30.
25. Lin, F.B. *Taiwan Highway Capacity Manual*; Institute of Transportation, MOTC: Taipei City, Taiwan, 2011.
26. Bureau of Energy, Ministry of Economic Affairs, Industrial Technology Research Institute Printed, Vehicle fuel Consumption Guidelines, February 2010. Available online: https://www.moeaboe.gov.tw/ecw/populace/content/wfrmStatistics.aspx?type=5&menu_id=1303. (accessed on 25 December 2017).
27. Jiang, M.F. Using 3D Remote Sensing Data to Analyze the CO_2 Balance in Vicinity of Road-Case Study of Highway No. 84 at Taiwan. Master's Thesis, Department of Resources Engineering, National Cheng Kung University, Tainan, Taiwan, 1999; pp. 6–31.
28. Lin, H.T. *Building Carbon Footprint*, 2nd ed.; Chan's Arch-Publishing Co., Ltd.: Taipei City, Taiwan, 2015.
29. Chen, J.H.; Lin, H.T. The Classification Model of Energy Use Intensity Based on Building Function Types. Master's Thesis, Department of Architecture, National Cheng Kung University, Tainan, Taiwan, June 2009.
30. Huang, P.H.; Huang, S.L. Metabolism Approach for Studying the Relationship Between Urbanization and CO_2 Emission and Sequestration, first edition. Master's Thesis, National Taipei University, Taipei, Taiwan, June 2014.

sustainability

MDPI

Article

An Integrated Carbon Policy-Based Interactive Strategy for Carbon Reduction and Economic Development in a Construction Material Supply Chain

Liming Zhang *, Wei Yang, Yuan Yuan and Rui Zhou

Business School, Sichuan University, Chengdu 610064, China; yang_benjun@163.com (W.Y.); yuanyuan1129@scu.edu.cn (Y.Y.); ruizhou_283@163.com (R.Z.)

* Correspondence: zhangliming@scu.edu.cn

Received: 17 October 2017; Accepted: 13 November 2017; Published: 18 November 2017

Abstract: Carbon emissions from the construction material industry have become of increasing concern due to increasingly urbanization and extensive infrastructure. Faced with serious atmospheric deterioration, governments have been seeking to reduce carbon emissions, with carbon trading and carbon taxes being considered the most effective regulatory policies. Over time, there has been a global consensus that integrated carbon trading/carbon tax policies are more effective in reducing carbon emissions. However, in an integrated carbon reduction policy framework, balancing the relationship between emission reductions and low-carbon benefits has been found to be a critical issue for governments and enterprises in both theoretical research and carbon emission reduction practices. As few papers have sought to address these issues, this paper seeks to reach a trade-off between economic development and environmental protection involving various stakeholders: regional governments which aim to maximize social benefits, and producers who seek economic profit maximization. An iterative interactive algorithmic method with fuzzy random variables (FRVs) is proposed to determine the satisfactory equilibrium between these decision-makers. This methodology is then applied to a real-world case to demonstrate its practicality and efficiency.

Keywords: construction materials; green supply chain; integrated carbon policy; interactive strategy; low carbon

1. Introduction

The "low carbon" concept was introduced at the World Climate Change Conference in Copenhagen, Denmark, 2009, after which low carbon economies became the major focus in many countries, leading to the development of the green supply chain (GSC) [1]. As one of the industries with the highest carbon emissions, the construction sector accounts for over one-third of global carbon dioxide emissions [2–5]. In addition to the carbon emissions from the daily operation of buildings, China has been undertaking many urban construction projects [6], which has led to a tremendous rise in construction carbon emissions [7]. In particular, as one of the six largest energy-consuming industries in China, the construction material industry represents 9% of the total energy consumption and 6% of total electricity consumption in China [8]. It is also a pillar industry in China since its added value makes up about 1% of the gross domestic product (GDP) each year [9]. The construction material industry has great potential with respect to energy conservation and carbon dioxide emission reduction, which could be of great significance to the achievement of total energy consumption control and transformation of low-carbon development. Enterprises, as the basic elements in the supply chain (SC), are required to take responsibility for the environmental performance of the supply chain participants [10]. As enterprises in supply chains are closely related, all are simultaneously affected by any carbon emission regulations. Therefore, SC enterprises must jointly adjust their operating and production plans to effectively achieve individual environmentally friendly performance [1]. Several advantages of the GSC have been identified, such as a positive corporate image, improved efficiency, and innovative leadership [1], all of which have encouraged more decision-makers to embrace GSC management (GSCM). When carbon emission regulations are imposed in a marketplace, scientifically designed environmental plans can enhance innovation, reduce total production costs, and highlight enterprise value [11]. Therefore, for each GSC member, low-carbon operations can represent a valuable, non-substitutable advantage [12]. Further, GSCM is a means for reducing potential losses from poor carbon emission performance that can intensify regulatory pressures [13], damage an enterprise's image, attract government fines, and lead to customer boycotts or order cancellations [14,15].

At the same time, the focus on the protection of benefits in environmentally-related construction issues has grown, becoming a primary norm for the development of socioeconomic policies [16–18]. Therefore, further environmental policies and institutional acts on this topic are urgently required for greener approaches in the area of construction engineering [19]. Governments around the world have promulgated various policies to reduce carbon emissions, with carbon trading and carbon taxes considered the most effective policy schemes for reducing carbon emissions [20,21]. Carbon trading, which is a mainstay in emission trading programs, is specifically aimed at reducing carbon emissions [22]. In the carbon trading market, enterprises which want more than their allocated carbon emissions can purchase rights to emit more, and firms who do not require their allocated carbon emissions can sell their carbon emission rights to other enterprises [22]. There has been a sharp rise in the number of carbon emission trading schemes in recent decades. For example, in 2005, 374 million t of equivalent carbon dioxide were exchanged, but by 2011, the carbon trading volume had risen to 10.28 billion CO_2 t, with the global carbon trading market valued at 176 billion US dollars [23]. Carbon taxes, which are a type of Pigovian tax [24], are a potentially cost-effective method for reducing greenhouse gas emissions [25]. Many European countries, such as the Netherlands, Sweden, Finland, and Norway, implemented carbon taxes many decades ago [26]. However, the Chinese government only introduced a carbon tax around 2013, which has severely affected the domestic market in China [27].

As stated above, most scholars have tended to study GSC from government or enterprise perspectives; however, while there have been many studies on carbon trading and carbon tax, many have only focused on the impact of a single policy on the macroeconomic development of carbon emission reductions, and the mutual relationships between supply chain enterprise operations and government policies have been ignored. In addition, there has been a lack of research on the performance of integrated carbon trading and carbon tax policies. To address this research gap, this paper explored the government and SC producer carbon reduction problems associated with integrated carbon trading and carbon tax policies. The government initially determines the annual free carbon emission allowances for the producer based on the average carbon emission level of the industry and its historical emission data. To control total carbon emissions and reduce the adverse impact of carbon emission reduction, the government, whose objective is to maximize social welfare, imposes a carbon tax on the producers. Under the dual constraints of emission allowance and carbon tax, the SC producers must be allocated sufficient carbon emissions to satisfy their daily operations. As the SC producers cannot exceed emission allowance limitations, they must either trade any remaining carbon emission allowances on the carbon trading market or directly purchase additional allowances to meet their emissions requirements. However, now carbon tax and the consumer's low-carbon preference must be taken into serious consideration, while at the same time considering the carbon tax and consumer preference for low-carbon operations. Producers can achieve emission reductions by flexibly combining emission reduction investments and emission rights purchasing. Finally, to maximize their own profits, the SC producers must weigh up the emission costs and benefits under different strategy combinations to determine the final emission level and the associated product prices.

Because of the multiple decision-makers and the complex interactions, bi-level mathematical programming is proposed as it can accurately describe the interests of the decision-makers. Bi-level models have been widely applied in SC management [28–32]. For example, Ghosh and Shah [28] developed a bi-level supplier/manufacturer SC to examine SC coordination issues under a carbon emission policy. Song and Leng [29] included the carbon emission factors into a single-cycle newsboy model to examine the influences of different carbon emission policies on producers' orders. Choi [30] examined the impact of a carbon footprint tax on bi-level fashion SC systems, and the importance of the carbon footprint tax on SC fashion management. Du et al. [31] considered an emission-dependent SC to examine an emission-dependent manufacturer and an emission permit supplier under a cap-and-trade system. Jaber et al. [32] researched bi-level manufacturer/retailer SC game processes and coordination mechanisms under carbon cap-and-trade conditions.

These studies have inspired researchers with novel management insights into government carbon emission regulations and GSC operations; however, the carbon emission regulation parameters have been generally regarded as exogenous variables, with the governments not being involved in the decision-making processes. Therefore, the main contributions of this paper are as follows. First, the integration of carbon reduction policies and their relationships within GSCs are explored. Second, optimal decision results are theoretically derived through the development of a bi-level optimization model, in which the leader, which has a social welfare maximization objective, determines the carbon tax and emission allowance allocations, and the following producers, which have a profit maximization objective, determine their production output and sales quantities. Third, it is shown that the sustainable GSC development and a trade-off between environmental protection and economic development can be achieved by employing the proposed methodology.

The remainder of this paper is organized as follows. Section 2 gives the research and problem statement, including the research background and the decision-making relationship analysis. In Section 3, a methodology, including a bi-level mathematical model and an interactive algorithm, is established as an abstraction of the real problem. To confirm the generality of the methodology, a general case, results, and some further discussions are given in Section 4. Finally, Section 5 gives the conclusions and suggestions for future studies.

2. Research and Problem Statement

In an integrated carbon policy-based carbon emission reduction problem, there are various decision-makers: the government as the leading decision-maker and the GSC producers as the following decision-makers who act based on the government's decisions. Both parties have individual contradictory carbon reduction targets. The government seeks to effectively reduce overall carbon emissions, while safeguarding the economic interests of the producers, with the aim of stimulating participation and enthusiasm for emission reduction, and maximizing total social welfare, while the producers seek to obtain as high a carbon emission allowance as possible to reduce their emission costs and maximize profits. Both of parties have individual but interacting decision-making variables; the government's decision-making variables are the free carbon emission allowances and the carbon tax; while the producer's variables are production and sales quantities. It is assumed that the GSC producers have an equal market position and each independently trades their carbon emission allowances on the open market. As the producers' profits are considered when the government sets the carbon emission reductions targets, the decisions made by the producers not only determine their own objectives but also influence the government's goals. Therefore, the government's decisions also need to consider the influence of the producers' responses to its own goals. Therefore, the carbon emission reduction problem in this paper is a dynamic optimization decision-making process, within which the government needs to monitor the carbon trading market, assess the effectiveness of the carbon tax level, and improve their emission reduction strategies based on the responses from the market and the producers.

The above analysis has shown that the carbon emission reduction decision-making process is an interactive decision-making mechanism comprised of the government as the leading decision-maker responsible for the overall carbon reduction plan and control, and the producers as the following decision-makers who have independent decision-making rights in terms of their own carbon reduction goals. As the government is in the lead decision-making position, it has the advantage of moving first. From this description, this integrated emission reduction decision-making policy problem has the same characteristics and mechanisms as a general bi-level decision-making problem, which is similar to the hierarchical decision leader–followers Stackelberg game, in which the leader is more powerful and the follower reacts rationally to the leader's decisions [33,34]. Therefore, the bi-level Stackelberg game can be used to examine this level of this government/producers carbon emission reduction decision-making relationship.

This problem can be abstracted as a bi-level mathematical model for calculation, which, along with the hierarchical structure makes it a complex problem, as shown in the concept model in Figure 1.

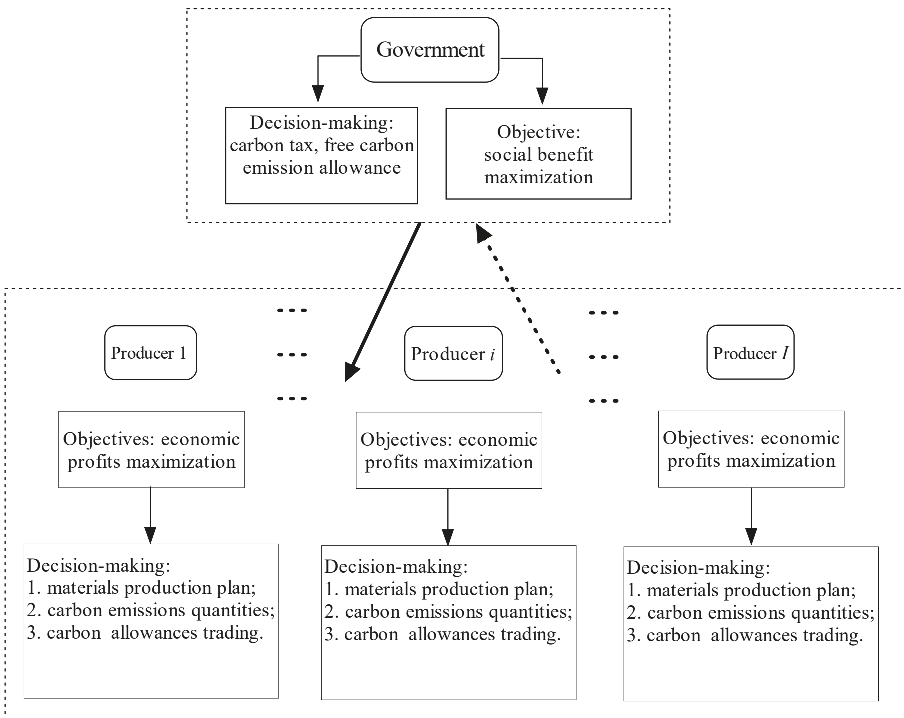


Figure 1. Model of the bi-level decision-making mechanism in carbon emission reduction.

3. Methodology

A bi-level mathematical model and a corresponding solution approach are proposed in this section.

3.1. Bi-Level Programming

Assumptions, notations, objective functions and constraints of an integrated emission reduction decision-making policy problem are introduced in this section.

3.1.1. Assumptions

Before formulating the model, the following assumptions are given:

A_1 This integrated carbon emission policy problem is a single-period decision-making problem; therefore, a static optimization problem is assumed.
A_2 The government is responsible for the initial free carbon emission allowance allocation and the producers freely transact with other producers in the CET market.
A_3 None of the producers can individually meet all the projects' requirements [35].
A_4 Each decision-maker fully understands the objective functions and inherent constraints, and behaves rationally [36].

3.1.2. Notations

Sets:
$\mathbb{I}$: Set of producers, $\mathbb{I} = \{1, 2, \cdots, I\}$.
$\mathbb{J}$: Set of projects, $\mathbb{J} = \{1, 2, \cdots, J\}$.
Indices:
i : Index for the construction material producers, $i \in \mathbb{I}$.
j : Index for the projects, $j \in \mathbb{J}$.
Decision variables:
α_i : Free carbon emission allowance for construction material producer i.
γ : Carbon tax rate for construction material production.
q_i : Total construction materials produced by producer i.
q_{ij} : Total construction materials purchased from producer i for project j.
Certain parameters:
Cap : Actual free carbon allowance allocation for the construction material industry in the last production period.
γ^l : Lower bounds for the unit carbon tax.
γ^u : Upper bounds for the unit carbon tax.
CE_i^u : Carbon emissions produced by producer i with no emission reduction measure.
CE_i^l : Carbon emissions produced by producer i after the carbon reduction efforts.
PC_i : Unit production cost for construction material producer i.
IC_i : Unit inventory cost for construction material producer i.
P_{ij} : Price of a unit of construction material k from producer i for project j.
GP_i : Production carbon emission coefficient for producer i.
PM_i^l : Lower bounds for the production capacity for producer i.
PM_i^u : Upper bounds for the production capacity for producer i.
$SC_i^{\max}$: Maximum storage capacity of producer i.
β : Market price of carbon emission trading.
λ : Sale taxes an enterprise pays for a unit of construction material.
Uncertain parameters:
$\tilde{\tilde{D}}_j$: Total demand of project j for construction materials.

3.1.3. Model Formulation

This section gives a detailed description of the global model including the model of the government and the model of the producers.

Objective 1: The government's social benefit objective. To balance the environmental protection and economic development of the construction material industry, the government must control carbon emissions while also considering the social benefits. However, the social benefits are the primary objective, which are made up of three parts; sales taxes on materials, revenue from carbon emission trading, and the carbon tax revenue. Let λ be the unit sales tax for the construction material. The total sales taxes for the materials are therefore $\lambda \sum_{i=1}^{I} \sum_{j=1}^{J} q_{ij}$. It is assumed that β is the carbon emission trading price. Therefore, the total carbon emission trading revenue is $\beta \sum_{i=1}^{I} (GP_i q_i - \alpha_i)$. Under the carbon tax policy, construction material producers have paid taxes for their carbon emissions. Let γ be the unit carbon tax for producing the construction materials. The total carbon tax revenue is therefore $\gamma \sum_{i=1}^{I} GP_i q_i$, and the overall social benefit for the government is:

$$\max W = \lambda \sum_{i=1}^{I} \sum_{j=1}^{J} q_{ij} + \beta \sum_{i=1}^{I} (GP_i q_i - \alpha_i) + \gamma \sum_{i=1}^{I} GP_i q_i. \quad (1)$$

Constraint 1: Free carbon emission allocation constraint. To limit the carbon emissions, the government initially allocates free allowances to the producers. To protect the construction material industry, the government cannot allocate a carbon emission allowance beyond a producer's capacity. Therefore, there exists an upper bound, $\leq CE_i^m$, for producer i, which represents the maximum carbon emissions emitted when producer i is under full-load production; this constraint is denoted as $\alpha_i \leq CE_i^m$. However, to guarantee each producer's basic rights, the government must allocate a carbon emission allowance that ensures that the producer can produce at capacity. Therefore, there exists a lower bound, CE_i^l, for producer i, which is the minimum carbon emission allowance allocation needed to maintain basic operations. This constraint is denoted as $CE_i^l \leq \alpha_i$. To ensure both sides are fully considered, the producers' restrictions when the government makes decisions are:

$$CE_i^l \leq \alpha_i \leq CE_i^m. \quad (2)$$

Constraint 2: Industry free carbon emission allowance allocation constraint. As the government must guarantee the atmospheric environment, they may alter their intentions to control the carbon emissions of the whole industry within an acceptable range, which cannot surpass the actual free carbon allowance allocation given to the construction material industry in the last production period,

$$\sum_{i=1}^{I} \alpha_i \leq Cap. \quad (3)$$

Constraint 3: Carbon tax constraint. The formulated unit carbon taxes must be within the minimum and maximum carbon tax limitation bounds, which can be expressed as:

$$\gamma^l \leq \gamma \leq \gamma^u. \quad (4)$$

Constraint 4: Demand constraint. As construction materials are required to ensure the project meets its construction deadlines, the producers must satisfy the demand for each type of project material. However, because of the inherent complexity and uncertainty in construction technology as well as the fluctuating demand, accurate data for the material supply level is difficult to obtain. Therefore, this demand is dealt with using an expected value operator. The material quantities provided to each project, therefore, must satisfy the respective demands, namely,

$$\sum_{i=1}^{I} q_{ij} \geq E\left[\tilde{\tilde{D}}_j\right]. \quad (5)$$

Objective 2: Producer's profit objective. With the integrated carbon policies, each producer, as an independent decision-maker, seeks to maximize his individual profit, which is the difference between total revenue and total cost. Total revenue comes from construction material sales $\sum_{j=1}^{J} P_{ij} q_{ij}$, while total costs are made up of material production costs $PC_i q_i$, inventory costs $IC_i \left(q_i - \sum_{j=1}^{J} q_{ij}\right)$, sales taxes $\lambda \sum_{j=1}^{J} q_{ij}$, CET costs $\beta (GP_i q_i - \alpha_i)$, and carbon taxes $\gamma GP_i q_i$. Therefore, the profit function is:

$$\max P_i = \sum_{j=1}^{J} P_{ij} q_{ij} - PC_i q_i - IC_i \left(q_i - \sum_{j=1}^{J} q_{ij}\right) - \lambda \sum_{j=1}^{J} q_{ij} - \beta (GP_i q_i - \alpha_i) - \gamma GP_i q_i. \quad (6)$$

Constraint 5: Producers' carbon emissions constraint. The amount of carbon emissions for each producer cannot exceed the emissions without a reduction measure but must not be lower than the amount of emissions with the greatest carbon reduction efforts, that is,

$$CE_i^l \leq GP_i q_i \leq CE_i^m. \tag{7}$$

Constraint 6: Production capacity constraint. When providing construction materials for multiple projects, the material production q_i of producer i must be within a specified range between the maximum and minimum production capacity. Therefore, the production capacity constraint is:

$$PM_i^l \leq q_i \leq PM_i^u. \tag{8}$$

Constraint 7: Inventory constraint. Each producer owns a warehouse for temporarily storing construction materials that are not yet sold. The construction material inventory level of producer i cannot exceed the storage capacity, namely

$$0 \leq q_i - \sum_{j=1}^{J} q_{ij} \leq SC_i^{\max}. \tag{9}$$

3.1.4. Global Model

To sum up, the global model is built as in Equation (10). The decision-makers impact on each other as the government's decisions (α_i, γ) affect the construction material producers' decisions (q_i, q_{ij}). The government attempts to expand the social benefit by reducing total carbon emissions, however, each construction material producer seeks profit maximization. At the same time, the producers' actions (q_i, q_{ij}) affect the government's subsequent actions (α_i, γ). Consequently, all decision-makers seek satisfactory solutions based on their respective optimization targets. At the beginning, based on previous information and its own objectives, the government determines the initial carbon emission allowance allocations, the decisions for which are then is delivered to the construction material producers. Each producer, as a follower, sets its own plan in view of the government's decisions, the market demands, and their own technological conditions. The producers' plans are then submitted to the government, after which the government adjusts its initial decisions in consideration of each producer's emission performance, and an improved plan is then sent to the producers. Therefore, the government influences the behavior of the construction material producers without completely controlling their actions, and the construction material producers' behavior affects the government's decisions. Relationships between each construction material producer are also assumed to be non-cooperative, as each producer makes decisions independently and without collaboration [37]. Each producer, therefore, has an optimization problem, in which the other producers' decisions are regarded as the certain parameters. Therefore, the problem can be expressed mathematically in a bi-level programming model. In summary, the global model is:

$$\max W = \lambda \sum_{i=1}^{I} \sum_{j=1}^{J} q_{ij} + \beta \sum_{i=1}^{I} (GP_i q_i - \alpha_i) + \gamma \sum_{i=1}^{I} GP_i q_i \tag{10}$$

$$\text{s.t.} \begin{cases} CE_i^l \leq \alpha_i \leq CE_i^m \\ \sum_{i=1}^{I} \alpha_i \leq Cap \\ \gamma^l \leq \gamma \leq \gamma^u \\ \sum_{i=1}^{I} q_{ij} \geq E\left[\tilde{\tilde{D}}_j\right] \\ \max P_i = \sum_{j=1}^{J} P_{ij} q_{ij} - PC_i q_i - IC_i \left(q_i - \sum_{j=1}^{J} q_{ij}\right) - \\ \qquad \lambda \sum_{j=1}^{J} q_{ij} - \beta (GP_i q_i - \alpha_i) - \gamma GP_i q_i \\ \text{s.t.} \begin{cases} CE_i^l \leq GP_i q_i \leq CE_i^m \\ PM_i^l \leq q_i \leq PM_i^u \\ 0 \leq q_i - \sum_{j=1}^{J} q_{ij} \leq SC_i^{\max} \end{cases} \\ \alpha_i, \gamma, q_i, q_{ij} \geq 0 \\ i \in \mathbb{I}, j \in \mathbb{J} \end{cases}$$

3.2. Iterative Interactive Algorithm

As is well known, bi-level programming optimization is a non-deterministic polynomial (NP) hard problem even in its most common formulation [38–40]. The decision variables of the government's upper-level mathematical model and the producers' lower-level mathematical models are therefore nested in each decision-maker's objective function and constraints of the model (10), for which an iterative interactive algorithm based on evolutionary game theory between the two decision-makers is established to deal with the complex model (10) interaction. The iterative interactive algorithm solves both the upper and lower optimization problems in the bi-level programming mathematical model. At first, all constraints in the government's upper-level optimization model are set using Matlab R2013a (MathWorks, Natick, MA, USA) and a feasible zone of the upper-level optimization model is built. Then a vector (α_i, γ) is generated, which is the initial solution to the upper-level optimization model, after which vector (α_i, γ) is put into the lower-level optimization model as the constant, and the model is transformed into a single-level programming model for $\left(q_i, q_{ij}\right)$. By employing the mathematical toolbox in Matlab R2013a, an initial solution to the producers' optimization model, $\left(q_i, q_{ij}\right)$, is obtained, which is fed back to the upper-level optimization model, and the model is also transformed into a single-level programming model for (α_i, γ) for the government. The mathematical toolbox in Matlab R2013a is employed again to obtain an improved solution, (α_i, γ). If the government is satisfied with the improved solution, the computation is terminated. If not, the new solution (α_i, γ) is again imported into the lower-level optimization model and the solution to the model calculated, thus generating a new vector for $\left(q_i, q_{ij}\right)$, which is then conveyed to the upper-level model again. As an interactive mechanism in this bi-level decision-making structure, this process is repeated several times until an overall satisfactory solution to both the upper and lower level optimization models is obtained, which is the final solution to the proposed bi-level optimization model. The procedures for this solution approach are shown in Figure 2.

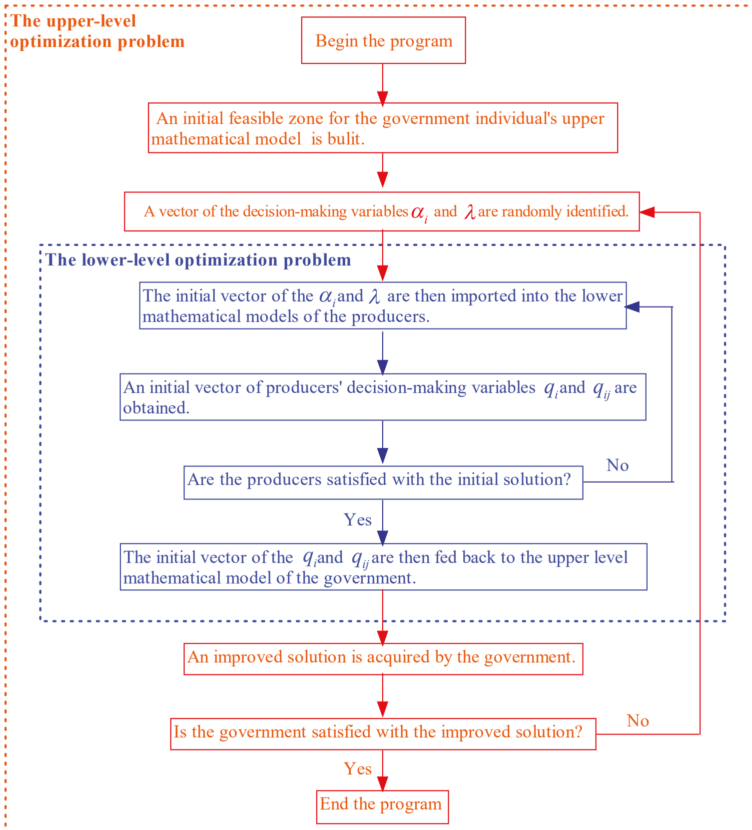


Figure 2. Framework for the iterative interactive algorithm.

4. Case Study

In this section, the construction material industry in City X is employed as a practical case to probe into the integrated carbon emission reduction policy and to demonstrate the practicality of the proposed optimization methodology.

4.1. Case Description

Industry is the dominant consumer of energy and producer of CO_2 emissions in China. China's urbanization process has undoubtedly promoted infrastructure construction, which has stimulated demand for cement, ceramics, glass, and other construction materials [41]. The emission reduction potential is of great significance to the achievement of the total carbon reduction control. City X, the main region for cement production in Shanxi province, supplies the Shanxi province with 20% of its cement demands. The cement industry plays a key role in the economic development of City X, however, emissions from material production are the primary source of carbon emissions, and represent a serious menace to local air quality. In terms of air quality, City X has been judged as one of the worst cities in the Shanxi province. Thus, reducing carbon emissions in construction material industry is regarded as the primary goal for the local government in the next production period.

4.2. Data Presentation

In City X, three main cement producers, referred to as A, B, and C, are engaged in the production and supply of cement for three key projects, referred to as I, II, and III. The carbon trading price was set at 60 CNY/t based on the average carbon allowance trading price at City X's Emissions Trading Institution. The lower and upper bounds for the carbon tax rate were 10 CNY/t and 30 CNY/t, respectively, based on the recommendations from National Development and Reform Commission experts. The unit sales tax for cement was 50 CNY/t, and the total carbon emissions in the last planning period Cap were about 3.2×10^6 t CO_2. Information for producers, such as the emission allowances, production capacity bounds, the carbon emission coefficient, production and inventory unit cost, maximum storage capacity, and unit prices, are listed in Table 1. From Table 1, it is clear that the production costs were slightly higher for Producer B, but fewer emissions were generated due to the advanced, more efficient machinery and manufacturing technology. The cement demands for the three key projects are listed in Table 2.

Table 1. Basic information for the cement producers.

Parameters	Producer A	Producer B	Producer C
Lower bounds for carbon emissions (10^5 t)	6.3	5.4	6.2
Upper bounds for carbon emissions (10^5 t)	14.7	13.3	14.3
Lower bounds for production capacity (10^4 t)	140	138	135
Upper bounds for production capacity (10^4 t)	180	175	180
Carbon emission coefficient (kg CO_2/t)	630	608	622
Unit production costs (CNY/t)	52	46	54
Unit inventory costs (CNY/t)	24	27	26
Maximum storage capacity (10^4 t)	54	52	55
Unit price of cement for Project I (CNY/t)	290	305	296
Unit price of cement for Project II (CNY/t)	292	310	305
Unit price of cement for Project III (CNY/t)	280	300	286

Table 2. Project demands for cement.

	Project I	Project II	Project III
Cement (10^4 t)	$(135, \mathcal{N}(160, 25), 197)$	$(146, \mathcal{N}(172, 18), 196)$	$(126, \mathcal{N}(155, 20), 173)$

4.3. Results Analysis

By importing the collected data into the proposed optimization model (10) and running the iterative interactive algorithm on Matlab R2013a, the results for the proposed model were determined, as shown in Table 3. Satisfactory solutions were obtained for both the government and the producers, in which the social benefits for the government were estimated at $W = 3.08 \times 10^8$ CNY, and the profits for Producers A, B, and C were respectively $P_A = 2.56 \times 10^8$ CNY, $P_B = 3.17 \times 10^8$ CNY, and $P_C = 3.24 \times 10^8$ CNY. The total carbon emission allowance for the construction material industry for the government was 29.5×10^5 t CO_2, of which 9×10^5 t CO_2, 9.5×10^5 t CO_2, and 11×10^5 t CO_2 were allocated to Producers A, B, and C, respectively. The optimal carbon emissions for Producers A, B, and C were 9.26×10^5 t CO_2, 9.72×10^5 t CO_2, and 11.20×10^5 t CO_2, respectively, and extra carbon emission allowances were purchased from the government.

Table 3. Satisfactory solution.

Decision-Makers	γ (CNY/t)	α_i (10^5 t CO_2)	q_i (10^4 t)	q_{ij} (10^4 t)			Social Benefits (Profits) (10^8 CNY)
				I	II	III	
Government	20	-	-	-	-	-	3.08
Producer A	-	9	147	55	50	42	2.56
Producer B	-	9.5	160	55	55	50	3.17
Producer C	-	11	180	50	67	63	3.24

4.4. Carbon Tax Analysis

In this section, different values for the carbon tax were set to verify its influence on the overall and individual emissions and economic performances, in which the γ ranged from 10 to 30 CNY/t in intervals of 5 CNY/t. Figures 3 and 4 show the influence of the different values for the carbon tax on industry carbon emissions, social benefits, and profits for the government and Producers A, B and C.

In Figure 3, as the carbon tax increased, the total carbon emissions in the construction industry continued to decrease, and when $\gamma \geq 20$ CNY/t, the total emissions were less than the government's annual emission objectives (i.e., 29.5×10^5 t CO_2). This indicated that the a carbon tax policy could be a good carbon emission reduction method. From the producers' perspective, with an increase in the carbon tax, the carbon emissions of Producers A and C decreased; however, the carbon emissions of Producer B increased, indicating that Producer B was a lower carbon emission enterprise than the other two producers. When the government imposed stricter carbon tax regulation, consumers tended to purchase materials from Producer B to avoid the carbon tax being passed on. Therefore, Producer B was able to produce a greater number of materials than previously, thereby generating greater carbon emissions.

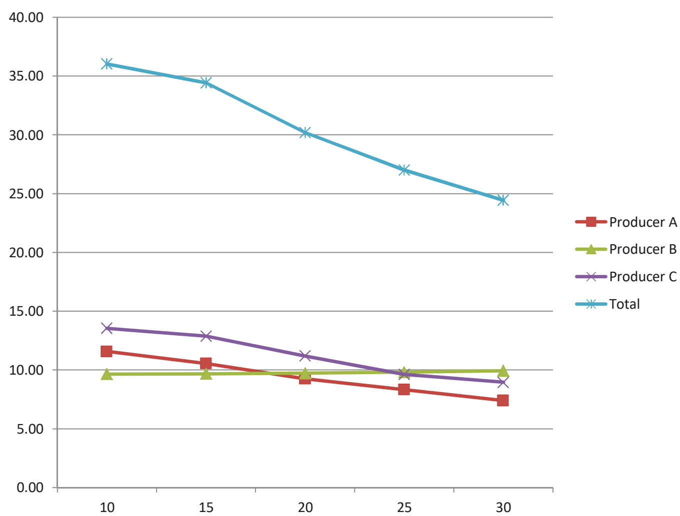


Figure 3. Influence of different carbon tax values on total carbon emissions (unit: 10^5 t CO_2).

In Figure 4, as the carbon tax grew, the government's social benefits and Producer B's profits increased, and the growth rates of both when $\gamma \in [20, 30]$ were obviously larger than when $\gamma \in [10, 20]$. Because the increased carbon tax revenue raised social benefits, the promoted projects purchased more materials from Producer B. However, under the pressure of a higher carbon tax, Producers A and C had to reduce their production output, leading to a decrease in profits. From the producers' perspective, when faced with different carbon tax changes, enterprises with lower carbon emissions would be more favored by the government and the market, and enterprises with higher carbon emissions would need to improve machinery and invest in cleaner manufacturing technology. From the industry perspective, total profits were relatively unchanged, which indicated that the carbon tax policy had little negative impact on the economic development of the construction material industry.

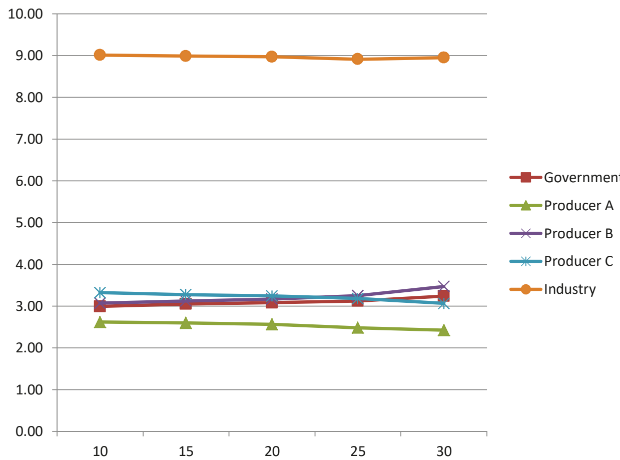


Figure 4. Influence of different carbon tax values on social benefits and profits (unit: 10^8 CNY).

4.5. Comparative Analysis in Different Decision-Making Environments

The computational results were acquired by employing some fuzzy random variables (FRVs) under a fuzzy random environment; however, the results may alter in different decision-making environments. To measure the robustness of the methodology when some parameters from model (10) had some perturbations, a sensitivity analysis was conducted to demonstrate the effect on the solutions under different decision-making environments. First, model (10) under a fuzzy random environment was compared to a model under a certain environment, in which the mean values for the FRVs were kept to eliminate uncertainty in the determined environment. For example, for the demands for Project I (i.e., $\tilde{\bar{D}}_I = (135, \mathcal{N}(160, 25), 197))$, the adopted value was 166, which was the mean value from 135 and 197. The computational results are shown in Table 4. Second, model (10) under a fuzzy random environment was also compared to a model in a fuzzy environment, in which in the fuzzy environment the fuzziness in the FRVs was retained, but the stochastic nature was neglected. To obtain useful data, Gaussian distributions were removed and the expectations were reserved. For instance, the demands of Project I in the fuzzy environment were denoted as $(135, 160, 197)$. The expected method was also used to convert the objective functions into equivalent crisp functions. The comparative results are also shown in Table 4.

The results in Table 4 indicated that the solutions in the determined environment had greater deviations than those in the fuzzy random environment, indicating that model (10) under a fuzzy random environment was able to provide more reliable references for the decision-makers. It was also found that the results under the fuzzy random environment were also better than in a fuzzy environment. Therefore, the proposed methodology was found to be robust in solving a carbon emission reduction problem for the construction material industry for the government, and the use of the fuzzy random environment was better able to match actual circumstances based on the post hoc analysis.

Table 4. Results comparison for the government in model (10) under different environments.

Objective	Unit: 10^8 CNY	Fuzzy Random Environment	Certain Environment	Fuzzy Environment
W	Best	3.34	3.38	3.32
	Average	2.95	2.86	2.94
	Worst	2.65	2.45	2.52

5. Conclusions

Carbon emission reduction is important to the sustainable development of the construction material industry. Most construction material activities, such as material producer selection, material production plans, dynamic inventories, and assignment problems, are interrelated, which means that contradictions between the government and construction material enterprises are unavoidable. Previous research has demonstrated that to achieve sustainable development in the construction material industry, these contradictions need to be reduced or fully resolved [2,4,36,42].

However, research on carbon emission reduction problems in the construction material supply chain has been restricted to a simple overall GSC system, or only a single carbon emission policy was assumed. Therefore, there were several difficulties that remained unresolved. Firstly, the hierarchical decision-making relationships between the government and the producers were not considered; however, as there are multiple stakeholders within this structure, contradictions must be considered. Secondly, linearization assumptions and simplifications were often employed to ensure model tractability, which led to loss of generality in the mathematical models. Thirdly, uncertainty and complications in the decision-making environment were not considered when dealing with the collected data.

To overcome these difficulties, this paper proposed an integrated methodology for carbon emission reduction problems under an integrated carbon reduction policy. The integrated methodology combined a bi-level mathematical model and an iterative interactive algorithm. The bi-level mathematical model was formulated to handle the leader–followers contradictions and competition between the stakeholders, and FRVs were used to reflect the inherent uncertainties in the problem, all of which made the bi-level mathematical model more complex but better related to the practical environment. An iterative interactive algorithm was designed to solve the non-linear bi-level mathematical model. Then, the proposed methodology was applied to a real-world case, the results from which clearly showed that satisfactory solutions for both the government and the producers could be obtained, and a suitable trade-off reached between economic development and environmental protection. Solution analysis, study of the impact of carbon tax, and comparative analysis in different decision-making environments were conducted to illustrate the applicability and robustness of the proposed methodology.

Acknowledgments: This research was supported by Social Science Research Project in Sichuan Province (Grant No. 17GL070), The Research Center for Systems Science & Enterprise Development, Key Research of Social Sciences Baseof Sichuan Province (Grant No. Xq17C03) and National Natural Science Foundation of China (71702118).

Author Contributions: Liming Zhang and Wei Yang conceived the idea and designed the structure of this paper; Liming Zhang and Wei Yang collected related study literature; Yuan Yuan and Rui Zhou contributed data; Liming Zhang analyzed the data; Wei Yang wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FRV	fuzzy random variable
GDP	gross domestic product
GSC	green supply chain
SC	supply chain

References

1. Wang, C.; Wang, W.; Huang, R. Supply chain enterprise operations and government carbon tax decisions considering carbon emissions. *J. Clean. Prod.* **2017**, *152*, 271–280.
2. Chau, C.K.; Hui, W.K.; Ng, W.Y.; Powell, G. Assessment of CO_2 emissions reduction in high-rise concrete office buildings using different material use options. *Resour. Conserv. Recycl.* **2012**, *61*, 22–34.

3. Atmaca, A.; Atmaca, N. Life cycle energy and carbon dioxide emissions assessment of two residential buildings in Gaziantep, Turkey. *Energy Build.* **2015**, *102*, 417–431.
4. Herrera, J.C.; Chamorro, C.R.; Martín, M.C. Experimental analysis of performance, greenhouse gas emissions and economic parameters for two cooling systems in a public administration building. *Energy Build.* **2015**, *108*, 145–155.
5. Shi, Q.; Chen, J.; Shen, L. Driving factors of the changes in the carbon emissions in the Chinese construction industry. *J. Clean. Prod.* **2017**, *166*, 615–627.
6. Zhang, X.; Wang, F. Life-cycle assessment and control measures for carbon emissions of typical buildings in China. *Build. Environ.* **2015**, *86*, 89–97.
7. Zhang, Z.; Wang, B. Research on the life-cycle CO_2 emission of China's construction sector. *Energy Build.* **2015**, *112*, 244–255.
8. Jiang, Z.; Lin, B. China's energy demand and its characteristics in the industrialization and urbanization process. *Energy Policy* **2012**, *49*, 608–615.
9. Dhakal, S. Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy* **2009**, *37*, 4208–4219.
10. Seuring, S.; Müller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710.
11. Porter, M.E.; Van der Linde, C. Green and Competitive: Ending the Stalemate. *Harv. Bus. Rev.* **1995**, *28*, 128–129.
12. Hollos, D.; Blome, C.; Foerstl, K. Does sustainable supplier co-operation affect performance? Examining implications for the triple bottom line. *Int. J. Prod. Res.* **2012**, *50*, 2968–2986.
13. Reid, E.M.; Toffel, M.W. Responding to public and private politics: corporate disclosure of climate change strategies. *Strat. Manag. J.* **2009**, *30*, 1157–1178.
14. Bansal, P.; Clelland, I. Talking Trash: Legitimacy, Impression Management, and Unsystematic Risk in the Context of the Natural Environment. *Acad. Manag. J.* **2004**, *47*, 93–103.
15. Hajmohammad, S.; Vachon, S. Mitigation, Avoidance, or Acceptance? Managing Supplier Sustainability Risk. *J. Supply Chain Manag.* **2016**, *52*, 48–65.
16. Miccoli, S.; Finucci, F.; Murro, R. A monetary measure of inclusive goods: The concept of deliberative appraisal in the context of urban agriculture. *Sustainability* **2014**, *6*, 9007–9026.
17. Miccoli, S.; Finucci, F.; Murro, R. Assessing Project Quality: A Multidimensional Approach. *Adv. Mater. Res.* **2014**, *1030*, 2519–2522.
18. Miccoli, S.; Finucci, F.; Murro, R. Criteria and Procedures for Regional Environmental Regeneration: A European Strategic Project. *Appl. Mech. Mater.* **2014**, *675*, 401–405.
19. Moretti, L.; Caro, S. Critical analysis of the Life Cycle Assessment of the Italian cement industry. *J. Clean. Prod.* **2017**, *152*, 198–210.
20. Sorrell, S.; Sijm, J. Carbon trading in the policy mix. *Oxf. Rev. Econ. Policy* **2003**, *19*, 420–437.
21. Weisbach, D.A.; Metcalf, G.E. The Design of a Carbon Tax. *Soc. Sci. Res. Netw. Electron. J.* **2009**, *33*, 499–556.
22. Carbon Emission Trading, 2017. Available online: https://en.wikipedia.org/wiki/Carbon_emission_trading (accessed on 11 November 2017).
23. Perdan, S.; Azapagic, A. Carbon trading: Current schemes and future developments. *Energy Policy* **2011**, *39*, 6040–6054.
24. Intergovernmental Panel on Climate Change. *Climate Change 2007 Synthesis Report*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2007.
25. Klemmensen, B.; Pedersen, S.; Rydén, L.; Dirckinck-Holmfeld, K.R.; Marklund, A. *Environmental Policy: Legal and Economic Instruments*; Baltic University Press: Uppsala, Swdden, 2007.
26. Baranzini, A.; Goldemberg, J.; Speck, S. A future for carbon taxes. *Ecol. Econ.* **2000**, *32*, 395–412.
27. Fang, G.; Tian, L.; Fu, M.; Sun, M. The impacts of carbon tax on energy intensity and economic growth—A dynamic evolution analysis on the case of China. *Appl. Energy* **2013**, *110*, 17–28.
28. Ghosh, D.; Shah, J. A comparative analysis of greening policies across supply chain structures. *Int. J. Prod. Econ.* **2012**, *135*, 568–583.
29. Song, J.; Leng, M. *Analysis of the Single-Period Problem under Carbon Emissions Policies*; Springer: New York, NY, USA, 2012; pp. 297–313.
30. Choi, T.M. Carbon footprint tax on fashion supply chain systems. *Int. J. Adv. Manuf. Technol.* **2013**, *68*, 835–847.

31. Du, S.; Zhu, L.; Liang, L.; Ma, F. Emission-dependent supply chain and environment-policy-making in the 'cap-and-trade' system. *Energy Policy* **2013**, *57*, 61–67.
32. Jaber, M.Y.; Glock, C.H.; Saadany, A.M.A.E. Supply chain coordination with emissions reduction incentives. *Int. J. Prod. Res.* **2013**, *51*, 69–82.
33. Von Stackelberg, H. *The Theory of the Market Economy*; Oxford University Press: Oxford, UK, 1952.
34. Gibbons, R. *Game Theory for Applied Economists*; Princeton University Press: Princeton, NJ, USA, 1992.
35. Xu, J.; Zhao, S. Noncooperative Game-Based Equilibrium Strategy to Address the Conflict between a Construction Company and Selected Suppliers. *J. Constr. Eng. Manag.* **2017**, *143*, 04017051.
36. Xu, J.; Yang, X.; Tao, Z. A tripartite equilibrium for carbon emission allowance allocation in the power-supply industry. *Energy Policy* **2015**, *82*, 62–80.
37. Nash, J. Non-cooperative games. *Ann. Math.* **1951**, *54*, 286–295.
38. Ben-Ayed, O.; Boyce, D.E.; Iii, C.E.B. A general bilevel linear programming formulation of the network design problem. *Transp. Res. Part B* **1988**, *22*, 311–318.
39. Bard, J.F. *Practical Bilevel Optimization*; Springer: New York, NY, USA, 1998; pp. 144–146.
40. Colson, B.; Marcotte, P.; Savard, G. An overview of bilevel optimization. *Ann. Oper. Res.* **2007**, *153*, 235–256.
41. Lin, B.; Ouyang, X. Energy demand in China: Comparison of characteristics between the US and China in rapid urbanization stage. *Energy Convers. Manag.* **2014**, *79*, 128–139.
42. Hong, J.; Shen, G.Q.; Feng, Y.; Lau, S.T.; Mao, C. Greenhouse gas emissions during the construction phase of a building: A case study in China. *J. Clean. Prod.* **2015**, *103*, 249–259.

sustainability

MDPI

Concept Paper

Environmental Activation of Inner Space Components in Sustainable Interior Design

Magdalena Celadyn

Academy of Fine Arts in Krakow, Faculty of Interior Design, pl. Matejki 13, 31-157 Krakow, Poland; mceladyn@asp.krakow.pl; Tel.: +48-667-899-959

Received: 21 May 2018; Accepted: 7 June 2018; Published: 11 June 2018

Abstract: Implementation of environmental responsibility issues into the interior design methodology considers many aspects of the design process, but analyzes them separately. These include building materials' and products' specifications based on the assessment of their parameters impact on the users of indoor environments, or resource management within an ecological efficiency context. This concept paper concentrates on the analysis of an environmental activation of inner space components, identified by the author as the holistic and systemic design model, which is to empower the foundation of a contemporary sustainable interior design model. The proposed design scheme is supposed to assure the environmental effectiveness of interiors and their structure, as well as complementing functional components. The contributions of interiors completed in accordance with this concept can refer to the enhancement of the performance of building mechanical systems and the improvement in the indoor environment quality parameters. They can be achieved with the appropriate environmental activation-oriented structural, technical, and material solutions, applied to the selected inner space components. The theoretical scheme presented should become the basis for further investigations and studies to establish the comprehensive methodology design framework assuring the integrative role of interior design in the creation of a sustainable near environment.

Keywords: environmentally responsible interior design; sustainable interior design; environmental activation of interior elements; indoor environment quality

1. Introduction

The environmental responsibility of the interior design profession has been explored by researchers, architecture critics, and academics since the 1990s [1–3]. The increasing recognition of environmentally-sustainable design [1,4–6] has imposed on designers the necessity for a comprehensive and informed approach toward the interior design process. The notion of environmental responsibility in interior design can be interpreted as comprising the issues of: (1) an object's ecological effectiveness, with regard to the minimization of its negative impact on the natural environment; (2) the economic consequences and implications of the building spaces' energy performance; and (3) complementing social system's considerations related to the inner space quality parameters and their influence on the occupants' psychological and physical comfort. The constant interconnectedness and interdependence of these three systems is a major factor affecting the stability of the human ecosystem model and should be the subject of continuous investigation of environmentally-responsible interior designers [1] when searching for the optimization of the functionality and quality of inner spaces [4].

Although the term 'green design' is interchangeably used with ecological, environmentally-responsible, or sustainable design [3,7], it applies to the micro-scale of the interior [1]. The interior is defined as part of the built environment being in direct mediation with the space occupants and constituting the nearest area for their activities. It directly influences their health and well-being, and stimulates their behavioral patterns [8], as created in accordance with the sustainability paradigm. The interior designers accomplishing this model are to respect the environmental implications, considering the multiple life cycle consequences of completed objects and, therefore, addressing global environmental problems [4]. The position of interior designers in the process of creation of the so-defined environmentally-oriented built environment is still not precisely and comprehensively determined [1] and appreciated. The possible range of their interventions into the indoor environment design is mainly based on the appropriate specifications of introduced building materials, products, equipment, and appliances. These are made with the introduction of the comparative and whole-life-material-cycle environmental preference method (EPM) [9], consideration of the embodied energy (EE) measures, inclusion of the life cycle assessment (LCA) method associating the energy and material flows with potential environmental impacts [10], and the multi-criteria environmental evaluation schemes into the interior design process. All are necessary for finding informed and knowledgeable interior design solutions.

All these issues reflect the environmentally-oriented consciousness of designers, although they are methodically verified under reliable research-based assessment schemes and, when being considered separately as subsequent sustainable goals to be achieved, lack a cohesive vision designed to establish and endorse their environment-oriented effectiveness.

The main objective of the presented study is to define the role and technical, as well as formal, opportunities for the specific interior components' environmental activation, which would enable the identification of sustainable goals for interiors and the successful achievement of sustainability requirements in architectural and interior design. The intention of the article is to propose an integrated interior design framework, enabling the development of a perspective demonstrating the range of the impact of interior design on the built environment performance, and the development of the holistic approach to interior design, as postulated for the built environments' design [11,12].

The author discusses the possible implications of the recommended comprehensive model on the improvement in the closed spaces' quality parameters through the coordinated design process. Subsequent sections identify the term of the interior design's environmental contextualization with regard to the accomplishment of the sustainability paradigm. They also provide an overview of possible effects obtained in the case of properly-conceived interior components which are oriented towards the ecological effectiveness in the creation of the sustainable built environment. The analysis of the effects of environmentally conscious interior design, presented in this article, is restricted to its substantial features which are the question of the means of improvement in the indoor environment quality parameters, achieved through the cohesive and evidence-based design of the interior [13], with emphasis on the role of interior components in the optimization of sustainability goals.

2. A Model for Environmental Contextualization of Interior Components

Design strategies that are supposed to be applied to the environmentally-conscious interior design involve meeting the demand for the sustainable use of environment and resources. This postulate combines demands for the reduction in material resources and the enhancement of the indoor environment quality, achieved due to the research findings derived from peer-reviewed journals or conducted observations and surveys, which constitute a basis for design solutions concerning the built environment [3].

The achievement of sustainable goals in interior design requires the redefinition of its position, and the provision of the contribution of interior design to shaping the quality of built environments. This has to be augmented by the advanced environmental contextualization [14,15] consequently imposed on the interior and its components' creation (Figure 1).

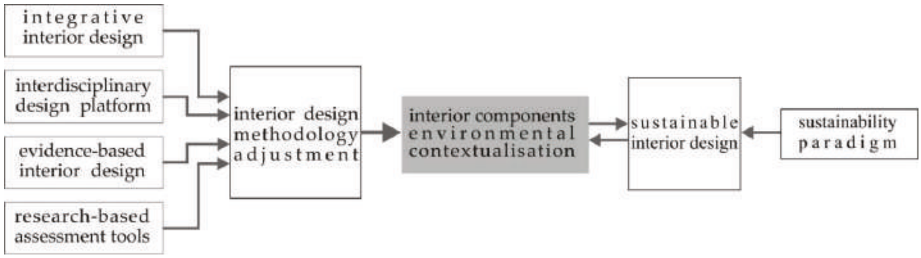


Figure 1. Interior components' multifaceted environmental contextualization as a function of the interior design methodology adjustment. Source: author's drawing.

The environmental context in the creation of internal spaces, by adding to this process a multidimensional perspective within which they can be analyzed and explored, requires the introduction of several adjustments concerning the conventionally-applied architecture design methodology. These corrections should be oriented on holistic thinking and interdisciplinary communication [1] marked with the inclusion of different specialists into the decision-making process; among them are interior designers, working as partners and co-learners [16] on the basis of integrative design teams. Intensive workshop sessions, as the interdisciplinary communication platform for professionals involved into the design process, enable the verification of proposals based on evidence provided by the participants in search of the optimization of buildings' performance. These eco-charrettes, focused on the design sustainability-compliance [6], allow the interior designers engaged in the multi-disciplinary integrated design process, to identify the area of their possible intervention in search for the healthy built environment and to contribute their knowledge to informing the design.

Applying research-based design tools, as the instruments assuring systemic and comprehensive pondering of the interior design postulates as detailed in the whole building certification system guidelines, may enable the interior designers to identify the sustainability goals to be achieved in their projects. Multi-criteria evaluation schemes based on the parametric assessment dedicated to the whole building, or its inner spaces' energy saving-, pro-ecological- and social-oriented solutions evaluation (e.g., Leadership in Energy and Environment Design Green Building Rating System for Interior Design and Construction LEED ID + C certification scheme established by the USGBC in 2004), have become a contemporary professional architectural design tool for defining and measuring the sustainability of green buildings [17]. It assists in the prevention of greenwashing effect [1]. The interior certification systems are considered by many researchers and practitioners as formal assessment schemes ensuring the rigorous approach leading to the achievement of sustainability features [4,6]. They are also the reliable and systemic verification tools for the compliance with the sustainability demands of indoor environment and are designed to define the quantitative and qualitative criteria for the main indoor environment evaluation categories (e.g., WELL Building Standard, a certification system conceived in 2014 and administrated by the International WELL Building Institute). They seem to be specifically recommended for interior design practitioners, enabling them a systematic approach to fundamental sustainability demands.

3. A Model for Environmental Activation of Interior Components

The effectiveness of environmental contextualization claimed by the author assigned to the designed inner space as an entity, and to its structural and complemented elements, relies on the simultaneous and equivalent consideration of several involved interior areas with regard to their impact on economic, ecological, and social systems. These design features, in terms of their role in the space structure, include the interior layout respecting the building orientation and climatic requirements, building materials specification based on the environmental preference methods, and the inner space multifunctional forming and supplementing components with emphasis on their technical and formal solutions. The interior components' design concept should be oriented toward their shaping considering an active response to the question of constant interaction of natural and man-made systems, with the provisions of its consequences as to the inner space quality endorsement and the building's performance.

Two aspects seem to mostly determine the components' environmentally-oriented features, and the effectiveness of the idea of environmental contextualization, as major sustainable interior design imperatives. These are the multi-functionality of interior components combined with the adaptability of inner spaces to accommodate different activities, along with the resources management framework. They might facilitate the fulfillment of environmental postulates in practice.

Elements of inner space, as indicated by researchers and academics for decades now, should not be created by designers in a traditional way, including functional, formal, and aesthetic contexts, but should be conceived by interior designers in a more complex [8] and environmentally-oriented context. This process of the creation of interior components should rely on their consideration as those conventionally formed with the sustainability features [3] (p. 267).

The typologies of components constituting the inner space, as proposed by critics and researchers [5,18,19], usually identify the groups according to their basic and auxiliary functions to be fulfilled. The structural forming of indoor components, as proposed in the author's classification [5], comprise: external walls determined as enclosures separating the inner space from the natural environment actively responding to the changing climate conditions and usually accompanied by various technical devices or natural finishing on the inner side; partitions and inner space dividers of various dimensions and finishes; raised floors; and suspended ceilings. Supplementing or completing interior components include: furniture, furnishings, equipment, and fixtures assigned to a separate category [5], enabling the proper usage of spaces in accordance with the exigencies.

The methods of structural forming of internal elements' and their integration with the building components, should be the consequence of designers' considerations of the interconnectedness of both natural and man-made environments, as well as predictions of possible consequences of their mutual interrelationship. As there are both direct and indirect relations between interiors and the environment [8] (p. 49), they should be specified, analyzed with scientific means, and reflected in the adjusted integrated interior design methodology.

The interior components' design strategy should identify the measures undertaken that respond to the users' needs, and positively affect their health and comfort, as well as minimize the objects' environmental load through the reduction in energy consumption by building systems. The strategies enabling the fulfillment of these, should combine the rational management of material resources, functional efficiency and formal diversity of components, their active inclusion into the overall integrated and indoor environment high-quality as supplementary means, and energy concepts.

Environmental Activation of Components

The presented model of multi-functionality of inner space components to be explored in the sustainable interior design framework, can be developed in order to identify its leading role in the consequent and comprehensive multi-faceted environmental activation of interior components. This design concept for complex components activation can be regarded as a valuable interior designers' contribution to the comprehensive accomplishment of sustainability imperatives.

A successful implementation of this model based on the comprehensive and environmentally-conscious interior design, and complying with the sustainability paradigm, requires designers to take into account the results of scientific studies in the field of technical disciplines including building physics, and climate engineering. The model can enable the integration of closed spaces in the built and natural environments obtained through: (1) endorsement of building systems as a substantial factor in the optimization of building's performance and related savings in energy consumption; (2) resource conservation as the result of rational management of building materials and products;

and (3) improvement in indoor environment quality parameters (Figure 2). The latter aspect of the suggested design model, discussed in further sections, concentrates on the presentation of the components' creation methods that are introduced into interior design as passive modes may influence and positively stimulate the interior's quality parameters.

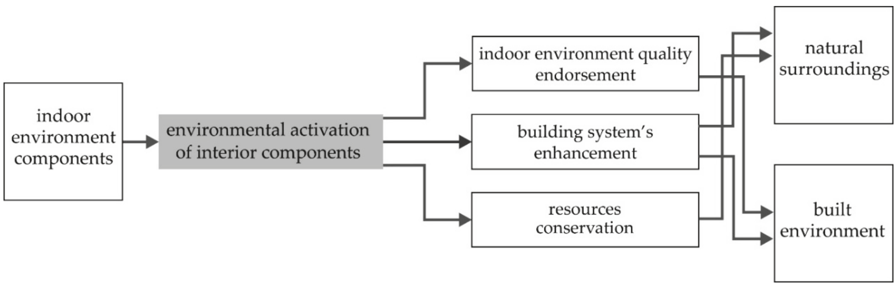


Figure 2. Design concept for environmental activation of interior components Source: author's drawing.

The improvement in lowering of the environmental impact of buildings on natural surroundings and inner spaces depends on the application of adequate technological and technical measures, as well as on the introduction of supportive passive methods. The latter may become a valuable contribution to the transition of interior design toward the accomplishment of sustainability paradigm, where the ecological, economic, and societal areas of human activities, are to remain in balance. The indicated requirements, being essential for the execution of sustainability issues in architectural design, can be met through the complex activation of inner space elements focused on the environmental responsibility.

Proposals for the definition of environmental activation of interior elements [14,15] are formulated as specific means of stimulation of these components to their action, performed and based on their' comprehensive and multi-criteria evaluation. This design method should play a substantial role in the interior decision-making process, for its multidimensional perspectives, identifying the functional, spatial, and temporal contexts. The main purpose of the environmental activation of interior elements, proposed in this paper, is to reduce the dependency of indoor environment quality on mechanical building systems, as well as to enhance the systems' performance. The recommended components' activation can be achieved by the properly analyzed setting of interior elements in inner spaces according to the users' individual requirements and organizational demands, by the elements' formal and structural forming, as well as their purposeful functional and formal integration with the main building structural components or building services.

The main objectives, which may be assigned to the activation concept, remain in accordance with a triple bottom line, which addresses the designers' responsibility in meeting the demands for the sustainability of economic, ecologic, and societal aspects of architectural design. These aims include the envisaged structurally, formally, and functionally combined solutions that should be considered as supportive building systems supplementing the passive means enabling:

- Enhancement of heating, ventilation, air conditioning (HVAC), and building lighting systems' effectiveness, assuring the increase in building performance and the decrease in energy and water consumption, as well as the reduction in operational costs;
- Reduction in the emission of toxic substances released in the production of building materials, and in the course of maintenance and conservation of buildings; and
- Optimization of the indoor environment quality (IEQ) parameters, related to the inner air characteristics, daylighting control, and acoustic conditions, in relation to the occupants' health and well-being.

The analysis of the selected parameters, presented in the following sections, indicates the possibilities of innovative spatial and technical methods to positively stimulate their optimization. The daylight transmission and its redistribution in interiors' regulation of solar thermal energy gains preventing the spaces from overheating, combine the demand for reduction in material resources with the enhancement of indoor environment quality through the applied structural solutions.

4. Components' Activation for the Optimization of Indoor Environment Quality

The complexity of indoor environment quality issues warrants the integrated approach to the design of buildings [20] (p. 430), which are functional-spatial-formal entities. This relates also to their inner spaces and, specifically, to these conceived in the course of refurbishments or adaptation of existing objects. The closer analysis of this problem being substantial for the interior evaluation proves, that there are many considerations within the Indoor Environment Quality category for the work of an interior designer [3] (p. 261) which should be identified while carrying out an environmentally-responsible design. Interior designers, along with other professionals involved in the design process, may contribute to the expected properties of the main components of integrated Indoor Environment Quality design [21]. These features combine the inner air quality with thermal, lighting, daylighting, and acoustic parameters, providing users with the health environment [22] having an impact on the occupants' health, physical and psychological comfort, well-being and productivity [1].

These objectives can be realized by interior designers with the applied different measures based on the determined sustainable goals, concerning the cautious selection of building materials, and the innovative and comprehensive approach to the formation of inner structural elements oriented toward their functional integration with the enhanced building components and systems (e.g., inner walls designed as thermal masses and means of reduction in the consumption of heating energy).

4.1. Indoor Air Quality

The indoor environmental and air quality is strictly health-related [23] (p. 242) and, thus, its significance should be recognized by interior designers while preparing the specifications of products and building materials to be introduced into an inner space, as the occupants' exposition to the pollutants contained in products or furnishings may cause several diseases (e.g., cardiovascular and respiratory diseases, multiple chemical sensitivity (MCS)). The selection procedures should be based on the credible information provided by independent institutions in the result of research-based measurement and certification processes concerning the occupants' health-affecting attributes. This would enable the provision of designers with the knowledge on building biology [10], which reveals the interrelationship between humans and their living environment.

The designers' ability to assessing impacts (. . .) leads to managing the risks [23] (p. 247) and, thus, to verifying of the consequences of their presence and effects on interiors features. Prior to the final decisions regarding the selection of constituting component products, the designers should provide the verification of possible influences of their introduction on the users' health, well-being, and comfort. The carefully selected building construction materials, structural components' solutions, as well as finishes can improve the indoor air quality. This refers to the following concerns:

- Regulation of the amount of pollutants in closed spaces and supported air purification;
- Reduction in solar heat gains and the enhancement of the monitoring of inner temperature, achieved by the individual users' control on thermal conditions and the way of spaces usage (e.g., presence of inner solar protection equipment manually adjustable);
- Reduction in daily fluctuations of inner air temperature by the free cooling effect (e.g., introduction of unfinished solid inner walls as passive thermal stores for the heating or cooling purposes and being exposed to solar heat [4,24], suspended ceilings, inner side finishes of external walls or space forming components, and partitions filled with integrated phase change materials PCM);

- Regulation of the radiant temperature and the usage of solid internal walls' thermal capacities with different finishes (e.g., porous surfaces of selected materials easy in maintenance, and increasing the heat absorption; removable wall finishing devices or hangings responding to seasonal climate changes and enabling the solid external walls to act as thermal masses in winter; and dark finishes of components situated in close proximity to glazed envelopes as thermal store and light finishes reflecting the heat [22]);
- Control of the relative humidity level of inner air (e.g., the supply of an adequate amount of water for growing plants and impeding the formation of mold in poorly-ventilated areas, 'bioclimatic' openwork inner walls made with materials of high permeability, components, or wall covering made with wood fiber panes).

These exemplary passive design methods should be recommended as environmentally-respons ible complementing means of maintaining the high-quality indoor air with the related reduction in the number of technologically-advanced and energy-consuming heating, ventilating, and air conditioning systems. Living walls, recommended for their air purifying- and conditioning potential, and vastly implemented in interiors, can become the essential passive means of maintaining good air quality, through the stabilization of the ambient temperature and indoor humidity level. The consequent installation of space dividers in the form of active green walls can contribute to the decrease in inner temperature, and play a complex role of airborne chemical filters, carbon dioxide absorbers, and the source of oxygen released during the daytime into the inner space. The indoor air quality can be further enhanced by the inclusion of living moss walls playing the role of internal buffers and helping in the removal of concentrated volatile organic compounds (VOC) and other chemical pollutants from the air and, thus, allowing the reduction in demanded ventilation rates. Plants broadly introduced into closed spaces assure for the users a connection to nature and affect their well-being, responding to the demand for the inclusion of the biophilic concept into the interior design model.

The 'bioclimatic' openwork inner walls and space dividers, made with gypsum, light concrete or ceramic tiles, may be seen as another valuable solution, which contributes to the thermal microclimate conditions and inner air relative humidity. These climate-stimulating structures in modernized and adapted buildings can be completed with building materials recovered and reused in new spatial contexts. Due to their abilities to exert a positive impact on the indoor environmental quality, they are examples of innovative techniques allowing the accomplishment of sustainability principles in interior design, through the concept respecting equally valuable design strategies.

4.2. Daylighting

The lighting scheme developed for interiors should include a vast amount of daylighting, since the use of natural light within the building and its interior is not only fundamental for the reduction in energy demand [5] but also for the minimization of the negative influence of seasonal affective disorder (SAD) which is a result of deficiency of daylight. Its abundance usually positively affects occupants' health and well-being with respect to the circadian stimulation and its positive influence on physical activity and perceptual effectiveness [25].

Apart from the technical devices assuring the users' individual control of the intensity of light at workplaces, the daylight-level and occupancy sensors or dimming devices keeping the electric energy demands on a reasonable level, there are many other possible solutions. The effective use of daylight can be a valuable contribution of interior designers frequently enhanced by consultations with lighting engineers. They may advance the occupants' well-being, ensuring their increased productivity and satisfaction.

These are supposed to ensure good daylighting levels on the floorplates and to provide a good amount of daylight in accordance with the enforced regulations, codes and standards. They have to be appropriate for space purposes, their functional requirements, and should enable the achievement of a high-quality visual environment. The main positive effects of designers' intervention into the methods of components' introduction with regard to the optimization of daylighting combine:

- Minimization of the negative glare effect by the introduction of some functional components (e.g., manually controlled internal solar control blinds, louvers, supplementing devices eventually mounted externally, screens modulating the brightness of glazed surfaces, other components in the proximity of openings with highly reflective finishes);
- Minimization of the solar thermal heat gain (e.g., blinds, manually-controlled curtains);
- Ambient daylighting in fully-glazed spaces obtained with the structures suspended from the glazed roof support, translucent perforated fabrics [6], or framing structures made with lightweight bright finished materials mounted to the glazed envelope;
- Maximization of the quantity of incoming daylight by its reflection (e.g., window reveals finished with light-colored surfaces or reflective materials, like safety glass or metal sheets, reflective surfaces of internal components adjacent to openings [3], and enclosures separating spaces situated in a distance from glazed walls with their upper parts made with transparent or translucent panels);
- Reduction in the distracting contrast on the surfaces of working area caused by direct sunlight (e.g., fabrics mounted to the ceiling next to windows [6];
- Penetration of distracting daylight (e.g., introduction of clerestory windows with the complementing reflective finishing materials of sloped ceilings to optimize their performance [1,3]);
- Redirection and transmission of daylight, as well as an increase in the illuminance of daylighting in the overall lighting supply (e.g., technical devices like reflective optical light tubes providing under-lit spaces with the demanded daylighting quantity, translucent inner light shelves integrated with the structure of the building's south side glazed envelope [1,8,24], or adjustable reflective panels suspended under the ceiling and anidolic integrated ceilings (AIC) [24,26]); and
- Diffusion of daylight (e.g., wall cladding with reflective materials supplementing the semi-translucent diffusing panes suspended from the glazed roofs to obtain an effective daylight distribution [27]).

The methods commonly introduced into inner spaces which enable the control of the amount of daylight through the use of reflected light, combine the installation of blinds, curtains, louvers configured depending on the window orientation, or more technically-advanced means including opaque and translucent inner light shelves provided with reflective finishes of suspended ceilings. The additional structures like passive-daylight devices introduced by designers with respect to the existing interior layout, building orientation, and the volume of the glazing of envelopes (e.g., translucent polymer mobile optic diffusors suspended from the skylight and integrated with passive solar optic systems PSO), may effectively participate in the redirection of the daylight and its transmission into the parts situated at a distance from the glazed external walls [28]. Other implemented components made with glass fiber reinforced gypsum and painted white may enable the control of the amount of incoming daylight and the reduction of the light contrast, or a negative glare effect inside. The above-mentioned possible effects of the installation of internal components as passive-daylight means, define the range of the interior designers' formal contribution to the daylighting quality through the supportive, innovative and complex design approach, as well as by the environmental implications of assigned components' activation. The daylighting concept, for its effectiveness, should be conceived in accordance with the site conditions and activity-related illuminance requirements, measured and verified with computer simulations and integrated with the artificial lighting concept from the pre-design planning phase [3].

4.3. Acoustic Conditions

The rising demands among users for the controlled noise levels and the improvement in acoustical conditions of interiors, as well as the postulates of necessary acoustic privacy, are other interior design issues that have to be carefully considered by the environmentally-conscious designer. As the surveys conducted on the contribution of different factors to the distraction of workplaces confirm [6,29], noise remains the one most complained about. The acoustical comfort is one of the substantial features in the occupants' assessment of interior quality, influencing their health and wellbeing. On the other hand, the internal acoustic quality still neither has been recognized by designers as a primary issue in sustainable design [22], nor as a substantial assessment criterion of the indoor environment quality. Interior designers can carry out a balanced acoustical design of inner spaces and obtain a 'non-intrusive' speech privacy level [6,29], including the elimination of uncontrolled transmitting of distractive internal noises, absorbing sound or its masking. The efficiency of these and other applied solutions is assured by the improved space planning, through the selection of proper building materials and adequate formal and structural characteristics of internal components.

The design methods and techniques directed toward the improvement in acoustical comfort consist of:

- Reduction of the internal noise transmission (e.g., a functionally-resolved interior layout and spatial zoning, ceiling height enclosures complemented with transparent upper panes to enable light transmission, broad introduction of the sound proofing building materials constituting the layers of enclosures, ceiling finishes, or functional interior components); and
- Absorption of sound (e.g., acoustic absorber panels mounted directly to the ceiling, parallel to the glazed walls, and complemented with a finishing layer adjusted to the interior's spatial and formal concept [24]).

The accomplishment of good acoustic conditions, through the introduction of sound-absorbing building materials, may provide the interior design with substantial quality parameters, as well as to enhance the space unique formal and stylistic values. The sound-absorbing finishing layer of the composite partition wall made with demolished parts reclaimed from building bricks or ceramic tiles, and other reused materials, can separate intensively-used circulation areas from adjacent spaces. The exposed rough texture of the cut hollow bricks forming the inner wall layer, being a sound-dissipating and sound diffusing multi-faceted space divider, may be seen as an innovative means of control of the sound level, and the reduction in the reverberation time.

In addition, the building material of the finishing layer, massively incorporated as a sound absorber, participates in the process of modification of the level of inner air relative humidity, being one of the substantial considerations related to comfortable inner thermal conditions. Therefore, the choice of reclaimed building materials, made on the basis of an analysis of their physical and chemical parameters, enables the fulfillment of yet another sustainable design demand, regarding the optimization of indoor environment parameters and interior microclimate characteristics, as essential for the users' comfort. The introduction of building materials reclaimed on site and implemented into the objects' structure, as presented in the example of the possible installation of interior components, allows to achieve compliance with the requirement for the reduction in the amount of demolition wastes [16], as well as the effective waste resources' management.

5. Conclusions

This concept paper provides a proposal regarding the modification of interiors and their structure, as well as complementing the component design methodology enabling the compliance with the environmental sustainability paradigm. It demonstrates the multi-dimensional environmental approach in the creation of closed spaces as the basic concept for a sustainable interior design process.

The environmental activation of interior components, as the substantial element of the design method, results in multi-faceted benefits addressing the optimization of buildings and their indoor environment performance, reduction of their negative impact on the natural environment, and the establishing of real interconnectedness between manmade and natural environments.

The benefits of components' environmental activation, as an interior design imperative enabling the consideration of sustainability issues and the achievement of sustainable goals, in terms of the optimization of building materials and product consumption include:

- Efficient management of interior components related to their multi-functionality;
- Resource management optimization due to the components' adaptability and applied structural and technical solutions; and
- Reclaiming of dismantled or removed components and their parts from refurbished spaces and their implementation into new structures as a design imperative to be considered within the environmentally-responsible design process.

The social benefits of the applied design method oriented on active response of components to their environmental interaction combine:

- Broad inclusion of stakeholders, including professionals of different specialties, owners, and end-users into the decision-making process;
- Responsible usage of the indoor environment treated as a scenery for the accommodation of different human activities, as well as a complex building product requiring rationality in its use affecting its performance;
- Increase in the environmental consciousness of the interiors' occupants through the understanding of interior component roles in shaping the quality of the indoor environment and their impact on natural surroundings; and
- Establishing a developed knowledge-based identity of occupants with their inner spaces in the process of experienced results of the environments' interconnectedness.

The components' environmental activation, as presented in the analysis, affects the performance of spaces within the following aspects:

- Enhancement of the building's artificial light system achieved with the optimization of daylight management through the implementation of multi-functional inner devices integrated with building components;
- Enhancement of ventilation systems through the properly executed space layout and space dividers' configuration; and
- Endorsement of heating/cooling, as well as air conditioning systems, with the assignment of additional functions to the components.

The qualitative assessment of the above-mentioned positive results derived from the enclosure of environmental activation concept into the interior design methodology indicate that this innovative cohesive approach toward the indoor environment and its components' creation may significantly affect the position of interior design discipline in the integrative sustainable design process. The examples of a range of structural and formal interventions by interior designers undertaken toward the effective compliance with the sustainability requirements presented above, prove that the concept of interior components' environmental activation, preceded by their multi-functionality model and multi-faceted environmental contextualization, can become a fundamental design method for the planning of inner spaces and the forming of components. This may assure the achievement of sustainable goals in the creation of interiors. The assignment of the essential meaning to the interior components' environmental contextualization in the interior design process, may become crucial in a search for synergy in sustainable interior and architectural design, as well as mechanical systems' designs.

The increasing recognition of environmentally-sustainable interior design [1,12] encourages designers to modify their design methodology in order to comply with the sustainability paradigm. The systemic problem solving applied to interior design, enabling the transition from degenerative architectural design through the transitional phase of sustainable design, assures the achievement of coexistence of natural and man-made environments. This can lead to a model actively supporting the idea of regenerative [30] architectural and interior design.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Jones, L. *Environmentally Responsible Design: Green and Sustainable Design for Interior Designers*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2008; ISBN 978-0-471-76131-0.
2. Pilatowicz, G. Sustainability in Interior Design. *Sustainability* **2015**, *8*, 101–104. [CrossRef]
3. Winchip, S.M. *Sustainable Design for Interior Environments*, 2nd ed.; Fairchild Books: New York, NY, USA, 2011.
4. Moxon, S. *Sustainability in Interior Design*; Laurence King Publishing: London, UK, 2012.
5. Raymond, S.; Cunliffe, R. *Tomorrow's Office. Creating Effective and Human Interiors*; E & FN Spon: London, UK; Taylor & Francis Group: New York, NY, USA, 2000.
6. Bonda, P.; Sosnowchik, K. *Sustainable Commercial Interiors*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2014.
7. Hayles, C.S. Environmentally sustainable interior design: A snapshot of current supply of and demand for green, sustainable or Fair Trade products for interior design practice. *Int. J. Sustain. Built Environ.* **2015**, *4*, 100–108. [CrossRef]
8. Pilatowicz, G. *Eco-Interiors. A Guide to Environmentally Conscious Interior Design*; John Wiley & Sons, Inc.: New York, NY, USA, 1995; ISBN 0-471-04045-2.
9. Anink, D.; Boonstra, C.; Mak, J. *Handbook of Sustainable Building. An Environmental Preference Method for Selection of Materials for Use in Construction and Refurbishment*; James & James (Science Publishers) Ltd.: London, UK, 1998.
10. El Khouli, S.; John, V.; Zeumer, M. *Sustainable Construction Techniques. From Structural Design to Interior Fit-Out: Assessing and Improving the Environmental Impact of Buildings*; Institut fuer internationale Architektur—Dokumentation GmbH & Co. KG: München, Germany, 2015.
11. Vale, B.; Vale, R. *Green Architecture. Design for a Sustainable Future*; Thames and Hudson Ltd.: London, UK, 1996.
12. Kang, M.; Guerin, D.A. The State of Environmentally Sustainable Interior Design Practice. *Am. J. Environ. Sci.* **2009**, *5*, 179–186. [CrossRef]
13. Nussbaumer, L.L. *Evidence Based Design for Interior Designers*; Fairchild Books: New York, NY, USA, 2009.
14. Celadyn, M. The inner space elements in shaping indoor environment quality parameters. In *Integration of Art and Technique in Architecture and Urbanism*; Wydawnictwa Uczelniane Uniwersytetu Technologiczno-Przyrodniczego: Bydgoszcz, Poland, 2017; Volume 5, pp. 41–50; ISBN 978-83-65603-35-7.
15. Celadyn, M. Inner space elements in environmentally responsible interior design education. *World Trans. Eng. Technol. Educ.* **2016**, *14*, 495–499.
16. Reed, B. Integrated design. In *Sustainable Commercial Interiors*; Bonda, P., Sosnowchik, K., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2007; pp. 28–31.
17. Vallero, D.; Brasier, C. *Sustainable Design. The Science of Sustainability and Green Design*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2008.
18. Brand, S. *How Buildings Learn. What Happens After They Are Built*; Penguin Books: London, UK, 1994.
19. Duffy, F. *Design for Change. The Architecture of DEGW*; Birkhauser Verlag: Basel, Switzerland; Boston, MA, USA; Berlin, Germany, 1998.
20. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*, 4th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2016; ISBN 978-1-119-05517-4.
21. Schoof, J. Vintage design or conservation of resources? Re-use and recycling in architecture. *Detail Green* **2015**, *1*, 6–11.
22. Owen, L.J. *A Green Vitruvius. Principles and Practice of Sustainable Architectural Design*; James & James: London, UK, 1999.
23. Keeler, M.; Vaidya, P. *Fundamentals of Integrated Design for Sustainable Building*, 2nd ed.; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2016.
24. Szokolay, S.V. *Introduction to Architectural Science: The Basis of Sustainable Design*; Architectural Press: Oxford, UK, 2010.
25. Schlaffle, E. Aspects of Office Workplace Lighting. In *A Design Manual Office Buildings*; Hascher, R., Jeska, S., Klauck, B., Eds.; Birkhauser: Basel, Switzerland; Boston, MA, USA; Berlin, Germany, 2002.
26. Yeang, K. *Ecodesign. A Manual for Ecological Design*; John Wiley & Sons: London, UK, 2009.
27. Hegger, M.; Fuchs, M.; Stark, T.; Zeumer, M. *Energy Manual. Sustainable Architecture*; Birkhauser Verlag AG: Basel, Switzerland, 2008.

28. Celadyn, M. Daylighting in sustainable design of office interiors. *Arch. Civ. Eng. Environ.* **2016**, *9*, 1–8.
29. Aronoff, S.; Kaplan, A. *Total Workplace Performance. Rethinking the Office Environment*; WDL Publications: Ottawa, ON, Canada, 1995.
30. Reed, B. Regenerative Development and Design: Working with the Whole. In *Sustainable Construction: Green Building Design and Delivery*, 3rd ed.; Kibert, C.J., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2013; pp. 109–111; ISBN 978-0-470-90445-9.

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Sustainability Editorial Office
E-mail: sustainability@mdpi.com
www.mdpi.com/journal/sustainability

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34
Fax: +41 61 302 89 18

www.mdpi.com

ISBN 978-3-03928-187-9