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Spatiotemporal Model to Quantify Stocks of Metal Cladding Products for a Prospective Circular Economy

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Abstract: The traditional linear economy (LE) approach based on a "take-make-dispose" plan that has been used in building activities over a long period has a significant impact on the environment. In the LE approach, the used materials are usually sent to landfills rather than recycled, resulting in resource depletion and excessive carbon emissions. A circular economy (CE) is expected to solve these environmental problems by promoting material "closed-loop systems". This study was intended to quantify and analyse the global warming potential (GWP) values of specific metal roofing and cladding products to promote CE thinking. A spatiotemporal model integrated with the life cycle assessment (LCA) tool was used to quantify the GWP value of the steel products in the investigated buildings. The study analysed ten case buildings located in six different cities in New Zealand: Auckland, Wellington, Hamilton, Palmerston North, Tauranga, and Christchurch. The production stages (A1–A3), water processing (C3), disposal (C4), and recycle, reuse, and recovery stages (D) were the focus of the study in analysing the GWP values of the product's life cycle. The study found that the production stages became the most significant emitters (approximately 99.67%) of the investigated steel products' GWP values compared to other selected life cycle stages. However, when considering the recycling stages of the steel products, the GWP value was reduced up to 32%. Therefore, by implementing the recycling process, the amount of GWP can be reduced, consequently limiting the building activities' environmental impacts. In addition, the integration of spatial analysis and LCA was found to have potential use and benefit in future urban mining and the development of the CE approach in the construction industry.

Keywords: spatiotemporal model; life cycle assessment; global warming potential; circular economy; metal cladding and roofing products; New Zealand

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1. Introduction

The construction industry makes an essential contribution to the global economy. It acts as the backbone of most nations' economic development and influences other economic sectors [1]. With approximately USD 10 trillion spent annually on construction-related goods and services, the construction industry contributes 13% of the world's gross domestic product (GDP) [2]. In New Zealand, the construction sector accounted for 7% of the nation's total GDP and became the fourth largest employer in 2019 [3]. However, despite its vital role in the world and nation's economic development, the construction industry negatively impacts the environment by generating a massive amount of building waste and emitting carbon.

Building materials are responsible for nearly half of all materials used and roughly half of all solid waste produced globally [4]. Waste arises at every step of the construction process, and determining an exact number is difficult. Construction activities can generate a wide variety of waste products, such as rubbish, undesirable materials, and excavated materials (e.g., rock, soil, concrete, and waste asphalt) [5]. In the European Union, over 450 million tonnes of waste in the construction industry are generated each year, which becomes the largest waste flow aside from agricultural wastes and mining wastes [6]. In China, construction was responsible for a large portion of total waste (between 30% to 40%) but the average recovery value was only 5% [7]. It is also a problem in New Zealand, where construction is the main source of waste, accounting for up to 50% of all waste [8].

Furthermore, the construction industry generates a significant amount of carbon, which is the primary driver of climate change [9]. Carbon emissions are produced during a building's life cycle and can be classified into operational and embodied emissions [10]. In the global context, the construction industry is responsible for approximately 40% of primary energy use and 33% of total carbon emissions [11]. As one of the world's top carbon emitters (accounting for more than 25% of total global emissions), China's carbon emissions from the building industry continue to rise [12]. It is anticipated that by 2030, it will have increased to 35% of the total carbon emissions in China [13]. In 2019, the UK's building activities were responsible for about 23% of the nation's carbon emissions [14]. The emissions problem from building activities has also occurred in New Zealand. The carbon emissions from the construction industry in New Zealand have climbed by 66% in the past decade [15], and in 2020, it accounted for 20% of the nation's total emissions [10]. The high contribution from the construction industry consequently increased the country's carbon emissions, along with other industries, by 26.4% between 1990 and 2019 [16]. Therefore, many countries have set their carbon reduction targets based on the Paris Agreement Act 2015, including New Zealand [17], to limit their emissions in the future and tackle climate change.

The Circular Economy (CE) has been getting more and more attention recently in industrial development discussions and is seen as a way to address environmental issues and promote sustainable development [18]. It is a zero-waste system in which the products of today are also the raw materials of tomorrow [19]. Waste generation is reduced in a CE through careful product design and an industrial process wherein materials continually circulate in a "closed-loop system" [20]. This approach contrasts with the present linear economy (LE) paradigm, in which items are often manufactured and then disposed of as waste [21].

In the construction industry, the current LE model has resulted in approximately 25% of solid waste being produced and more than 30% of the world's natural resources being extracted [22]. The transition to the CE is expected to be a possible option for the industry in which production flows may be reintegrated as secondary resources [23], such as reusing and recycling building materials in order to prolong their life cycle. Therefore, the CE is considered an approach with the greatest potential to reduce carbon emissions and create value to help ameliorate the environmental contamination caused by the construction industry [24]. The main goal of CE in the construction industry is to preserve the value of buildings and their components while minimising as much construction and demolition waste (C&DW) as possible [25]. Accordingly, with the benefits of the adaptation of CE in the construction industry, governments and enterprises worldwide have put this approach on the agenda to deal with serious environmental problems. In addition, to improve the decision-making process towards sustainability, an economic analysis could be performed to analyse the options' performances based on their economic values, such as economic feasibility. Some methods can be used to undertake this analysis, such as the net present value, the future value, and the annual cost methods, which have been used in several previous studies [26–28].

Urban mining can be considered a formalisation of the CE approach, which has excellent potential for producing value [29]. In recent times, more people are showing an interest in urban mining from economic and environmental protection aspects since the raw materials of construction can be substituted by the in-use stocks in buildings, and construction activities are a large source of municipal waste [30]. Urban mining promotes environmental preservation and resource conservation by reusing or recycling building waste after its service life.

Research regarding materials has been extensively undertaken for many years, particularly in steel materials [31–34]. As one of the most common materials used in buildings, steel is used for several building components (e.g., beams and columns) [35–38]. Many studies analysed the performance of this material, including its strength [39–43] and capacity in some conditions [44–47], and proposed the design of the steel [48–52]. In terms of environmental performance, the carbon emission from steel materials has been investigated to understand the impact of this material [53–55]. Steel is deemed to have the highest recovery rate among construction waste materials, which can reach a repetitive recycling rate of 100% without losing its quality [56]. According to the Building Research Association of New Zealand (BRANZ), about 70–75% of steel material will be recycled in the typical nation-building practise at the end of its service time [57]. Besides, some steel materials, such as metal cladding, can sometimes be reused instead of recycled for production. For example, roof sheets from a commercial building may be used as fencing or in a farm warehouse [58]. Therefore, this research will focus on the construction of metal products, specifically steel, to investigate the CE approach.

In recent years, investigations into the carbon emissions of building products have become popular as the awareness of the environmental issue continues to grow. Several methodologies are being used for quantifying the carbon emissions of building products, such as the life cycle assessment (LCA), the most well-known methodology [59–62]. An accurate data collection process is required for reliable LCA calculation results. Building materials data are traditionally collected from a project's bill of quantities (BoQ). However, with the advancement in technology, the calculation of in-stock building materials data based on the actual map can be performed using a spatial model via a tool such as the Geographic Information System (GIS). It is an application that stores, manipulates, analyses, and displays spatially referenced data [63]. Therefore, the calculation of building stocks can be conducted using the spatial model in GIS, confirmed by previous studies (Table 1).

Table 1. Previous research papers on mapping and quantifying the urban building stocks and specific building materials (i.e., steel, concrete, and brick) using GIS technology.

References	Aim	Scope	Data Sources	Method	Time Span	Embodied Energy/LCA
[64]	Quantify and map the in-use structural bricks	Three cities	GIS map, building types, footprint perimeters, relevant height, historical landscape characterization, ordnance survey	Bottom-up approach	Yearly	Yes
[65]	Assess GIS-based MFA as a prospecting approach of secondary resources to promote urban mining	One city	GIS map, Material Flow Analysis	Bottom-up approach	Yearly	No
[66]	Quantify and map embodied energy and urban material stocks	One city	GIS map, footprint perimeters, relevant height	Bottom-up approach	Yearly	Yes
[67]	Quantify and map urban material stocks	One city	GIS map, Google Earth, U.S. Environmental Protection Agency, building models, design codes, manufacturer's product data, US DOE	Bottom-up approach	Every two years	No

Table 1. *Cont.*

References	Aim	Scope	Data Sources	Method	Time Span	Embodied Energy/LCA
[68]	Map the energy consumption of building materials in the urban area	One city	GIS data, statistical data, regulations, footprint, PostgreSQL	Bottom-up approach	Yearly	Yes

According to Table 1, the previous papers used the bottom-up approach and concentrated on mapping and quantifying the building stocks in the urban scope with a time dimension. The bottom-up method emphasises gathering the weight of construction materials for entire buildings and a small range of areas. This approach utilises typology to show the architectural complex [69]. The data resources from previous studies seem to be varied, but all the researchers used GIS to conduct their research. GIS was applied in the previous studies due to the more accurate product information they could collect as the tools combine map, space, and time aspects to produce definite results. With accurate product information, the previous studies could expand their scope of study to include the embodied energy of urban construction stocks. However, to present a comprehensive evaluation of the potential environmental effects of a particular material or product in urban mining, it is required to integrate the life cycle assessment, urban building stock model, and energy requirement model. In addition, among the previous papers, only one study [64] focused on a specific construction product, while the others [65–68] aimed to map and quantify the material weights and volumes in the urban areas.

GIS allows people to make better strategic decisions using geography, which can be simply described as capturing, analysing, and presenting information on a map. Although the application of GIS has been started in the building industry, the use of this tool in expanding the context of the environmental assessment of specific building products is still limited. The majority of papers took a bottom-up approach to quantifying urban building stocks, focusing on material weight or volume rather than specific construction products such as steel. Although steel products have a high recovery rate for recycling, there is a lack of studies on quantifying steel products. Due to the manufacture of new steel that will generate carbon emissions, the global warming potential (GWP) values in the production and recycling stages of the specific metal products were the focus of this research. Therefore, three different types of particular steel roofing and metal cladding products, long run roofing profiles with seven ribs and five ribs and a tray roofing profile with a pan width of 450 mm, were analysed in this paper.

The aim of this research was to use a bottom-up method to quantify and map the steel roofing and cladding profiles used for urban construction stocks for the purpose of demonstrating the potential value of urban mining and helping to make strategic decisions for the construction circular economy and building environment for future use. The objective of using the GIS software was to quantify the existing roofing and wall cladding products, and the results were used to calculate the GWP values and potential carbon offsets from the products. The analysis of GWP values from the steel roofing and wall cladding products was performed by considering the modules A1–A3, C3, C4, and D of the building's life cycle stages. The results from the investigated products were compared and analysed to identify the environmental performance of the steel roofing and wall cladding products. In addition, a comparison between the current product's carbon emissions from the manufacturing stages and the future carbon offset was presented. The percentage of potential carbon offsets from the roofing and wall cladding products was expected to improve understanding of the potential carbon savings of the steel products with the current recycling practice.

2. Methods

Ten case buildings were investigated in this study, and they were located in six different areas in New Zealand: Auckland City, Wellington City, Hamilton City, Palmerston North City, Tauranga City, and Christchurch City. A GIS application and an LCA method were performed to analyse the buildings' GWP values of the roofing and wall cladding metal products. Several building life cycles, such as production stages (A1–A3), end-of-life (EOL) stages (C3 and C4), and potential carbon offset after the EOL stage (D), were considered in analysing the GWP values of the steel products. Figure 1 shows the overall method and workflow of this study.

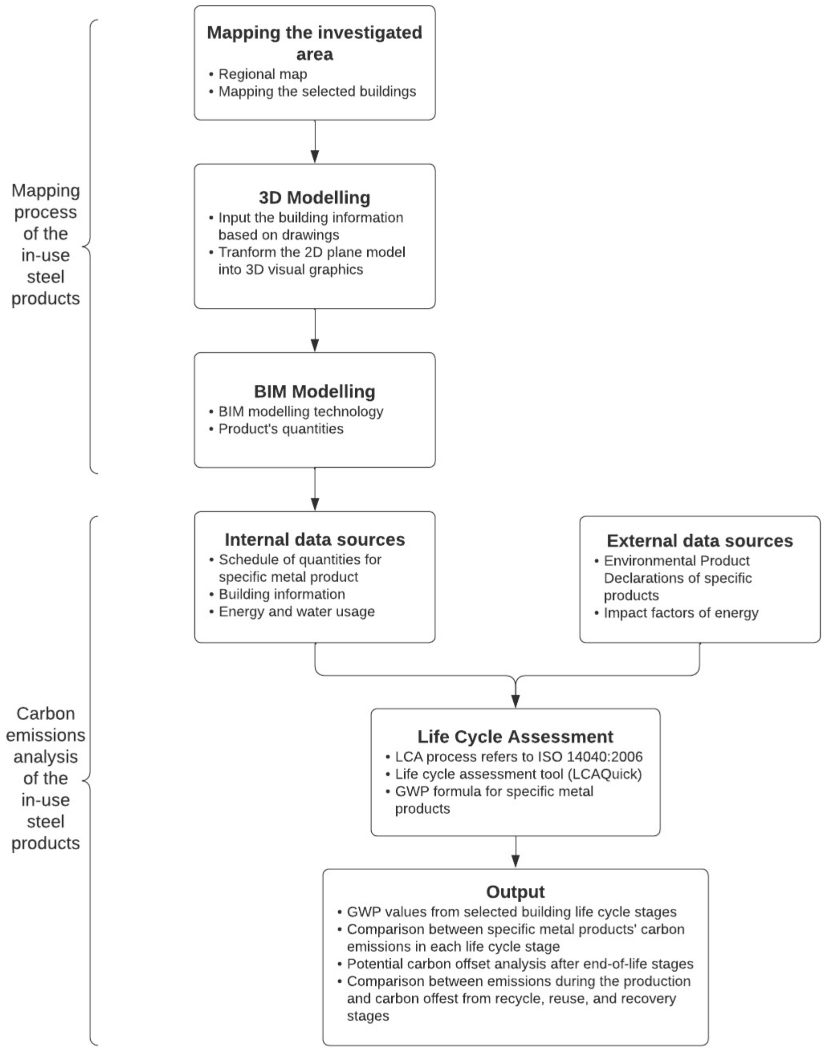


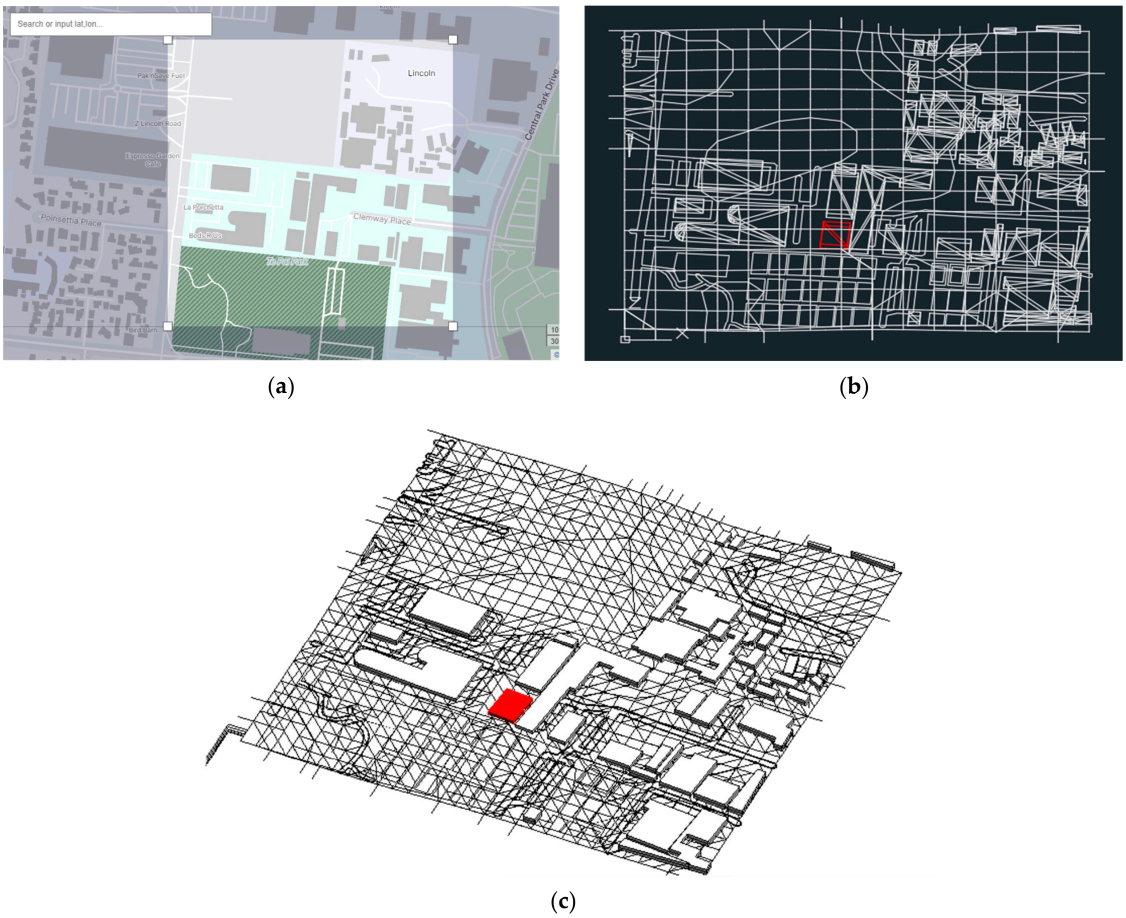
Figure 1. Overall modelling and workflow of the study.

According to Figure 1, two steps were undertaken in this study: mapping the in-use steel products and analysing the carbon emissions from the investigated products. The first step of the study was to map the in-use steel products by utilising the GIS technology in the case buildings. With the use of the application, a spatial model of the case studies could be obtained. The model was used to calculate the products' quantities by integrating the GIS technology with several tools such as Building Information Modelling (BIM). Therefore, by obtaining the quantities of materials, the analysis of the products' GWP values could be undertaken by adopting the LCA approach based on ISO 14040:2006 [70] in the second step. The carbon emissions quantification was completed using a New Zealand-based LCA tool developed by BRANZ, LCAQuick V3.4.4 [71], and an additional formula for specific products was used. The output of this LCA was the GWP values from the assessed metal roofing and wall cladding products in each life cycle stage. The results were used to analyse and compare the carbon emissions from each type of roof and wall cladding product. After recycling, reusing, and recovering the products, the potential carbon offsets were considered and compared with the emitted carbon during the production processes.

2.1. Mapping the In-Use Steel Products

The spatiotemporal models of the investigated case buildings were created by GeoMaps [72], AutoCAD [73], and Revit [74]. The buildings' dimensional data, such as floor area, year of construction, and exterior geometry, were combined with topographic data from the map to present the metal product categories applied to the building in 3D form. The spatiotemporal models on the map were used in conjunction with BIM technology to link the inventory of in-use building products in order to quantify metal cladding product quantities. The mapping and calculating procedures of the in-use steel product are outlined below.

- Step 1: Dividing a 0.2 km × 0.2 km area using GeoMaps to include the selected buildings in the investigated area, such as Auckland (Figure 2a).
- Step 2: Importing the regional map into the AutoCAD software (Figure 2b) for data input based on the drawings, such as the building height and the area of the residential or commercial buildings, and transforming the 2D plane models into 3D visual graphics.
- Step 3: Utilising BIM technology (Figure 2c) to determine the quantity of the in-use metal roofing and cladding products in case buildings from the 3D visual graphics in collaboration with the cost estimation function.



(**a**) (**b**) (**c**)

Figure 2. Mapping the in-use steel products procedures for the case building in Auckland (201 Lincoln Drive Henderson): (**a**) Capturing the selected area by GeoMaps; (**b**) Importing regional map into AutoCAD; (**c**) BIM modelling of investigated building.

In addition, the area of the building's geometric surface illustrates the number of metal roofing and cladding products used, and the colour represents the type of metal product. The red colour (Figure 2c) indicates the long run roofing profile with seven ribs metal product. The green colour reflects the tray roofing profile with a pan width of 450 mm metal product. The blue colour represents the long run roofing profile with five ribs metal product.

2.2. GWP Values Analysis of Investigated Steel Products

LCA was used to analyse the impact on the environment in terms of the metal products' GWP value. By utilising the LCA approach, the GWP value of the products could be quantified throughout the selected building life cycle stages (Figure 3). The LCA in this study referred to ISO 14040:2006 [70], in which four steps were conducted: goal and scope definition, inventory analysis, impact assessment, and interpretation analysis. Figure 3 illustrates the selected building life cycles (inside the red box) in analysing the metal cladding product's GWP value in this study, which was adopted from the building life cycle stages and modules in the BRANZ database and BS EN 15978:2011 [57,75].

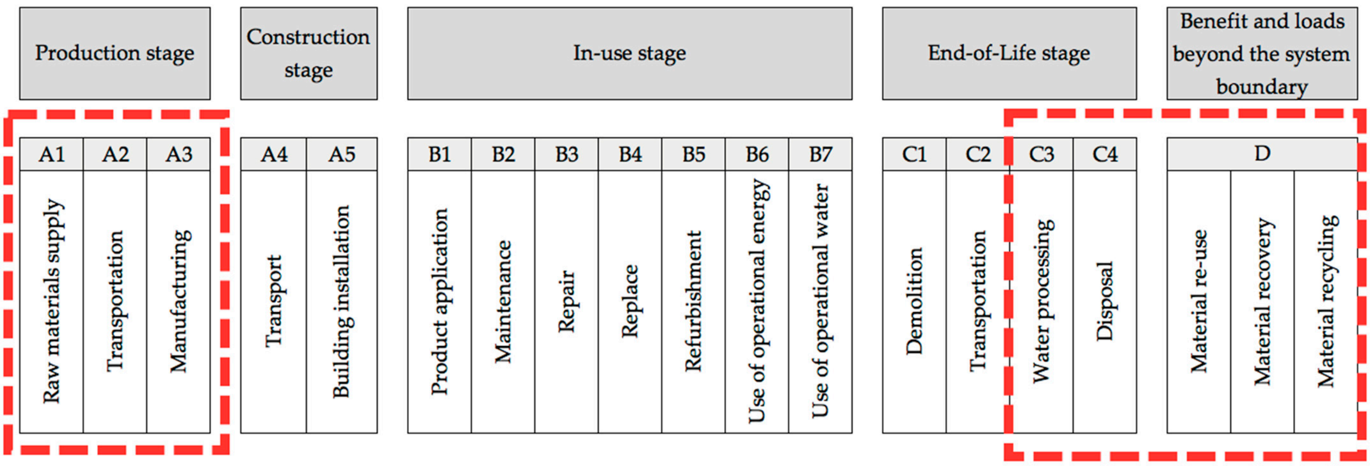


Figure 3. Selected building life stages of the investigated metal cladding products.

According to Figure 3, the scope of the system's analysis in this study involved the upstream processes of the supply and manufacturing of raw materials (A1–A3), water processing (C3), disposal (C4), and material recycling, reuse, and recovery stages (D). The selection of the investigated life cycle stages of the products was made in reference to the primary goal of this study, which was to analyse the GWP values of the specific steel products. The A1 through A3 modules in the production phases were required to be computed when analysing specific architectural components, while the other stages are optional computations. In addition, the construction and in-use stages for the specific metal roofing and cladding products were not assessed due to a lack of knowledge or information on how these processes occurred in the New Zealand construction industry. Thus, the production stages, EOL stages, and potential carbon offset from the recycling process were assumed to be the critical life stages and became the focus of the study. In addition, the geographical boundary in this study was the six mentioned cities in New Zealand, with 90 years of service life based on the BRANZ database [57]. The functional unit of this study was one square meter of roofing and wall cladding metal products used for 90 years in New Zealand buildings.

Furthermore, LCAQuick [71] was performed to quantify the GWP values of the investigated steel products. Two main data sources were required to calculate the GWP values using the LCA tool: internal and external data. The internal data were sources of information about the buildings or products, such as the products' quantities, building functions, and service time, whereas the external data involved the impact factors of energy and water and the environmental product declaration (EPD) of the specific metal products. Therefore, the spatialised material inventory map was included in the LCAQuick tool for the carbon emission calculation in collaboration with the LCA approach and GIS technology.

However, due to the limitation of the LCAQuick tool in calculating GWP values from specific metal products, an additional formula was used to develop the analysed data from the tool. The equation to calculate the GWP of these specific metal roofing and wall cladding products is given below in Equation (1). Two essential elements in this equation are the total quantity of the product and the emissions from the product's life cycle stage.

$$\mathrm{GWP}_{T\&S,cladding} = \sum_{t} (MS_{T\&S(t)} \times LCE_{T\&S} \times CF_{T\&S(t)}), \quad (1)$$

The formula was used to measure the GWP values of specific metal roofing and wall cladding products (*T&S(t)*). The term "*LCE*" refers to the life-cycle emissions contributing to the GWP value of the metal products per square meter ($kgCO_2eq/m^2$). This value was calculated based on the calculation from the LCA tool. *CF* was a characteristic factor derived from the life cycle impact assessment model. From the construction stock analysis, the *MS* value was found. It was based on the mapping of metal products that were in use in the project (m^2).

3. Results of the Case Study

In total, ten buildings were investigated to analyse the GWP values of the in-use roofing and wall cladding metal products. The analysis of these case buildings was based on a collaboration between GIS and LCA approaches. The result from the GIS approach was used as an input for GWP analysis, in which the products' quantities were required inputs to undertake the quantification.

3.1. In-Use Steel Products' Material Quantities

Using GeoMaps, AutoCAD, and Revit software, the study obtained the schedule of quantities of the investigated metal wall cladding and roofing products from the assessed buildings. The main output of the mapping process was to identify the type of metal products attached to the buildings and estimate the metal products' quantities. Table 2 shows the buildings and product information from the investigated case buildings.

Table 2. Schedule of quantities of investigated specific metal products.

Area	Site Address	Building Type	Metal Product Type	Width of the Metal Sheet (mm)	Linear Meter of Roof (m)	Linear Meter of Wall Cladding (m)
Auckland	201 Lincoln Drive, Henderson	Residential	Long Run 7 Ribs	934	303	289
	59 Arabella Lane, Snells Beach	Commercial	Tray Roofing Profile	630	504	326
	77 Rotu Drive, Massey	Commercial	Long Run 5 Ribs	765	920	956
	380 Cowes Road, Waiheke Island	Residential	Tray Roofing Profile	630	142	169
	Manawa View, Kerikeri	Residential	Long Run 5 Ribs	765	376	242

Table 2. *Cont.*

Area	Site Address	Building Type	Metal Product Type	Width of the Metal Sheet (mm)	Linear Meter of Roof (m)	Linear Meter of Wall Cladding (m)
Christchurch	53 Glenmark Drive	Residential	Tray Roofing Profile	630	524	906
Hamilton	NZ Honey Office-Warehouse	Commercial	Long Run 5 Ribs	765	2328	1695
Palmerston North	14 Poplar Grove, Feilding	Residential	Long Run 5 Ribs	765	310	79
Tauranga	44 Marshall Rd, Katikati	Commercial	Long Run 5 Ribs	765	509	263
Wellington	3 Ara Hekere Waikanae	Residential	Tray Roofing Profile	630	623	308

3.2. GWP Values from Investigated Steel Products

The GWP values of the investigated roofing and wall cladding metal products were calculated using the LCAQuick tool and the GWP Equation (1). The quantification focused on four life cycle modules, which were the production stages (A1–A3), the water processing stage (C3), the disposal stage (C4), and the potential carbon offset from recycling, reusing, and recovering processes (D). Table 3 presents the GWP values of the assessed building products by using the LCA approach.

Table 3. GWP values of investigated specific metal products.

Area	Site Address	Product Type	Base Metal Thickness (BMT)	Global Warming Potential (GWP) (kgCO_2eq)/m^2			
				A1–A3	C3	C4	D
Auckland	201 Lincoln Drive, Henderson	Long Run 7 Ribs	0.40 mm and 0.55 mm	15.60	0.03	0.02	−4.72
	59 Arabella Lane, Snells Beach	Tray Roofing Profile	0.55 mm	14.21	0.03	0.02	−4.42
	77 Rotu Drive, Massey	Long Run 5 Ribs	0.40 mm	8.65	0.02	0.01	−2.52
	380 Cowes Road, Waiheke Island	Tray Roofing Profile	0.55 mm	17.60	0.04	0.03	−5.91
	Manawa View, Kerikeri	Long Run 5 Ribs	0.40 mm and 0.55 mm	15.61	0.03	0.02	−4.81
Christchurch	53 Glenmark Drive	Tray Roofing Profile	0.55 mm	17.60	0.04	0.02	−5.48
Hamilton	NZ Honey Office-Warehouse	Long Run 5 Ribs	0.40 mm and 0.55 mm	17.91	0.04	0.02	−5.39
Palmerston North	14 Poplar Grove, Feilding	Long Run 5 Ribs	0.40 mm and 0.55 mm	16.86	0.04	0.02	−4.99
Tauranga	44 Marshall Rd, Katikati	Long Run 5 Ribs	0.40 mm and 0.55 mm	17.53	0.04	0.02	−5.24
Wellington	3 Ara Hekere Waikanae	Tray Roofing Profile	0.55 mm	20.53	0.04	0.03	−6.35

According to Table 3, the GWP values from different assessed metal products seem to vary. In terms of product life cycle modules, the production stages (A1–A3) were the most significant GWP emitters compared to the other selected modules. However, the recycling processes of the steel products could reduce the emissions from the production stages by up to 34%. For instance, the tray roofing profile with a pan width of 450 mm metal roofing and wall cladding products were attached to 380 Cowes Road, Waiheke Island, Auckland case building. The GWP value emitted in the production stages was 17.60 $kgCO_2eq/m^2$, and it was reduced to 11.69 $kgCO_2eq/m^2$, or approximately 33% less, when module D was analysed. The potential carbon offset from module D was quantified in other case buildings. In the Auckland region, the Lincoln Drive, Henderson case building (long run roofing profile with seven ribs) had -4.72 $kgCO_2eq/m^2$, or about a 30% potential reduction, from the production stages. The other investigated building cases in Arabella Lane (tray roofing profile), Rotu Drive (long run roofing profile with five ribs), and Manawa View (long run roofing profile with five ribs) had approximately 31%, 29%, and 30% potential carbon offset from the production stages' emissions, respectively. In other regions, the case building in Christchurch (tray roofing profile) had about a 31% carbon reduction from the manufacturing stages after the recycling, reuse, and recovery processes. At the same time, the long run roofing profile with five ribs in Hamilton, Palmerston North, and Tauranga had around 30%, 29%, and 29%, respectively, while the tray roofing profile in Wellington had a 31% carbon reduction. Overall, the long run roofing profiles with five ribs and seven ribs were identified to potentially have about a 30% reduction in carbon emissions by applying the recycling, reusing, and recovering processes after the EOL stages. The tray roofing profile with a pan width of 450 mm had approximately a 32% potential reduction. In addition, the effect of the painting on the roofing and wall cladding metal products is important and was considered in the recycling processes of the LCA. The three metal types were coated with a similar product, which follows AS/NZS 2728 (corrosion resistance) [76], and the output of the study included the coating processes of the roofing and wall cladding metal roofing.

4. Discussion

A comprehensive spatiotemporal model of the in-use stock metal roofing and cladding of case buildings was created by collaborating and promoting GIS and BIM technologies. The model contained the geometry of the building's surface area, a specific product type division, and a clear geographical location in time and space. BIM was used to turn 2D graphics into 3D time-and-space modelling with an information library and display the different product types in different colours on the space map. By having the spatial model of the case buildings, the specific product stock was quantified. In addition, there was prerequisite data for creating the model, including the construction date of the building, the floor area, the specific material type, and the height of the building. This building information must be obtained before creating a spatial model of the case buildings and is useful for further assessment, such as LCA.

The study analysed and mapped ten case buildings (residential and commercial) in six different cities in New Zealand. It was found that the stock of metal roofing and cladding in commercial buildings was greater in number than that in residential buildings. The metal cladding product in residential buildings mostly covered the roofs, while in commercial buildings, it almost covered the entire surfaces of the building, including walls and roofs. Among all the case buildings, a long run roofing profile with seven ribs was only used for the residential building located at 201 Lincoln Drive, Henderson. The tray roofing profile with a pan width of 450 mm was identified to be attached in residential buildings only, and the long run roofing profile with five ribs metal product was the most common in-use metal product in the case buildings. It was found that the long run roofing with five ribs product is suitable for both residential and commercial buildings in New Zealand, performs well in wind and rain protection, and has a particular advantage in price.

Furthermore, the environmental assessment of the GWP values of the investigated in-stock metal products from the case buildings was performed. The carbon emissions quantification was carried out using the LCA approach with LCAQuick. Data such as the products' quantities were utilised from the GIS modelling in the early steps of the study. The study found that the GWP values of the different investigated metal cladding and roofing products were varied. The variation in GWP values from the investigated metal cladding and roofing products was caused by the different profile designs of the products. The long run roofing profiles with seven ribs and five ribs were long run roofing systems with 0.40 mm and 0.55 mm BMT, and the investigated buildings used a range of BMT for the roofing and wall cladding systems, which can be seen in Table 3. The long run roofing profile with seven ribs product had a 934 mm width and a 36 mm height, with a 1.40 m end span and a 1.70 m internal span for the 0.40 mm BMT type, while the 0.55 mm BMT of this product had a 2.10 m end span and a 2.70 m internal span in its design. The long run roofing profile with five ribs had a 765 mm width and a 29 mm height, with a 1.10 mm end span and a 1.60 mm internal span for the 0.40 BMT type; this profile had a 1.50 mm end span and a 2.20 mm internal span for the 0.55 BMT type. The tray roofing profile with a pan width of 450 mm was a wide tray roofing system roll-formed in single-length trays. The profile had a 450 mm tray pan and a 45 mm overall height. Therefore, with a range of profile designs, the products' surface areas varied and resulted in different quantities of material required in the manufacturing processes of these products. Thus, the varied GWP values were affected by the different numbers of materials utilised in the production stages of the roofing profiles.

According to Table 3, the long run roofing profile with seven ribs product had 10.93 $kgCO_2eq/m^2$ during the A1–A3, C3, C4, and D modules. The five ribs product's long-run roofing profile had a range of GWP values among the investigated buildings that attached this product to their roofing and cladding systems. The product had total carbon emissions ranging from 6.16 to 12.58 $kgCO_2eq/m^2$ during the assessed building life cycles, while the tray roofing profile with a pan width of 450 mm produced GWP values ranging from 9.83 to 14.11 $kgCO_2eq/m^2$. The production stages of roofing and wall cladding metal products were the greatest GWP value emitters compared to other assessed life cycle stages. The long run roofing profile with the seven ribs model's production stages emitted 15.60 $kgCO_2eq/m^2$; the five ribs model's average emissions were 15.31 $kgCO_2eq/m^2$; and the tray roofing profile produced 17.45 $kgCO_2eq/m^2$ during these life cycle stages. The study aligned with the LCA report from Thinkstep ANZ regarding the emissions from the production of steel roofing and cladding products in New Zealand. The report found that emissions from the 0.40 mm and 0.55 mm BMT roll-formed roofing and cladding in New Zealand were between 11.2 and 18.3 $kgCO_2eq/m^2$ [77]. However, the values are different from those in the Athena Sustainable Materials Institute report, which found that the carbon emissions from steel cladding production processes in Canada ranged from 7.74 to 10.42 $kgCO_2eq/m^2$ [78]. The difference between the study and the Athena results was caused by the different geographical conditions, leading to the carbon emissions gap. Besides that, the C3 and C4 modules only made up a small amount of GWP, which was about 0.48% of all tested metal products.

When considering the products' recycling, reusing, and recovering stages, a potential carbon offset of up to 34% of the GWP values produced from the production stages can be achieved. Figure 4 compares the average GWP values from the production stages and the potential carbon offset after the EOL processes for each specific metal product. The study found no significant difference between the three products' potential carbon offsets in the future. The investigated long run roofing profile with the seven ribs model had a possible 30.28% carbon savings per one meter squared of production of the product. The long run roofing profile with the five ribs model had a potential carbon offset range between 29.11% and 30.81%, while the tray roofing profile with a pan with 450 mm ranged from 31.14% to 33.61%.

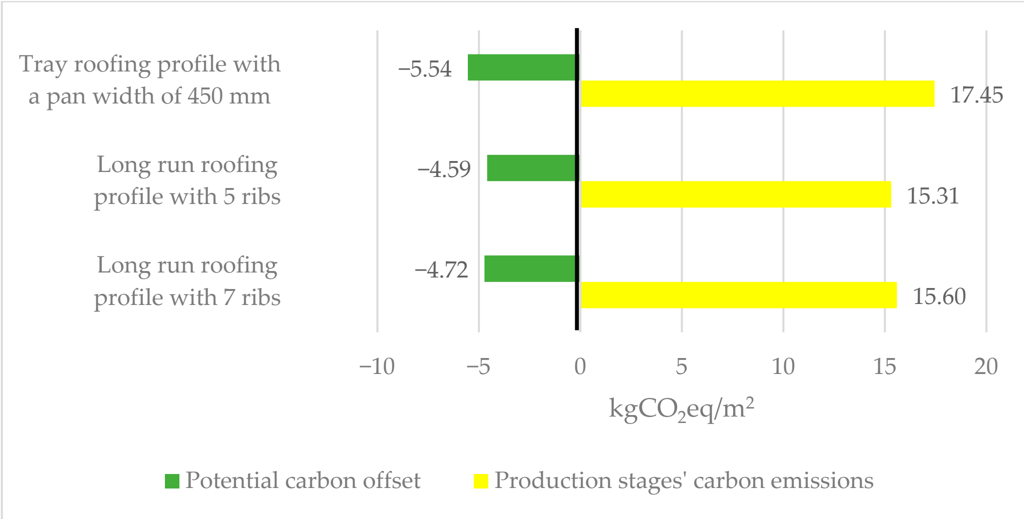


Figure 4. Comparison between average GWP values from the production stages and the potential carbon offset from each investigated metal roofing product.

The high percentage of potential carbon offset of steel products was driven by steel's relatively high recovery rates for recycling. The role of recycling, reuse, and recovery seemed to be necessary due to the high benefits in the future of reducing the carbon emissions from the buildings, especially the roofing and wall cladding systems. In New Zealand, 75% of the waste steel sheet's mass proceeds to the recycling process for the typical practise [57]. This value led to the higher potential of the steel roofing and wall cladding having carbon offset after the EOL processes. Steel can be made either from virgin raw materials or from reclaimed materials. However, the production process from raw materials can result in five times the embodied energy and carbon than using recycled materials [79]. Therefore, carbon emissions can be reduced if steel roofing and wall cladding are recycled and used to make new products.

The study focused on analysing the environmental impact of GWP in the production stages and recycling stages of specific metal roofing and wall cladding products. Simultaneously, the study promoted the use of GIS technology and the LCA approach in quantifying the GWP values of building products, laying the foundation for the future development of the CE. The research model can be used not only for metal products but also for other building materials, such as brick and timber. It can provide good suggestions for the CE approach in the construction industry. In addition, the developed space–time model is not limited to quantifying the building products' quantities. This model can be applied to analysing and planning the urban environment in various spatial and geographic forms. Thus, practitioners can use this model to simulate the geographical environment and design buildings to prepare for the circular economy in the future.

5. Conclusions

The study provides a detailed analysis and high-value information for future urban mining through a spatiotemporal model and data analysis created by combining building types, specific building products, time dimensions, and global warming potential (GWP) values. The nation's current recycling practise for steel was considered in this study to estimate the potential carbon savings of the products. The spatial analysis and geographical location tracking of specific building material products can help relevant practitioners quantify the in-use building materials and store them in the cloud database. The integration of spatial analysis and the LCA approach will provide a good foundation for future recycling and remanufacturing of building materials and products. Recycling building materials has greatly reduced the potential impact on the environment and has relatively reduced carbon emissions from building activity. The study was able to quantify that the potential carbon offset from recycling processes of the investigated metal roofing and wall cladding products was up to 34% of the carbon emission of the production stages. This percentage was obtained by applying the current typical New Zealand recycling scenario, but it is not limited to future EOL technology that could increase the carbon offset from the material. In addition, the ten investigated buildings were in big cities, and their geographical locations were easily obtained. However, the research model is not suitable for buildings in remote areas because the geographical information cannot be displayed on the map, and the results are not applicable for subsequent research. In addition, the study can be applied to a group of buildings in an urban area. Therefore, it will contribute to the future of urban mining and the development of the CE approach in the construction industry.

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