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Measuring the correlation between carbon embodied emissions, economic and social impacts of building elements in Spain

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Abstract. Buildings produce significant environmental impacts, as well as economic and social impacts in society. The Life Cycle Sustainability Assessment (LCSA) is recognised as an appropriate method to assess their impact following a Triple Bottom Line (TBL) approach. In the European context, incoming regulations for building are beginning to consider the embodied environmental impact of new construction. However, the economic and social implications of those concerns have been scarcely explored. Implementing the LCSA on different building elements involves a great amount of data. Difficulties in data management and the weighting of different dimensions are also detected as methodological challenges. To reduce the effort in the LCSA implementation in the building design process the Building Information Modelling TBL (BIM_TBL) database includes a collection of the most frequently used building elements in Spain, which is integrated in BIM. This study presents the main results of data analysis of the BIM_TBL database to determine the correlation between the environmental, economic, and social impacts generated by different constructive solutions. To that end, a Knowledge Discovery Database (KDD) analysis was performed to support the multi-dimension integration in the design process. This study provides recommendations to integrate a multi-dimension approach in the building design process.

1. Introduction

Given the existing climate change scenario and the dramatic consequences that have deviated from resource consumption and CO2 emissions to the atmosphere, the building sector is one of the largest contributors to this situation, being responsible for around 40% of greenhouse gas (GHG) emissions [1]. This fact provides evidence of the potential of this sector in impact reductions. To correct this situation, existing international sustainability strategies such as the United Nations Sustainable Development Goals [2] and European strategies such as the Green Deal [3] and the Circular Economy Plan Action [4] propose radical changes in our development model, towards implementing more effective and innovative measures to bring about radical changes. One of them is the decarbonisation of our economy, which means the progressive and absolute reduction of greenhouse gas emissions (both embodied and operational carbon footprint) of all our activities, being the 2050 year the horizon for achieving neutrality of these emissions. To contribute to the decarbonisation of the building sector and to start moving

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towards impact reduction, the new version of the Energy Performance of Buildings Directive [5] proposes the calculation of whole-life carbon emissions for both the embodied and the operational carbon footprint using the Life Cycle Assessment (LCA) [5,6] method. Nevertheless, the calculation of embodied carbon footprint is still rarely used in practice. The main obstacles lie in the costs of software and databases, the lack of training to create an internal technical capacity to implement LCA in practice, the lack of sufficiently robust tools to help technicians to use the methodology correctly, as well as the lack of tools that help to visualise the economic and social impacts of construction solutions. The construction sector in Spain contributes to around 5% of GDP, as well as being an important source of employment for the country [7]. The wide variety of building typologies existing in the country [8] and the complexity in assessing the different building performance and the consumption of resources, provides evidence of the difficulty in addressing the sustainability assessment. Hence, in the coming years in Spain one of the main challenges is to bring the building sector into a more sustainable pathway. Emerging methods such as the Life Cycle Sustainability Assessment (LCSA) [9] are growing interest to advance in measuring and assessing the sustainability a more holistic approach, seeking to provide solutions to these issues.

The LCSA [9] is recognised as a valid method to enrich the environmental assessment based on the LCA. The method enables to integrate the economic and the social dimension into the evaluation along the building life cycle [10]. It is a fundamental aspect to move from existing scenario to a decarbonised, affordable, and socially feasible pathway. The LCSA is a data intensive method that requires to manage different type of data sources [11–13], because it implies the simultaneous application of the LCA (environmental assessment), Life Cycle Costing (LCC) and the Social Life Cycle Assessment (S-LCA). The three methods involve the data acquisition of the different dimensions assessed, which has certain difficulties depending on the product to which the method is applied and the scope of the analysis.

To reduce the effort on the LCSA implementation in buildings the authors have developed different works [14–16]. One of those are the Autodesk Revit Plug-ins [14,15] and defined the main steps to conduct real-time LCSA calculations in BIM [12,17]. The plug-ins [14,15] are supported by a BIM-TBL database [16] that includes predefined information about the building elements that compose the BIM model, which is needed to conduct the LCSA to buildings. The BIM-TBL database was developed for the Spanish context and includes environmental (CO_2 eq. emissions), economic (economic cost), and social (working hours) data about the building elements covering the production stage (A1-A3), construction stage (A5), maintenance (B2), repair (B3), replacement (B4), demolition (C1). This database aims to simplify the data acquisition and support the material selection process, as well as to propose a harmonised data structure for the triple dimension inventory [12,17]. Nonetheless, what else can be learnt from the BIM-TBL building elements database to improve the LCSA implementation? What other analysis can be useful to better understand the values tendencies and their correlation? Which are the implications of the different variable growing tendencies and why?

To answer those questions the authors propose using the KDD (Knowledge Discovery from Databases) process to extract the "hidden knowledge" [18] from this database. The method enables to detect patterns, correlations, relationships, and anomalies in the values [18]. In the field of dada science, the KDD refers to the “overall process of discovering useful knowledge from data, while the data mining refers to a particular step in the process”, applicating algorithms for extracting patterns from data [19]. The KDD method can provide reliable results and effectively assist in analysis of data and extraction of knowledge [20]. Its application to the BIM-TBL database could support the detection of the growing tendencies for environmental, economic, and social dimensions. The KDD process has been applied in other studies related to the building design [20–23]. For example, to discover patterns using KDD and semantic data modelling to establish design patterns [20]. He et al. [37] analysed the correlations between the Climate Parameters (CPs) and Building Parameters (BPs) using Data Mining technology. However, its application to databases holding information on building materials and on the LCSA of buildings remains scarce.

The present paper goal is to understand the "hidden knowledge" of the LCSA application at the building element scale, applying the KDD process to the BIM-TBL database of building elements, adapted to the Spanish context.

2. Methods

The methodology focuses on an existing database and on Data Mining. It has been designed to achieve the research objectives through six steps, as shown Figure 1: 1) Data selection, 2) Data pre-processing and transformation, 3) Data Mining, and 4) Interpretation.

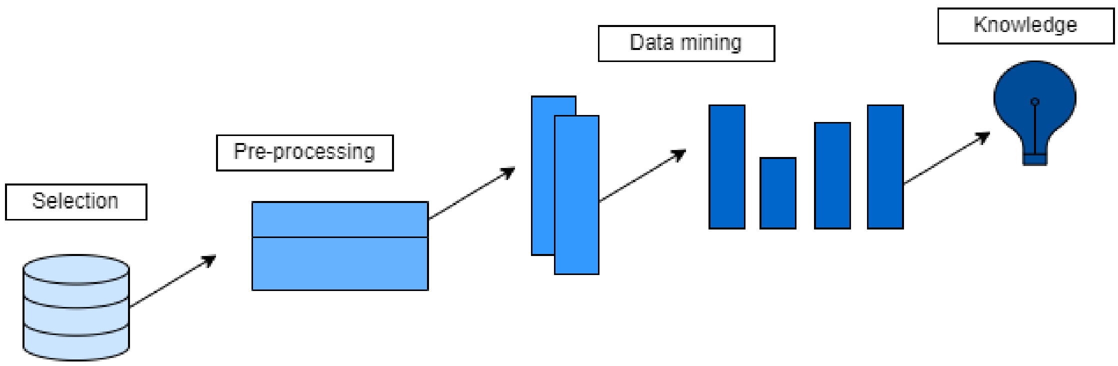


Figure 1. Scheme of the method framework used in the study.

2.1 Data selection

This step starts from the development of the BIM-TBL database that has been implemented in MS Access [24] as a relational database architecture, following the principle of modularity for building information organized according to ISO 21931-1 [25]. The database includes the information about building elements (including beams, slabs, columns, plate, wall, roof, floor, door, window, ceiling, covering) to conduct the LCSA, including a selection of most frequent constructive solutions used in Spain [26]. The structure of the database was based on the classification system and systematic building decomposition [27] of the BCCA [28], a construction database that organizes building information for cost estimation purposes, including the necessary building materials, machinery, and labour for the construction of different building elements. The environmental data and emissions factors for the product stage (A1-A3 modules) and construction (A5 module), maintenance (B2), repair (B3), substitution (B4) and deconstruction (C1) were estimated using ecoinvent v3.7.1 [29], the most widely used environmental database for generic data, to the BCCA building materials [28]. Economic and social data were estimated using BCCA costs and work-hour values [28]. The criteria to define the LCSA assumptions and method for the calculation is specified in [14,17]. The information included in the database considered one impact category per dimension; this approach aims to balance the integration of the three dimensions. The environmental dimension included the impact category Global Warming Potential (GWP) measured in kg CO2 equivalence emissions indicator. The economic dimension is measured in euros, and the social dimension measured the employment indicator in working hours since it is the most widely used inventory indicator for S-LCA [30].

2.2 Data preparation and classification

In this stage, the data was prepared and transformed for the analysis. All the values were normalised to enable the comparison of the different dimensions (environmental, economic, and social) to a common scale to enable their comparison. The results of the statistical analysis were carried out in a spreadsheet.

2.3 Data analysis

In this a series of statistical analysis techniques and algorithms were used to obtain the results. The goal of this analysis was to find correlations between the economic, environmental, and social data of the building elements database. The study included the calculation of three types of correlations coefficients: Pearson Correlation Coefficients (PCCs) [31], Kendall Correlation Coefficients (KCCs) [32], and Spearman Correlation Coefficients (SCCs) [33], the most frequently used in similar studies [21]. including. Pearson's coefficient measures the linear relationship between two variables, and it is appropriate when the variables do not have a normal distribution or when the data has outliers [31].

Kendall's and Spearman´s correlation coefficients measure the strength and direction of association that exists between two variables measured on at least an ordinal scale [32]. Spearman rank correlation is useful for testing a null hypothesis of independence between two variables, while Kendall rank correlation shows the strength of the dependence between the variables being compared [34] and show the strength and direction of the association between two ranked parameters [35].

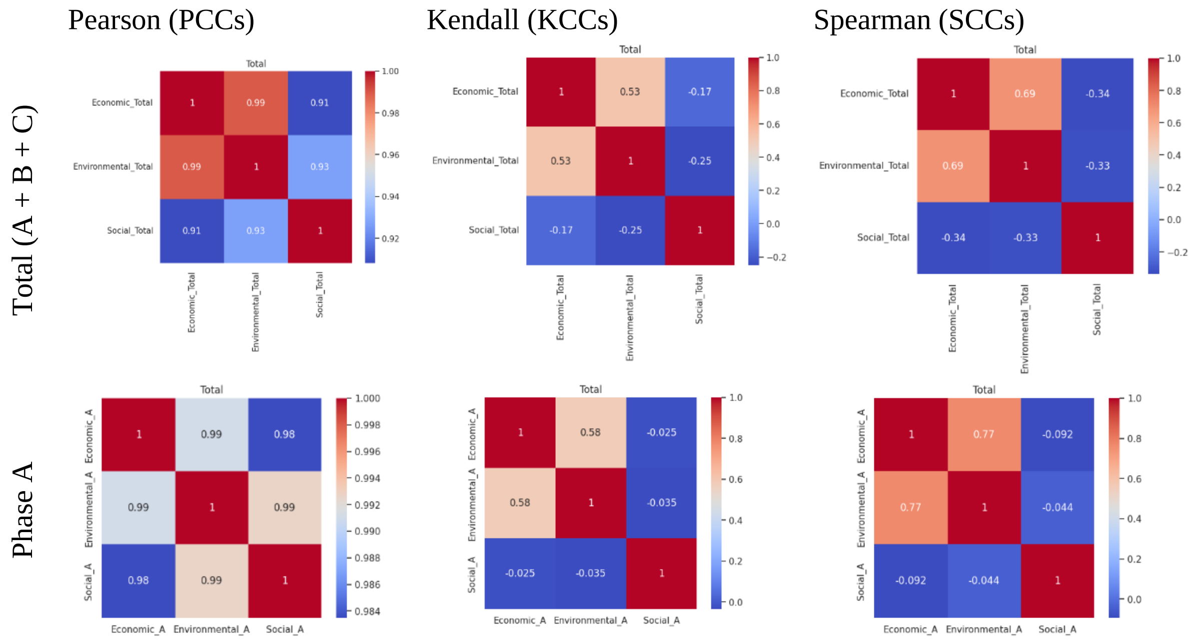
To the analysis of the three correlation coefficients, three ranges of correlations were defined: coefficient between 0.50 and 1.00 indicates a strong direct correlation, moderate correlations were detected in the coefficient values were 0.5 and -0.5 and strong inverse correlation were detected when the coefficient, are between -0.50 and -1.00.

2.4 Data interpretation

This stage included the interpretation and evaluation of correlation coefficients, the identification of relationships and the conclusion drawing for the LCSA implementation.

3 Results

Figure 2 shows that the total results for the 59 building elements including beams, slabs, columns, plate, wall, roof, floor, door, window, ceiling, covering. The complete list of building elements is included in the Supplementary data.



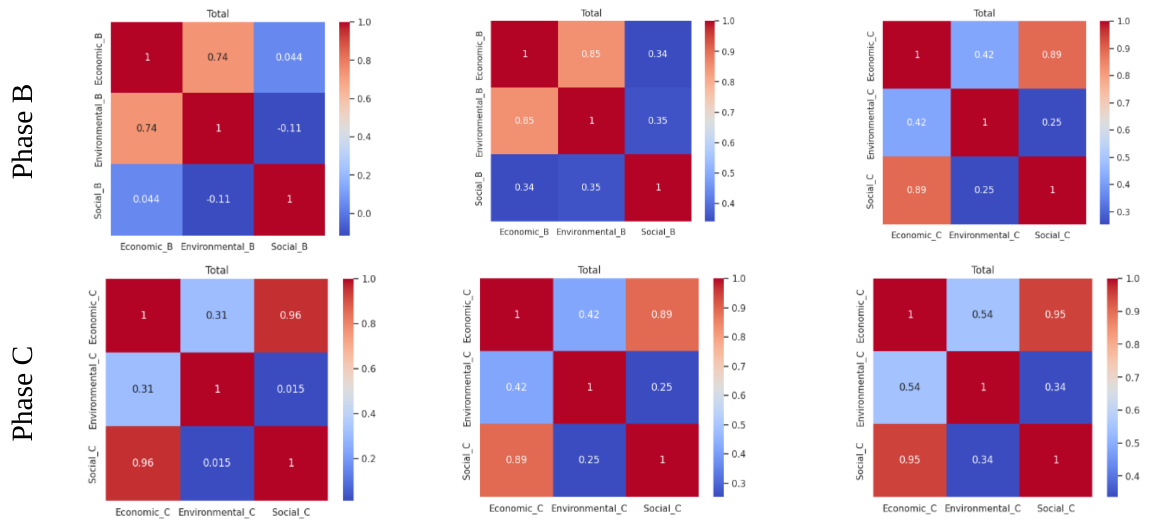


Figure 2. The correlation-strength heat map of parameters ((PCCs), (KCCs), (SCCs)) of the 59 building elements analysed. (Phase A includes modules A1-A3 and A5; Phase B includes B2-B3 and B4; Phase C includes C1).

The correlation analysis for the total number of building element (59), in the total values, phase A and B (see Figure 2) shows that the PCCs have a strong correlation for environmental and economic dimensions. It means that there is a linear relationship between them, thus, the growing tendencies are positive for the three dimensions. While the KCCs and SCCs shows moderate correlation for social and economic, and social and environmental dimensions. The economic and environmental have a strong to moderate correlation.

To better understand if the correlation analysis can differ depending on the functional unit consider results for m^2 and m^3 FU are analysed separately. Table 1 and 2 show the values obtained.

Table 1. The correlation-strength heat map of LCSA dimensions ((PCCs), (KCCs), (SCCs)) of the 46 building elements analysed (m^2).

		Pearson (PCCs)	Kendall (KCCs)	Spearman (SCCs)
Total (A+ B+C)	Environmental / Economic	0.68	0.54	0.65
	Environmental / Social	-0.33	-0.22	-0.33
	Economic / Social	-0.36	-0.18	-0.36
Phase A	Environmental / Economic	0.65	0.49	0.64
	Environmental / Social	-0.30	-0.13	-0.20
	Economic / Social	-0.47	-0.12	-0.23
Phase B	Environmental / Economic	0.7	0.56	0.69
	Environmental / Social	-0.27	-0.22	-0.35
	Economic / Social	-0.14	-0.22	-0.37
Phase C	Environmental / Economic	**-0.071**	**0.43**	**-0.062**
	Environmental / Social	-0.071	0.25	-0.062
	Economic / Social	1	0.89	1

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Table 2. The correlation-strength heat map of LCSA dimensions ((PCCs), (KCCs), (SCCs)) of the 13 building elements analysed (m^3).

		Pearson (PCCs)	Kendall (KCCs)	Spearman (SCCs)
Total (A+ B+C)	Environmental / Economic	**0.99**	**0.22**	**0.22**
	Environmental / Social	**1**	**-0.13**	**-0.072**
	Economic / Social	**0.99**	**0.29**	**0.33**
Phase A	Environmental / Economic	**0.99**	**0.22**	**0.22**
	Environmental / Social	**1**	**-0.13**	**-0.072**
	Economic / Social	**0.99**	**0.29**	**0.33**
Phase B	Environmental / Economic	-	-	-
	Environmental / Social	-	-	-
	Economic / Social	-	-	-
Phase C	Environmental / Economic	-0.90	-0.65	-0.82
	Environmental / Social	-0.98	-0.65	-0.82
	Economic / Social	0.97	1	1

Table 1 shows similar tendencies in the three correlations coefficients for the values obtained for the 45 building elements that used m^2 as a FU (including Roof, Floor, Door, Window, Wall, Ceiling, Covering). The exception was KCCs of the phase C, where the coefficients were positive to moderate (-0.071, 0.43, -0.062). This indicates that depending on the coefficients and the functions to which the values are subjected these coefficients can change, in this case varying from strong (PCCs) to moderate (KCCs and SCCs). This also shows that the values obtained do not have a perfect behaviour that perfectly fits to the functions to which it is subjected.

Table 2 shows the correlation coefficient for the 13 building elements analysed that used m^3 as a FU (including Beam, Slab, Column, Plate, Wall). It revels the relevance of Phase A in total values tendencies and that the correlations coefficients were strong for PCCs, while moderate correlations were detected for the KCCs and SCCs. The negative correlation between the environmental and economic values of phase C derived from the higher values for the environmental dimension were the lower values for the economic dimension and vice versa.

4 Discussion

This study focuses on detecting the possible correlations between the LCA, LCC and S-LCA values of building elements (beams, slabs, columns, plate, wall, roof, floor, door, window, ceiling, covering), to understand the hidden relationships between three dimensions assessed, to detect those dimensions that are more interdependent and those that are not. The study showed that by separating the analysis into different functional units, the values obtained can be better analysed.

The results shows that the correlations coefficients were generally positive and moderate, and provided evidence that that the way in which environmental, economic, and social values grow is different. It means that the sustainability strategies to reduce the impacts of one of the dimensions will positively affect the other dimensions. On the other hand, it indicates that when performing an LCSA it must be considered that the LCA, LCC and S-LCA values will increase in different ways depending on the dimension, the life cycle phase, and the building element under consideration.

The strong PCCs for the environmental and economic dimensions indicated that as the environmental values of the building elements increased, the economic values growth proportionally as well (for example Figure 2, Table 1 and 2). This trend has been verified in the Total values (Figure 2), Table 1 and Table 2, for Total (A+ B+C) values. Considering the m^2 FU, the social and economic, and social and environmental dimensions the correlation coefficients were moderate to inverse (-0.33 to -0.47). It indicates that social values do not correlate in the same way that economic and environmental values is that the growth jumps in social values are less pronounced than in the other two dimensions (e.g. in phase B).

The incidence of the life cycle phases with higher weights in the total values can also be seen in the trends of the coefficients. For example, the case of m^3 FU, where the phase A values were around 98% of the total values for the three dimensions, (see Table 1), the correlation coefficients for phase A were very similar to the total values. Nevertheless, when this difference becomes less accentuated, for example, for m^2 FU, where the values for phase A were around 50%, the results for each of the dimensions had different growth trends (see Table 1 and Figure 2).

3 Conclusions

Given the existing climate crisis, the existing regulation, and efforts to move towards the decarbonization of our economy, the affordability and social feasibility of implementing these measures became more and more important. Addressing these objectives, this study focused on identifying the correlations of the environmental, economic, and social dimensions of the different building elements.

Finding focus on the practical implications for local stakeholders related to the construction sector show that knowledge discovered in the BIM-TBL database provide evidence that in general the environmental, economic, and social values have a positive and strong to moderate in linear correlation (PCCs), which means that if one variable grows, the other also grows. However, in KCCs and SCCs differences has been detected, which means that not all the correlations are similar. According to the research results the same design strategies can be used for similar purposes, reducing environmental, economic, and social impacts. Nevertheless, the effectiveness of this measures can differ because the growing tendencies of the values are different.

Future research can focus on including a larger number of life cycle stages in the analysis, as well as integrating a greater number of building elements covering a wide range of construction solutions (e.g., bio-based materials). This study helped to detect the phases that have the greatest influence in the correlation coefficients and therefore those that will most affect the total results. The present study can be useful to measure the effectiveness of sustainability strategies to reduce the environmental impacts, reducing the cost and social benefits in the LCSA implementation to buildings. More impact indicators such as water footprint, acidification, toxicity, etc. could also be included to better understand the effectiveness of these strategies, avoiding carbon tunnel vision and enrich the approach and the scope of the sustainability assessment.

Supplementary data

More information about the data included in this study can be found in this link: https://uses0.sharepoint.com/:b:/s/BIM-ZEN/ES3qjpucexFAh3HpawEicVABopTGqAi2aL4XFvEFnL8QuQ?e=nOwuMY

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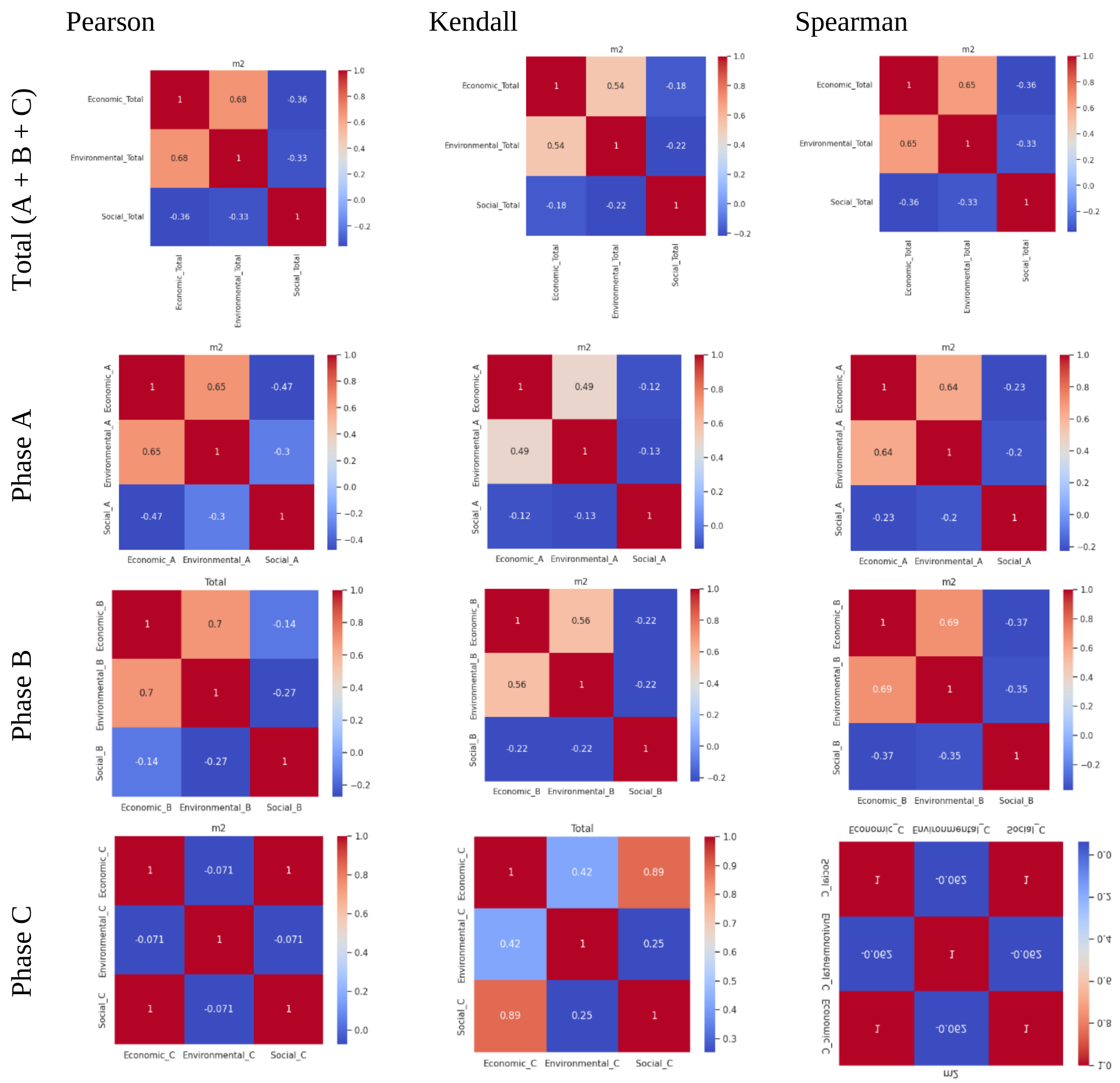
Appendix A

(m2)



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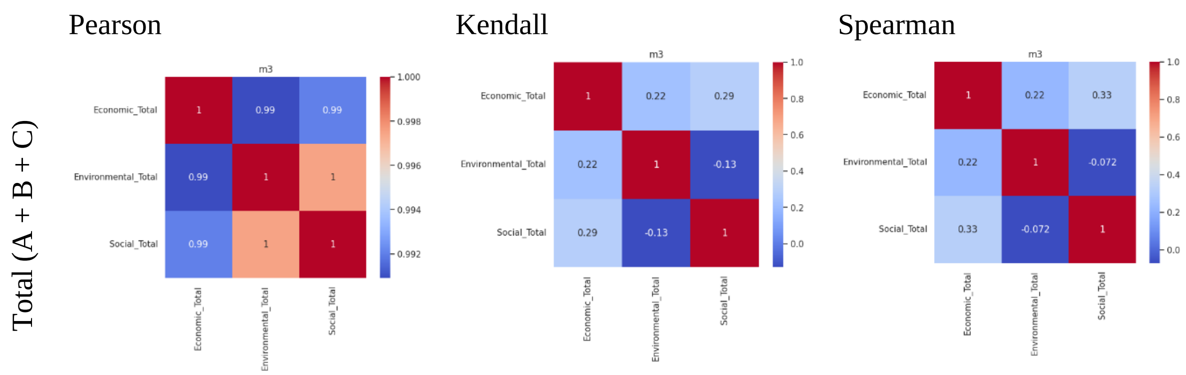

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