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Sustainable Construction Logistics in Urban Areas: A Framework for Assessing the Suitability of the Implementation of Construction Consolidation Centres

Victoria Muerza [1,*,†] and Cindy Guerlain [2]

1 Department of Quantitative Methods for Economics and Business, University of Zaragoza, 50005 Zaragoza, Spain
2 Department of IT for Innovative Services, Luxembourg Institute of Science and Technology (LIST), 5 Av. des Hauts-Fourneaux, Esch-sur-Alzette, L-4362 Luxembourg, Luxembourg; cindy.guerlain@list.lu
* Correspondence: vmuerza@unizar.es
† Research was performed at: Aragon Institute of Engineering Research (i3A), University of Zaragoza, 50018 Zaragoza, Spain.

Abstract: Transport in construction is responsible for up to 30% of freight movement in cities, with a subsequent impact in terms of pollutant emissions. Different solutions have been provided to alleviate the negative impact of freight transport related to construction activity, although no guidance has been provided for replicability in cities. One solution whose potential benefits are being studied with the support of policy makers is Construction Consolidation Centres (CCC). This paper proposes a method based on the Analytic Hierarchy Process (AHP) and provides an index based on 45 indicators to evaluate the suitability of the implementation of a CCC in terms of the pillars of sustainability in combination with a technical pillar. Three real construction projects were assessed in Luxembourg City, Paris, and Valencia. Two critical attributes were identified: the estimated operational costs of the construction company and the potential demand level in the area. The results of the analysis allow for: (i) the extraction of knowledge related to the sustainability of the construction project, and (ii) logistics to be integrated into the planning and design stages of the construction activity. Furthermore, a general structure is also proposed for integrating other construction solutions where CCC is not suitable.

Keywords: sustainable urban logistics; Construction Consolidation Centre; AHP; multicriteria evaluation

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1. Introduction

The construction industry is of great importance to the economic activity of a country. The construction of buildings (residential and non-residential) accounts for around 77% of the total construction in Europe and generates more than 5% of the value added [1]. However, it is also one of the primary contributors of global greenhouse gas (GHG) emissions [2]. In 2017, it was estimated that construction activity was responsible for 58,840,688 tonnes of CO_2 emissions in Europe [3]. Construction in urban areas also impacts sustainability through its related activities. Thus, the construction of new buildings and infrastructures, refurbishment of existing ones, delivery of building materials, and removal of waste from urban construction sites affect traffic congestion, air pollution, noise, and accidents. Waste related to construction activity accounts for about 25–30% of all waste generated in the European Union (EU) and is one of the heaviest and most voluminous waste streams generated in the EU [4].

To solve these issues, the Construction Consolidation Centre (CCC) [5] is considered to be a potential solution to improve the performance of construction logistics while reducing the negative socio-economic and environmental impacts of urban deliveries. The CCC is an innovative approach that reduces the number of deliveries and, therefore, increases the efficiency and effectiveness of logistics processes.

It is at a logistics facility where building materials are dropped off for consolidation, classification, and delivery to construction sites [6]. A CCC allows for optimized delivery at construction sites, reduced congestion, improved working environments, as well as reduced energy use and emissions. Furthermore, the implementation of CCCs is linked to the concept of sustainable transport, making use of different possibilities (e.g., night distribution and reverse logistics).

Existing studies have mainly focused on the use of consolidation centres for the retail industry, the characteristics of which are different to those of the construction industry. The literature has presented the CCC approach as a representative Urban Consolidation Centre in response to urban freight problems (e.g., [7–9]). Recently, Guerlain et al. [6] tested the possible positive impact of using a CCC in four case studies with strong variability depending on the scenario, and Guerlain et al. [10] provided a decision support system for consolidation centre locations. Nevertheless, to the best of our knowledge, no attempt has been carried out to measure the suitability of these solutions in terms of the pillars of sustainability.

Furthermore, policy makers, with the objective of reducing emissions, have focused on reducing the negative impacts and costs of urban freight transport caused by the construction sector through improved supply chain management and CCC implementation. In the framework of the SUCCESS project, funded by the European Union's Horizon 2020 programme, this paper will answer the following research questions (RQ):

- **RQ1.** *How can the suitability of CCC implementation be measured, based on the sustainability pillars, as a supported solution by policy makers?*
- **RQ2.** *How can guidance be provided for the replicability of construction logistics solutions and for improving the use of existing transport infrastructure?*

By developing the RQs, this paper contributes to the literature in addressing one of the future directions of decision-making in construction supply chain management, as identified by Le et al. [11]: the support of logistics-based planning in the early planning and design phases. Furthermore, we present both a methodology and a set of indicators to measure a sustainable urban logistics solution, supporting the claim made by Gonzalez-Feliu [12]. RQ1 will be addressed by proposing and applying a multicriteria method and a measurement index to three real cases studies, based on the Analytic Hierarchy Process (AHP). This method is based on the pillars of sustainability (i.e., economic, social, and environmental) in combination with a technical pillar. RQ2 will be addressed by proposing the structure of a methodological framework that integrates different construction logistics solutions [10].

Recent research focused on solutions to alleviate the negative impact of freight transport related to construction activity included the effective management of materials in a confined construction site [13]; decision-making modelling for construction supply chain optimization [14]; the coordination of transport and logistics activities in construction for better efficiency [15]; a simulation-based approach for modelling and logistics integration of facilities that temporarily contain materials in construction projects [16]; decision-making simulation of a construction Project Delivery System [17]; the appropriate kitting to organize just-in-time material deliveries [18]; and the analysis of problems and solutions applied to construction site deliveries [19]. However, to the best of our knowledge, no guidelines have been proposed that integrate the different solutions.

The paper is structured as follows: Section 2 provides the background to the work; Section 3 presents the methodology followed in this research, describes the multicriteria approach developed for the CCC suitability evaluation, and presents a methodological framework for the integration of construction logistics solutions; Section 4 presents a case study to evaluate the suitability of CCC implementation in three real construction projects; Section 5 discusses the main findings of the paper; and Section 6 presents the conclusions.

2. Construction Consolidation Centre Concept

The concept of the Consolidation Centre (CC) was initially used in the retail and manufacturing sectors. At an urban level, the concept is known as an Urban Consolidation Centre (UCC) and applies mainly to retail, HoReCa (Hotel, Restaurant, Café), and offices. From a review of the literature performed by Allen et al. [20], a total of 114 UCC schemes in 17 countries worldwide were identified in the period 1970–2010. Of those, only seven corresponded to construction projects (five in the UK, one in Germany, and one in Sweden). The concept was first set up in the construction industry with a CCC in 2001, for the construction of terminals 1–4 of Heathrow Airport [5,21]. Experiences in the UK were supported by Transport for London [22].

A CCC is a facility used to supply and distribute building materials to several construction projects (see Figure 1). CCCs are normally located strategically near motorways or railway stations to facilitate logistics [23]. Some characteristics are related to their operation—they can serve either one single or several major building project(s)—and their nature: they can exist for the lifetime of a building project or be ongoing, serving new major building projects as they begin to run [20].

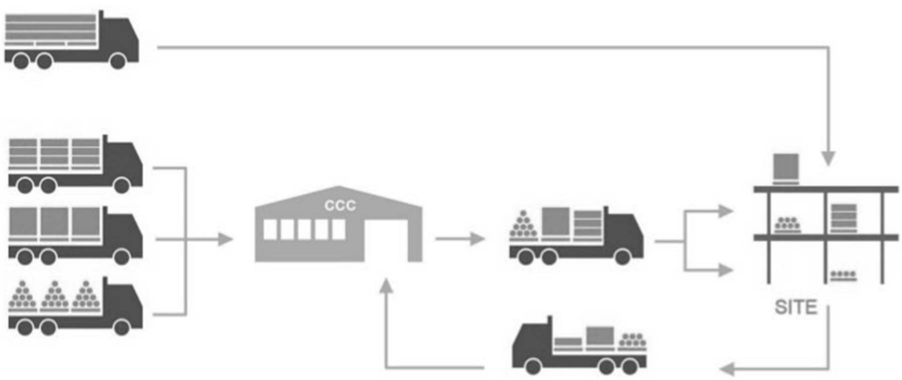

Figure 1. A Construction Consolidation Centre (CCC) concept [10].

CCCs can be made mandatory through the planning permission process because of traffic concerns, or more usually, promoted by the site developer or main contractor to reduce project costs [9]. CCCs can be considered a type of UCC. These centres provide safe and efficient material flows from the supplier to the construction site making it an effective supply chain management solution. The CCC can also provide a great variety of other value-added logistics and retail services, for instance, mock-up space, warehousing, assembling, kitting, quality control, and reverse logistics.

The benefits of using a CCC include [5,24]: (i) a reduction in construction traffic; (ii) environmental effects, including a reduction in congestion, noise pollution, carbon emissions and waste; (iii) social effects related to health and safety with a reduction of disruptions on-site as a result of lower stocks, fewer vehicles, and reduced material handling; and (iv) productivity and programme certainty effects, regarding the reduction of on-site handling, which supposes an increased productivity of the labour force (up to 30 min per day), and fewer shortages.

Despite these advantages, these initiatives have seen a high degree of failure. In this regard, the literature has mainly focused on studying the financial viability of CCs in the retail industry (e.g., [25,26]), which is determined by two aspects [25]: (i) revenues, which must be higher than the expenses; and (ii) good cooperation between actors and viability from a cost-benefit perspective [23,27]. Other perspectives used are location-based accessibility [28], operative [23], and location-operational [29]. Recent research has demonstrated the potential positive impact of the introduction of a CCC in different locations [6].

3. Methodology

With the objective of a better knowledge of the fundamentals of CCCs, we established collaboration with a group of seven experts in the construction industry. The experts were part of the SUCCESS project team and had from 10 to 25 years of experience, including the participation in different typologies of construction projects (e.g., the House of BioHealth, Interreg NWE IVB LaMiLo project): four experts from the construction industry (one construction company, one consultant, and two researchers) and three logistics and supply chain professionals from the research field. The research was divided into two main steps to comply with the RQs as defined in Section 1:

1. The preconditions for evaluating the suitability of implementing a CCC and AHP-Hierarchy model construction and assessment for suitability evaluation.
2. A framework for the integration of construction logistics solutions.

A general overview of the research methodology can be seen in Figure 2.

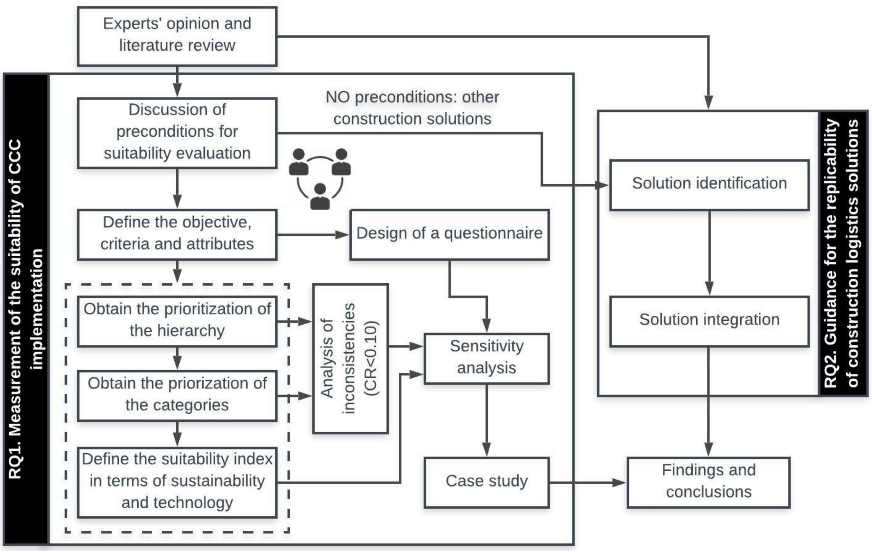

Figure 2. A general overview of the research methodology.

The participation of the experts in the research is described in more detail as follows: starting from a literature review on the criteria that should be included in the model, a first discussion meeting was organized with the experts. The objectives of the meeting were: (i) to present the AHP fundamentals and (ii) to discuss the criteria identified in the literature to be included in the model, thus, structuring the problem in a hierarchy. As a result of the discussion, and based on the experience of the experts, it was suggested the model must be preceded by the study of the minimum preconditions that the construction project must comply with to consider the study of the suitability of implementing a CCC.

Initially, the structure of the hierarchy considered the three pillars of sustainability (i.e., economic, social, and environmental). However, as an outcome of the discussion, the technical criterion was included in the hierarchy. A second discussion meeting was organized to assess the hierarchy model in two steps: (i) the valuation of the hierarchy elements and (ii) valuation of the alternatives with regard to the attributes. The details of the process are provided in Section 3.2.2.

A third meeting was organized to obtain consensus on the indicators identified to evaluate the 14 attributes that shape the model. The 45 indicators (see Section 3.2.2) were provided in the framework of the knowledge developed in the SUCCESS project [30]. A fourth meeting was organized to discuss the results of the sensitivity analysis performed in collaboration with a construction company to adjust the model. The rest of the communication needed to complete the research took place by email.

3.1. Preconditions for Evaluating the Suitability of Implementing A CCC

Some authors have established rules to decide when to implement a CCC. Thus, for example, Sullivan et al. [23] proposed project-specific constraints, and Lundesjo [5] came up with two questions to identify when a CCC is the right solution: (i) What are the material supply characteristics of the project? (ii) What are the main characteristics of the construction site? With regard to the first question, the author asserted that, when full vehicle loads do not come directly from suppliers/manufacturers, there is some demand for consolidation, and a CCC is needed.

With regard to the second question, the author proposed the need for secure, dry, and accessible material storage, and a warehouse operative, driver, and an administrator for stock control and communication with the site and suppliers, and identified a minimum CCC size. In this paper, we propose some preconditions (P) for the analysis of suitability, based on the sustainability pillars in combination with a technical pillar. These are the result of the experience of the expert group taking part in this study of the different typologies of construction projects:

- P1. The city or the main contractor is involved/interested in the implementation of a CCC.
- P2. The construction site is located in an urban area.
- P3. The type of construction activity involves building construction.
- P4. A minimum construction activity: Turnover > €20 M and building size > 7000 m^2, considering all the construction sites that could be served by the CCC.

The preconditions are a mandatory requirement in the analysis of the construction project. All must be met to consider the CCC suitability evaluation. Otherwise, the suitability analysis is not needed, and other construction solutions different from a CCC should be considered.

3.2. AHP-Hierarchy for CCC Suitability Evaluation

The Analytic Hierarchy Process (AHP) is a method that allows the information and reasoning used in decision-making to be organized by structuring a problem into a hierarchy. It allows the resolution of highly complex problems that involve the participation of multiple actors, the existence of multiple scenarios, and criteria (tangible and intangible). It is based on the binary comparison between the elements of the decision model, i.e., criteria and alternatives. AHP measures the inconsistency of judgements elicited by the actors. The Consistency Ratio [31] for the Eigenvector method, and the Geometric Consistency Index [32] for the Row Geometric method are the corresponding inconsistency measures. Its main limitation concerns the ranking from which the priorities are derived, which can vary when introducing new alternatives.

The method consists of three stages [31,33]:

1. Modelling of the problem and construction of a hierarchy.
2. Valuation or elicitation of judgements by decision-maker(s).
3. Prioritization (derivation of local and global priorities) and synthesis.

AHP has become a useful tool for solving multi-objective problems in various applications. It has been used in several disciplines and areas of research, including suitability analyses [34] and sustainable development [35]. This multicriteria methodology has been widely used in the resolution of complex problems. Some reasons include its capacity to integrate the individual with the collective, the small with the large, and the objective with the subjective. It also allows the incorporation of the multiple actors' different visions of reality into the model problem solution [36]. A review of AHP applications can be seen in Vaidya and Kumar [37], and Emrouznejad and Marra [38]. The potential of AHP from a cognitive perspective strongly recommends its use [39] in the CCC suitability implementation analysis carried out in this paper.

The CCC suitability evaluation involved the development of the AHP-Hierarchy: model construction (Section 3.2.1), and model assessment (Section 3.2.2).

3.2.1. AHP-Hierarchy: Model Construction

The construction and assessment of the hierarchy were carried out in collaboration with seven experts (see Section 3). The experts, working in a decision-making context [36,40], structured the problem on three levels: Goal, Criteria, and Attributes. The objective was to develop a multicriteria approach, which can be used to assess different construction sites. The model is based on the pillars of sustainability (i.e., economic, social, and environmental), in combination with a technical pillar. Previous research in the literature has focused on developing frameworks addressing the sustainability concept in different sectors, including construction, based on the three pillars (see the discussion provided by Pan et al. [41]).

However, in this research, the technical pillar, derived from the practical experience of the experts participating in the research, was also considered. AHP with absolute measurements was selected. In this variant of AHP, modelling used two blocks [34]: relevant aspects of the problem (goal, criteria, sub-criteria, and attributes) in a hierarchy; and valuation of the alternatives with regard to the attributes. One advantage of this method relies on the fact that there was no rank reversal of the alternatives in the case where a new alternative was added or another deleted [42]. The structure of the hierarchy can be seen in Figure 3.

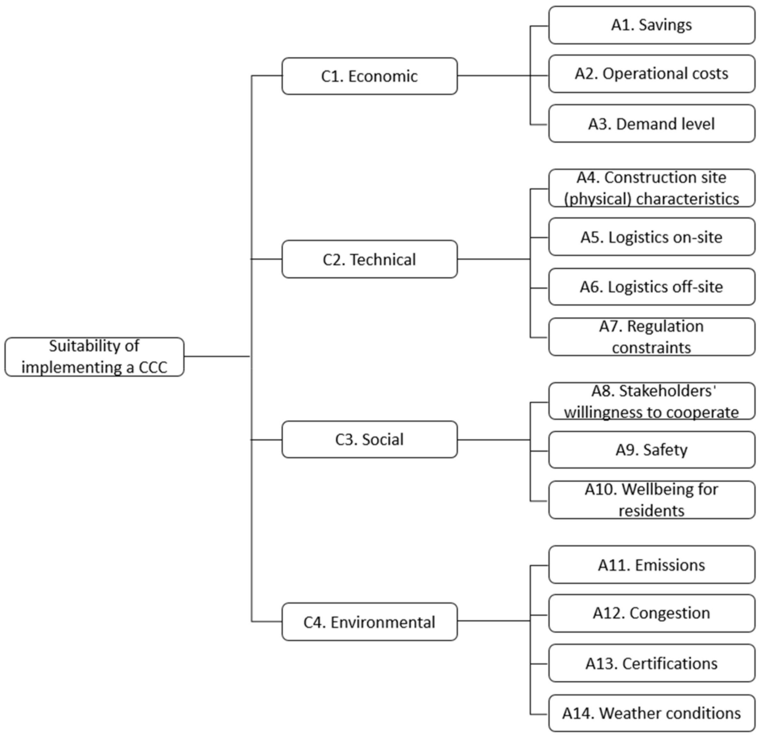

Figure 3. Structure of the problem.

The elements of the hierarchy include:

One goal (G): to assess the suitability of implementing a CCC in a particular area of study.

Four criteria (C): to analyse the suitability of implementing a CCC based on the three pillars of sustainability, and on technical issues (as an additional pillar). Thus, the criteria selected for the first level of the model were: Economic (C1), Technical (C2), Social (C3), and Environmental (C4).

Fourteen attributes (A): for each criteria, attributes were defined inspired by a literature review of city logistics (e.g., [43,44]) and construction logistics (e.g., [23,24,45]).

A1. Savings derived from the use of a CCC. All participants in a construction project can benefit from using a CCC [5]. The potential savings identified were defined in terms of the distance from suppliers to the construction site, travel time in the urban area, availability of public subsidies, and costs.

A2. Estimated operational costs of the construction company. The operational costs are related to the operation of a business. This analysis reflects the importance of logistics in the overall budget and the economic horizon of the construction company in the construction sector.

A3. Potential demand level in the area. The demand level is linked to the capacity to absorb costs and, hence, to the feasibility of implementing a CCC. The existence of big construction sites and/or the choice of several sites positively impact the financial sustainability in the long-term [10]. The indicators used to evaluate this attribute are: (i) the turnover of the candidate sites to integrate the CCC; (ii) number of sites, i.e., the potential customers of a CCC; (iii) time pressure, referred as the amount of time available to complete the development project; (iv) willingness to pay for extra services; and (v) economic outlook for the next five years. This indicator is measured in terms of the growth rate of the company. A higher growth rate implies a better willingness to make investments.

A4. Identification of the characteristics of the construction site. Construction site characteristics have a direct impact on the necessity of implementing a CCC. The indicators used to evaluate this attribute are: (i) the storage capacity, referred to the availability of space on-site for the storage of materials; (ii) handling equipment, referred to the type and number of pieces of handling equipment used to bring the materials from the delivery vehicle to the point of use; (iii) security, linked to the existence of high value material; (iv) construction building size defined in terms of the gross floor area (this indicator is used to estimate the material volume needed); and (v) nature of the construction activity, which is directly linked to the transport flows the activity generates and the material needs.

A5. Logistics complexity on-site. This attribute is related to the flows and movements of the materials at the construction site and those elements that affect it. The indicators used to evaluate it are related to (i) the restrictions limiting vehicle access [46]; (ii) number of delivery areas used by the construction site; and (iii) accessibility to the site in order to supply and remove materials (The nature of the construction site layout affects the management of materials. On the other hand, their accessibility influences the site's productivity and the traffic and safety conditions outside the site.); and (iv) logistics strategy, referring to the services that the main contractor offers to their subcontractors to support certain activities.

A6. Logistics off-site. This refers to the characteristics that affect the running of the construction activity in the area of study. The criteria used to evaluate the logistics off-site regarding the suitability of using a CCC include:

(i) The location of the construction site in the city. The difficulty of accessing a construction site in a city depends on the city's size and the site location within the city. Traffic conditions are specific to each city. Unfavourable traffic conditions increase travel time and delays.
(ii) The slope and topography describe the shape and relief of the land. Topography has a direct impact on the energy consumption, emissions, and manoeuvrability of delivery vehicles.
(iii) The topology, which refers to the organization of the roads in a city. The road pattern greatly affects the mobility in a city.
(iv) The construction activity. This refers to the number of construction sites in the neighbourhood. The volume of construction activities in the neighbourhood has a direct impact on the evaluated construction site and congestion. However, the higher the number of construction sites, the better the probability of being able to share costs in the implementation of a CCC.
(v) The number of sites operated by the same contractor. The experts considered that the more construction sites that were operated by the same contractor, the more suitable it would be to implement a CCC in terms of cost reduction.

A7. Traffic and transportation regulation constraints. Traffic and transportation regulations have a direct impact on urban freight distribution and congestion, air pollution, noise, road damage, accidents, etc. Local authorities implement regulatory and fiscal measures to improve the existing urban freight distribution system. A list of solutions was provided by Sanz et al. [47].

A8. Stakeholders' willingness to cooperate in the use and operation of a CCC. Stakeholders' involvement and collaboration were identified as main elements that influence the success of this type of scheme [26].

A9. Safety in the area is evaluated in terms of adequate signalling, number of road accidents in the city area, and number of accidents within the construction site. Safety is related to the use of a CCC. Thus, it is considered that, the safer the area, the less need there is for the implementation of a CCC.

A10. Wellbeing for residents derived from the implementation of a CCC. A construction site generates noise, pollution, dust, and visual nuisance and could have a negative impact on the vegetal elements, street furniture, and economic attractiveness of the area. The implementation of a CCC can moderate this effect by decreasing the transport flows and congestion. Public acceptance of the scheme has been identified as one of the factors of success in the implementation of CCCs [48].

A11. Analysis of emissions. This attribute refers to the city pollution exposure. Transport to and from construction sites causes negative effects, e.g., air pollution and urban noise. As road traffic is responsible for noise and air pollution, highly polluted cities are expected to implement solutions to limit transport movements, e.g., CCCs.

A12. Congestion in the area. This attribute refers to the level of congestion in the city. Traffic congestion has a great impact on the economy of a city. Although construction vehicles account for a significant proportion of congestion, traffic congestion tends to increase delays in construction, vehicle operating costs, collision probability, and pollutant emissions. The indicators used to measure this attribute are: (i) the traffic level in the area, (ii) urban surface area occupied, and (iii) number of inhabitants.

A13. Certifications in construction. Construction contributes significantly to environmental deterioration by consuming resources and energy and generating waste. However, there are some initiatives that promote sustainable construction through the implementation of certificates both at the national and international level, e.g., green buildings. Due to the implementation of certification, logistics activities are better coordinated during the audit process.

A14. Weather conditions in the construction area. Weather conditions affect the materials used, delivery, storage and equipment, design, construction, and performance of buildings. In rainy conditions, sediment and erosion control measures need to be implemented. The treatment of storm water or groundwater pumped from excavations may also be necessary. In windy conditions, dust control may be necessary—for example, making rounds with a water truck. In addition, there are health and safety concerns for workers due to dust, rain, and excessively hot or cold temperatures. The existence of extreme weather conditions affects the suitability of a CCC. The weather conditions identified by Crissinger [49] and the number of days without construction activity due to bad weather conditions were included in the model.

3.2.2. Hierarchy Model Assessment

The assessment of the hierarchy was carried out by means of a consensus process, where the experts acted as a single group to provide their judgements. A total of 24 judgements were elicited using Saaty's Fundamental Scale [31]. Of those, six judgements corresponded to the pairwise comparison matrix when comparing the economic, technical, social, and environmental criteria with respect to the goal; and 18 (3 + 6 + 3 + 6) judgements for comparing the relative importance of the attributes with respect to the criteria (four pairwise comparison matrices). All pairwise comparison matrices obtained acceptable inconsistencies (Consistency Ratio < 0.10).

The prioritization of the hierarchy elements is seen in Figure 4. The local priorities of all nodes (except the goal) were obtained using the eigenvector method. The global priorities of the 14 attributes with regard to the goal were derived by means of the hierarchical composition principle.

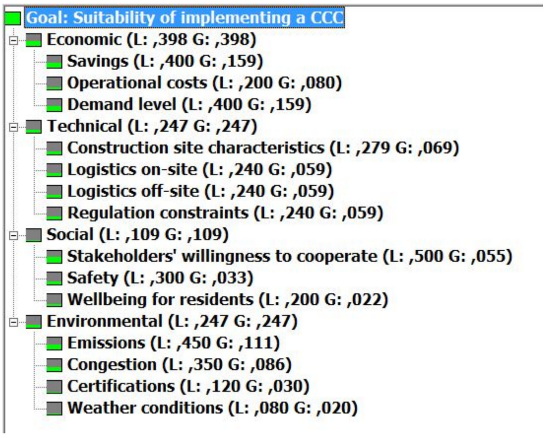

Figure 4. Local (L) and global (G) priorities of the hierarchy elements.

Five categories were considered for each attribute: Very High (VH), High (H), Regular (R), Low (L), and Very Low (VL). The prioritization of those categories was obtained by applying the absolute measurement model. The categories were used for the valuation of the alternatives with reference to the attributes. This step required the assessment of 14 (5 × 5) matrices and the elicitation of 140 (14 × 10) judgments.

Table 1 shows the priorities (normalized in an ideal mode) of the five categories considered for the 14 attributes. In addition, it includes the thresholds (in bold) fixed by the experts for attributes A1–A14.

Table 1. Prioritization of the model (excluding the goal).

	C1			C2				C3			C4				Index
Global	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	
	0.159	0.08	0.159	0.069	0.059	0.059	0.059	0.055	0.033	0.022	0.111	0.086	0.03	0.02	
Ideal	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	
VH	1.000	1.000	1.000	0.086	1.000	1.000	1.000	1.000	0.077	1.000	1.000	1.000	1.000	1.000	
H	0.510	**0.592**	**0.592**	0.275	0.653	0.750	0.750	0.510	0.416	0.750	0.619	0.510	0.748	0.619	
R	**0.252**	0.306	0.306	**0.516**	**0.524**	**0.516**	**0.516**	**0.252**	**0.554**	**0.516**	**0.278**	**0.252**	**0.554**	**0.278**	
L	0.124	0.065	0.065	0.750	0.272	0.275	0.275	0.124	0.748	0.275	0.195	0.124	0.416	0.195	
VL	0.065	0.062	0.062	1.000	0.127	0.086	0.086	0.065	1.000	0.086	0.066	0.065	0.077	0.066	SI
Min. threshold	0.252	0.592	0.592	0.516	0.524	0.516	0.516	0.252	0.554	0.516	0.278	0.252	0.554	0.278	0.427

Note: C1 (Economic); A1 (Savings); A2 (Operational Costs); A3 (Demand level); C2 (Technical); A4 (Construction site characteristics); A5 (Logistics on-site); A6 (Logistics off-site); A7 (Regulation constraints); C3 (Social); A8 (Stakeholders' willingness to cooperate); A9 (Safety); A10 (Wellbeing for residents); C4 (Environmental); A11 (Emissions); A12 (Congestion); A13 (Certifications); A14 (Weather conditions); and SI (Suitability Index). In bold it is shown the thresholds fixed by the experts for attributes A1–A14.

The total value of the alternatives (construction projects), defined in this research as the Suitability Index for CCC implementation (SI), can be calculated through a linear multi-additive function, as follows:

$$\text{SI (Construction project}_i) = \sum_{j=1}^{n} v_{ij} w_j \tag{1}$$

where v_{ij} is the priority (normalized in an ideal mode) for the category or effect (VH, H, R, L, and VL) assigned when evaluating the construction project i (i = 1, . . . , n) with regard to the attribute j (j = 1, . . . , 14), and w_j is the global priority of the attribute j. The objective was to evaluate the suitability of a CCC for one construction site. The evaluation process should be applied during the planning stage before the construction activity has started. The process is defined in more detail next.

In addition to the recommended thresholds, two attributes where identified by the experts as critical, A2 and A3, and the following rules (R) were applied when evaluating a construction project:

- R1. The analysed construction project had to exceed the SI to indicate the suitability of implementing a CCC (0.427).
- R2. A2 and A3, identified as critical attributes when studying the suitability of implementing a CCC in a given construction project, were allowed to score one level below the recommended level.
- R3. A4: Construction site characteristics, and A9: Safety in the area, were identified as attributes that influenced the decision-making in the opposite way (the higher the level of this attributes, the less suitable the implementation of a CCC).

A questionnaire was designed to obtain the information needed in the evaluation of the alternatives according to the elements identified in the model. A sensitivity analysis was performed in collaboration with a construction company. Table 2 shows a summary of the 45 indicators (I) used to evaluate the 14 attributes.

Table 2. Indicators for the evaluation of the attributes (source: adapted from [5,12,23,24,26,27,30,43–45,49–53]).

A1. Savings	**A2. Operational Costs**	**A3. Potential Demand Level in the Area**
I1. Distance from the supplier location to the construction site I2. Travel time I3. Availability of public subsidies I4. Cost of lost pallets I5. Cost of unsorted bins I6. Material savings	I7. Human resources dedicated to logistics activities I8. Fixed assets (buildings, vehicles, equipment) I9. Relative weight of logistics costs in the overall budget	I10. Turnover (economic value of the projects) for the CCC I11. Number of sites I12. Time pressure I13. Willingness to pay for extra services I14. Economic outlook for the next five years
A4. Identification of the Construction Site Characteristics	**A5. Logistics Complexity on-site**	**A6. Logistics off-site**
I15. Storage capacity I16. Handling equipment I17. Security I18. Construction building size I19. Nature of the construction activities	I20. Restrictions limiting vehicle access I21. Delivery areas I22. Accessibility I23. Logistics strategy	I24. Location I25. Topography I26. Topology I27. Construction activity I28. Number of sites operated by the same contractor
A7. Traffic and Transportation Regulation Constraints	**A8. Stakeholder Willingness to Cooperate in the Use and Operation of a CCC**	**A9. Safety in the Area**
I29. Level of constraint implemented in urban freight transport I30. Solutions driven by Local Authorities for urban freight distribution	I31. Stakeholder willingness to cooperate	I32. Adequate signalling I33. Number of road accidents in the city area I34. Number of accidents on the construction site
A10. Wellbeing for Residents	**A11. Analysis of Emissions**	**A12. Congestion in the Area**
I35. Population density I36. Public acceptance of the scheme I37. Measure of the neighbourhood's environmental sensitivity	I38. Noise pollution during the day in working conditions I39. Level of gas emissions	I40. Traffic level in the area I41. Urban surface area occupied (ha) I42. Number of inhabitants
A13. Certifications in Construction	**A14. Weather Conditions**	
I43. Level of compliance with construction certifications	I44. Weather conditions I45. Number of days without construction activity due to bad weather conditions	

3.3. Methodological Framework for the Integration of Construction Logistics Solutions

In addition to CCCs, other construction logistics solutions have been proposed in the literature to alleviate the negative effects of freight transport (see discussion in Section 1). Nevertheless, to the best of our knowledge, no guidelines have been proposed for integration. This section aims at providing a general framework to allow a path toward the implementation of other logistics solutions to be defined in the event that the suitability of CCC is not identified. Three phases have been defined (see Figure 5): (i) Suitability evaluation, (ii) Business model (BM) selection and solution implementation, and (iii) Evaluation of the implemented solution.

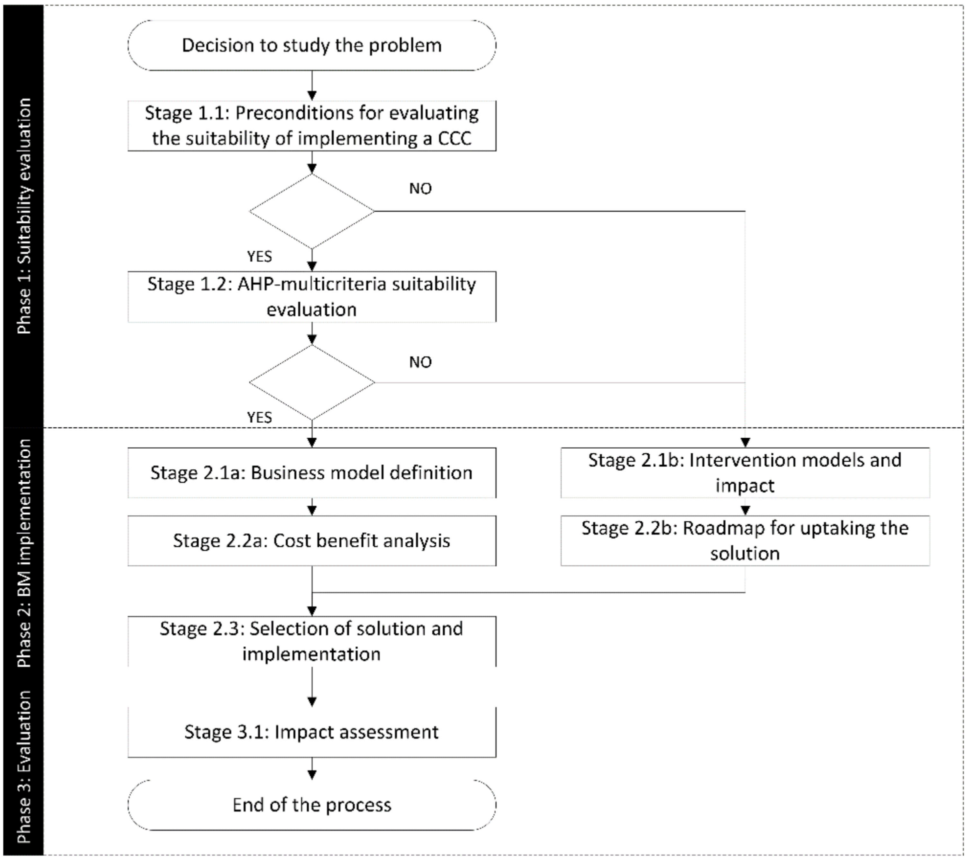

Figure 5. Methodological framework for the integration of construction logistics solutions.

Phase 1 starts by analysing the CCC preconditions and suitability (stages 1.1. and 1.2) as a solution recently supported by policy makers. However, other solutions are also considered if no suitability is identified. Phase 1 is a strategic phase where the involved stakeholders can analyse the global picture during the design and planning stage. Phases 2 and 3 are technically-oriented and require a higher cost (time and resources) for the analysis. Phase 1 makes the analysis process more agile. Next, brief descriptions of phases 2 and 3 are provided.

- Stage 2.1a: BM Definition

This stage starts when the construction site is deemed suitable for CCC implementation (a result of stage 1.2). It includes a literature review of previous UCC and CCC experiences. In addition, the assessment of the identified alternatives is provided. For this, the Canvas BM [54] was selected.

- Stage 2.2a: Cost-Benefit Analysis

This stage involves a cost-benefit analysis. The objective is to guarantee the financial viability of a CCC. This stage was addressed in Guerlain et al. [10] with the development of a Decision Support System. The tool allows the expected benefits of a CCC implementation to be compared with the associated costs. Other approaches have been put forward by Van Duin et al. [55], Nimtrakool et al. [56], and Janjevic and Ndiaye [26], which consider the cost attractiveness of a UCC.

- Stage 2.1b: Intervention Models and Impact

In this paper, the term "intervention model" refers to a set of parameters identified as the most relevant to improve the logistics and supply chain management of a given construction project [10]. This stage starts in the event that no preconditions for evaluating a CCC have been identified (stage 1.1) or no suitability has been identified (stage 1.2). Different models are provided to address challenges in construction logistics, based on the evaluation of the urban area and construction site complexity to assess the logistics profile of the construction site.

- Stage 2.2b: Roadmap for the Uptake of the Solution

The implementation of solutions (i.e., intervention models) at each construction site depends on the challenges, e.g., the needs and constraints as well as resources available [10]. Thus, this stage provides the decision-maker (e.g., construction company or public administration) with additional attributes.

- Stage 2.3: Selection of the Solution and Implementation

This stage starts by applying the choosing by advantages method [57]. It is a decision-making system that supports successful decision-making using comparisons of advantages among alternatives. It is based on five phases: (i) the stage-setting phase, (ii) innovation phase, (iii) decision-making phase, (iv) reconsideration phase, and (v) implementation phase. Thus, if the CCC is suitable, the selection consists of choosing the best BM alternative. Otherwise, the selection is made considering the output of stages 2.1b and 2.2b.

- Stage 3.1: Impact Assessment

The final stage focuses on the definition of Key Performance Indicators (KPIs) and the collection of data related to the implemented solution in a specific context to evaluate its impacts. In this stage, other KPIs provided for the London CCC [5,24] should be considered (e.g., increased transparency along the supply chain and reduced time spent taking inventories), as the solution implemented may be different from a CCC as a result of the suitability evaluation (stage 1.2) and the definition of intervention models and impact (stage 2.1b).

4. Case Study and Results

The suitability study was performed on three construction projects (CP) in three urban locations (Luxembourg City (CP1), Paris (CP2), and Valencia (CP3)) within the framework of the SUCCESS EU project. The construction project in Luxembourg City comprised the transformation and renovation of an old factory into buildings for different uses (office/residential/commercial) in a district situated in a valley. The site was located along the main road of a residential area close to the business district and the airport.

The project in Paris comprised the transformation and renovation of two office buildings. The eight-storey complex was designed to host government departments. The architecture dated back to the 1930s. The site was located in the city centre in a prestigious arrondissement. The project in Valencia comprised the transformation of former railway yards. The four buildings to be refurbished were located in a commercial area of the city centre near the main train station.

Stage 1.1 (preconditions for suitability evaluation) was studied. The main contractor at each site was interested in the implementation of a CCC (P1). The rest of the preconditions were satisfied: site location in an urban area (P2), building construction (P3), and minimum construction activity (P4). Table 3 shows a summary of the construction sites.

Table 3. Characteristics of the CPs.

CP	Site Location (P2)	Type of Activity (P3)	Turnover (€ Million) (P4.1)	Building Size (m^2) (P4.2)
CP1	Residential area in the suburbs	Demolition and renovation	20.8	11,400
CP2	City centre	Demolition and renovation	230	55,475
CP3	City centre	Construction and renovation	15.8	7515

For the application of stage 1.2 (AHP-multicriteria suitability evaluation), the questionnaire designed with 45 indicators was completed by the main contractor. Table 4 shows the results obtained for the three CPs. As can be seen, the suitability of the CCC is only identified in CP2 as the score exceeds the SI fixed to indicate suitability and meet the other requirements defined by the group of experts.

Table 4. Multicriteria suitability evaluation in the three CPs.

CP	C1			C2				C3			C4			Score
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	
CP1	0.252	0.306	0.306	0.516	0.272	0.516	0.086	0.065	0.077	0.516	0.195	0.252	0.554	0.195	0.282
CP2	0.124	0.306	0.592	0.275	0.653	0.750	0.275	0.065	0.416	1.000	0.619	0.510	0.554	0.278	**0.430**
CP3	0.124	0.592	0.306	0.086	1.000	0.516	0.086	0.124	0.416	1.000	0.195	0.510	0.554	0.195	0.356
MT and SI	0.252	0.592	0.592	0.516	0.524	0.516	0.516	0.252	0.554	0.516	0.278	0.252	0.554	0.278	0.427

Note: C1 (Economic); A1 (Savings); A2 (Operational Costs); A3 (Demand level); C2 (Technical); A4 (Construction site characteristics); A5 (Logistics on-site); A6 (Logistics off-site); A7 (Regulation constraints); C3 (Social); A8 (Stakeholders' willingness to cooperate); A9 (Safety); A10 (Wellbeing for residents); C4 (Environmental); A11 (Emissions); A12 (Congestion); A13 (Certifications); A14 (Weather conditions); MT (Minimum Threshold); and SI (Suitability Index). In bold it is shown the result over SI.

CP1 (Luxembourg City) results showed that a CCC implementation was not suitable as the score was below the SI (0.282 < 0.427). Eight attributes (A2, A3, A5, A7, A8, A9, A11, and A14) scored below the recommended levels. Of those, A7, A8, and A9 scored two levels below the recommended levels, while, A2, A3, A5, A11, and A14 scored one level below the recommended levels. The analysis showed that cooperation in the use and operation of the CCC was not needed according to the main contractor. The site is extremely safe in terms of adequate signalling and the low number of road accidents in the city area (less than 200 per year). A low level of emissions (noise pollution and gas emissions) was reported.

On the other hand, CP2 (Paris) was found to be suitable for CCC implementation, as the score obtained was over the SI (0.430 > 0.427). However, six attributes (A1, A2, A4, A7, A8, and A9) scored one level below the recommended levels. The analysis showed that the space available on the site was extremely limited. In addition, the construction site had a fence around the perimeter and entrance access control for vehicles and people, and the construction activities included demolition and renovation activities. Cooperation in the use and operation of the CCC was not needed according to the main contractor.

The CP3 (Valencia) results showed that a CCC implementation was not suitable as the score was below the SI (0.356 < 0.427). Eight attributes (A1, A3, A4, A7, A8, A9, A11, and A14) scored below the recommended levels. Of those, A4, A7, and A14 scored two levels below the recommended levels. A1, A3, A8, A9, and A11 scored one level below the recommended levels. Suppliers are close to the construction site, and travel time in the urban area was very short (less than 15 min). In addition, there was space available on-site for the storage of construction materials, and high security due to several measures being in place (e.g., a fence around the perimeter of the construction site, a security guard, and entrance access control).

The following observations can be made from the results:

- The three CPs scored below the recommended level in A7 (traffic and transportation regulation constraints). This is mainly due to the fact that the respondent (main contractor) considered a low number of constraints (or no constraints) implemented in urban freight transport (I29) in the cities analysed and/or few solutions driven by the Local Authorities (I30).
- The respondents for CP1 and CP2 considered the willingness of one contractor to cooperate and operate a CCC, meanwhile the respondent for CP3 considered that collaboration between the main contractor and hauliers or suppliers was needed (A8).
- Safety in the area (A9) is very high in CP1 and high in CP2 and CP3. This was due to the efforts of the construction companies to implement prevention measures.
- Emissions (A11) in CP1 and CP3 were low in terms of noise pollution and gas emissions. This limits the suitability of implementing a CCC as the benefits in this sense will not be highly appreciated.
- Savings derived from the use of a CCC (A1) were low in CP2 and CP3. This was mainly due to the location of the construction site close to the suppliers, the low costs for contractors, and low material savings.
- Operational costs (A2) in CP1 and CP2 were low in terms of human resources and fixed assets.
- Potential demand level in the area (A3) was regular in CP1 and CP3, mainly due to the turnover at the construction site, the number of several small construction sites that would use the CCC, little time pressure, and a low willingness to pay for extra services.

The analysis performed in the case study comprises the suitability study. This paper proposes a methodological framework for the integration of construction logistics solutions in case suitability is not identified. However, more research is needed toward its application. This step will be addressed in further research.

5. Findings on Sustainability and Technical Pillars

In this section, we outline the findings of the analysis performed on the three CPs from the standpoint of the economic, social, environmental (sustainability), and technical pillars.

5.1. Economic

The savings (A1) derived from the implementation of a CCC in CP1 ranked higher than in CP2 and CP3 (0.252 > 0.124). This was due to a greater distance to the supplier location (I1), time to access the construction site (I2), and medium cost of lost pallets (I4) and material savings (I6), which are low in CP2 and CP3. Policy support for CCC implementation (I3) was only provided in CP2. The cost of unsorted bins (I5) was low in the three CPs.

The estimated operational costs (A2) of the construction company were ranked as regular in CP1 and CP2 (0.306) and high in CP3 (0.592). Compared to CP2 and CP3, CP1 lacked an in-house construction waste manager, in-house logistics team, and outsourced construction waste manager (I7). CP3 was highly equipped in terms of buildings, vehicles, and equipment (I8). Meanwhile, the logistics costs in the overall budget (I9) were medium in CP2 and low in CP1 and CP3.

The potential demand level in the area (A3) was ranked high in CP2 (0.592) compared to CP1 and CP3 (regular). The turnover was high in CP2 (I10), at between 100 and 250 million euros, where at least one large construction site would accept the use of a CCC (I11), and the development project was considered extremely time-constrained (I12). In addition, CP2 was the most willing to pay for additional services (I13) compared to CP1 and CP3. The three respondents considered a positive growth rate of the company (I14).

5.2. Technical

Construction site characteristics (A4) were ranked as regular in CP1, high in CP2, and very high in CP3. Nevertheless, the higher the level of this attribute, the less suitable the implementation of a CCC. Storage capacity (I15) was extremely limited in CP2. However, several cranes were available on-site to handle materials (I16) from the truck, while only one was available in CP1 and CP3. The highest Security (I17) measures were taken in CP3, followed by CP2 and CP1. The building size (I18) was bigger in CP2 (50,000 to 200,000 sqm). The nature of construction activities (I19) is defined in Table 2.

The logistics complexity on-site (A5) ranked very high in CP3, high in CP2, and low in CP1 (1.000 > 0.653 > 0.272). CP1 had no restrictions limiting vehicle access (I20), where one fixed delivery area (I21) remained available throughout the entire project duration, unlike CP3, where there was enough space on-site for an ad-hoc delivery area. Access to the site (I22) in CP2 and CP3 was via two entrance and exit gates (one in CP1). The main contractor moderately centralized the logistics resources (I23) in CP1, and mostly centralized them in CP2 and CP3. On the other hand, Logistics off-site (A6) was ranked high in CP2 and CP3, and regular in CP1 (0.750 > 0.516).

The construction site was located (I24) in the suburbs in CP1 and in the city centre in CP2 and CP3. The three cities have different Topography (I25): Luxembourg City is characterized by medium slopes, Paris has a flat topography, and Valencia a very flat topography. In addition, Luxembourg has an irregular road organization (I26) with several small construction sites in the neighbourhood (I27), as in Valencia. The organization of the roads in Paris is concentric. There are no other construction sites operated by the same contractor (I28) in CP1, several small ones in CP2, and several large ones in CP3.

Traffic and transportation regulation constraints (A7) ranked low in CP2, and very low in CP1 and CP3 (0.275 > 0.086). Several constraints in urban freight transport (I29) were implemented in CP2 and CP3, and solutions driven by the local authorities for urban freight distribution (I30) included renting public space for temporary loading/unloading in Paris, in addition to blocking streets temporarily in Luxembourg City, and traffic lights to regulate delivery vehicle access to the road.

5.3. Social

Stakeholder willingness to cooperate in the use and operation of a CCC (A8) ranked low in CP3 and very low in CP1 and CP2 (0.124 > 0.065). Only the respondent in CP3 considered the collaboration of one contractor with hauliers or suppliers necessary (I31). Safety in the area (A9) ranked high in CP2 and CP3, and very high in CP1. This limits the need for a CCC. The three CPs have implemented adequate signalling measures (I32). CP1 presents the lowest level of road accidents in the city area (I33).

The three CPs all have a low number of accidents within the construction site (I34). Finally, Wellbeing for residents (A10) ranked as very high in CP2 and CP3, and as regular in CP1 (1.000 > 0.516). The highest population density (I35) was found in CP2 (more than 10,000 inhabitants/sqm). A CCC has high public acceptance (I36) in CP2 (moderate in the other CPs). The urban areas in CP2 and CP3 were very sensitive to construction activity (I37).

5.4. Environmental

Emissions (A11) were ranked as high in CP2 compared to low in CP1 and CP3 (0.619 > 0.195). The high level is due to moderate noise pollution during day (I38), and a high level of gas emissions (I39). Congestion in the area (A12) was ranked as high in CP2 and CP3 compared to moderate in CP1 (0.510 > 0.252) due to a high traffic level in the area (I40), and a high number of inhabitants (I42)—more than 500,000 inhabitants. The highest surface occupation (I41) was found in CP1 and CP2 (between 5000 and 20,000 ha).

The three CPs had the same ranking (regular) in terms of certifications in construction (A13), with one certification (I43). Finally, the weather conditions (A14) were more favourable for CCC implementation in CP2 than in CP1 and CP3 (0.278 > 0.195 > 0.066). CP3 did not have any special climate severity conditions (I44), and had less than 5 days without construction activity due to bad weather conditions (I45).

The true value of this analysis, in addition to the measurement of suitability that can be used during planning and design stages, is the extraction of knowledge. It provides the stakeholders with a better understanding of the problem in terms of economic, social, environmental (sustainability), and technical criteria.

6. Discussion and Conclusions

Transport in the construction industry can be identified as one of the main contributors to pollutant emissions due to the high number of freight movements in cities. A CCC is a logistics solution that improves the performance of construction logistics and reduces the negative socio-economic and environmental impacts of urban deliveries, by reducing the congestion, energy use, and emissions and improving the working environment.

This paper provides a multicriteria method and an index (SI) based on the AHP to measure the suitability of CCC implementation based on the sustainability pillars, in combination with a technical pillar through 45 indicators. It can be applied in any urban context. In addition, it proposes a general framework for the integration of other construction solutions in the event that a CCC is not suitable. By doing this, the paper addresses one of the future directions of decision-making in construction supply chain management as identified by Le et al. [11]: the support of logistics-based planning at the early phases of planning and design.

Case studies for the suitability study in this paper were related to three existing construction projects in various urban locations in Europe: Luxembourg City, Paris, and Valencia. The analysis showed that a CCC was only suitable for the construction project in Paris, as this was the only construction project that surpassed the recommended SI (0.430 > 0.427). In this construction project, five attributes were over the recommended levels: A5 (logistics on-site), A6 (logistics off-site), A10 (wellbeing for residents), A11 (emissions), and A12 (congestion in the area). In the cases of Luxembourg (0.282 < 0.427) and Valencia (0.356 < 0.427), according to this analysis, the main contractor should increase the potential level in the area (A3) by targeting larger projects (I10) or addressing several construction projects (I11).

At both construction sites, a low level of noise and gas emissions was observed (A11), limiting the suitability of the CCC. The estimated operational costs (A2) of the construction company were very high in Paris, and regular in the other two cases. This shows that logistics is very important in the overall budget of the company operating in Paris. In addition, the respondents to the questionnaire considered the main contractor as the only stakeholder involved in the operation of the possible CCC implementation (A8) in Luxembourg and Paris; however, for Valencia, the respondent included hauliers or suppliers in collaboration with the main contractor.

This may impact the success of this initiative as collaboration between stakeholders has been identified as necessary for its success [26]. The wellbeing of residents derived from the implementation of a CCC (A10) was recognized (very high category) in Paris and Valencia. However, in Luxembourg City, it was classified as regular. This may be because of the low population density in the city, a moderate acceptance of the scheme, and a moderate environmental sensitivity.

The research carried out provides the stakeholders with a user-friendly tool to identify the suitability of implementing a CCC in urban areas, which is linked to the development of one or more construction projects that involve building construction, and a better knowledge of their impact in terms of sustainability. Two critical attributes were identified in the construction project evaluation: the estimated operational costs of the construction company (A2) and potential demand level in the area (A3).

Managers of construction companies will benefit in terms of better knowledge of the sustainability of the construction project through the analysis of the 14 attributes and 45 indicators. In particular, we observed from the case studies that, for Paris—the only CP suitable for CCC implementation—no attributes were two levels below the recommended thresholds; however, sustainability (economic, social, and environmental) and technology needed to be improved.

The construction site characteristics (A4) of Valencia negatively impacted its suitability as they ranked in the very high category (storage capacity, handling equipment, and security). Furthermore, traffic and transportation regulation constraints (A7) ranked very low in Luxembourg and Valencia. Although this methodology is specific to the construction industry, some indicators can be adapted to other areas of activity. Furthermore, the methodology could be used at a larger scale than a city.

The limitations of this research are mainly linked to the context of application (Europe). Different findings may be obtained in other geographical, regulatory, and social contexts. In addition, for all three cases, the respondents represented the main contractor. Responses in collaboration with other stakeholders could have slightly varied the results. More research is needed to help stakeholders throughout the three integration stages of construction logistics solutions.

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