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A Combined Multi-Criteria Decision-Making and Social Cost–Benefit Analysis Approach for Evaluating Sustainable City Logistics Initiatives

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Abstract: Decision making in city logistics (CL) is complex due to the numerous concepts and alternatives, as well as the intricate relationships between measures and effects. This study introduces a novel approach to evaluating urban freight transport (UFT) by combining multi-criteria decision making (MCDM) and social cost–benefit analysis (SCBA). This combination aims to improve decision making for sustainable CL concepts, particularly in reducing externalities in last-mile delivery. The model assesses various CL initiatives and urban consolidation center (UCC) concepts for their impact on UFT externalities. It uses the MCDM for ex ante scenarios assessment and prioritization. Input data were collected through a survey of experts from various sectors, and the Analytic Hierarchy Process (AHP) was applied in the case study of Novi Sad, Serbia. The prioritization highlighted the significance of implementing restrictive regulatory measures, alternative transport modes, and operational optimization within UCC concepts. By estimating capital, operational, and external costs, SCBA was applied to the prioritized UCC concepts, which were then further evaluated using the SCBA outputs. Sensitivity analysis was employed to assess the robustness of the proposed model. This paper offers valuable insights into the potential use of existing tools within a hybrid model to enhance decision making in CL.

Keywords: sustainable city logistics; urban freight transport; urban consolidation centers; initiatives; external costs; multi-criteria decision making; social cost–benefit analysis

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1. Introduction

With the growing urban population and increased demand for goods, the negative impacts of freight transportation have become increasingly prominent. These challenges are particularly critical in urban areas, where they directly affect quality of life. As a result, a rising number of both academic and empirical investigations have focused on the environmental and other adverse effects of urban freight transport (UFT). Consequently, sustainable goals in UFT development have been introduced at global (UNCTAD Sustainable Freight Transport Framework [1]) and European levels (Green Deal [2]). Sustainability aims to balance between economic growth, environmental goals and society wealth [3]. However, conflicts often arise between these objectives and among stakeholders involved in sustainable city logistics (CL) development [4].

In recent years, numerous sustainability initiatives in freight transportation have been implemented in Europe [5], with urban consolidation centers (UCCs) gaining particular attention [6]. UCCs enable goods to be delivered in an environmentally friendly manner to specific urban or suburban areas, or particular places (shopping centers, construction sites, etc.). Despite their potential to enhance sustainability, UCCs often face substantial challenges, leading to operational failures [7]. Key issues include financial inefficiencies, insufficient freight volume, limited stakeholder involvement in planning and decision making, inadequate fleet selection, and suboptimal UCC locations [8–10]. Moreover, implementing UCCs independently does not necessarily result in a sustainable or competitive CL system [11]. However, UCCs facilitate the cohesive implementation of other CL initiatives, commonly referred to as UCC concepts, maximizing synergistic effects and mutual benefits [6,12].

The process of selecting appropriate UCC concepts is further complicated by the diverse range of additional CL initiatives and scenarios, each with unique implications. Research shows that a one-size-fits-all solution for mitigating UFT's negative externalities and creating a sustainable CL system is unlikely [13]. This complexity has led to a variety of approaches and solutions in the literature, emphasizing the need for tailored strategies that consider local contexts and specific stakeholder needs [14–16]. Multi-criteria decision-making (MCDM) methods, for instance, offer robust frameworks for addressing complex relationships among decision criteria. Social cost–benefit analysis (SCBA), on the other hand, evaluates the overall societal impacts of CL initiatives from a financial perspective [17], considering direct, indirect, and external costs (ECs). ECs, as an essential component of SCBA, provide decision makers with comprehensive insights into the sustainability implications of UCC concepts.

While MCDM approaches are widely used for prioritizing CL initiatives, they rely on subjective assessments, leaving the quantitative evaluation of costs inadequately addressed. Conversely, SCBA studies focus on monetizing effects but often fail to account for multiple CL initiatives and scenarios in a systematic manner. This fragmentation highlights the need for a hybrid approach that integrates MCDM and SCBA to bridge the gap between qualitative prioritization and quantitative economic evaluation. Such an approach enables the derivation of multiple benefit–cost ratios, supporting sustainable decisions and addressing the complexities of CL initiatives.

Surprisingly, the hybrid use of these techniques in evaluating CL initiatives remains underutilized. Some previous studies have demonstrated the value of combining these methods in transport project appraisals to address economic, strategic, and sustainable impacts systematically and transparently. For instance, Barfod et al. [18] presented a composite model that integrates MCDM and SCBA, showcasing its effectiveness in supporting complex transport project decisions by ensuring systematic and transparent assessments. Similarly, Guhnemann et al. [19] highlighted how incorporating SCBA results into an MCDM framework facilitates consistent project prioritization, links appraisals to policy goals, and enhances stakeholder confidence through robust sensitivity analyses. Furthermore, Barfod and Salling [20] developed a decision support framework combining MCDM and SCBA for transport infrastructure projects, demonstrating its ability to simultaneously address economic, strategic, and sustainability considerations. These studies underscore the potential of hybrid models to enhance decision-making processes.

Building on this foundation, this paper aims to propose a combined MCDM–SCBA model, providing comprehensive support for decision makers in selecting UCC concepts for sustainable CL planning. The main contribution of this research lies in enhancing the application of SCBA to enable a thorough evaluation of the financial viability and sustainability of diverse UCC concepts and scenarios. Furthermore, the proposed model contributes to the existing literature by addressing the intersection of environmental and economic domains, highlighting the necessity for stronger integration between these areas in both sustainable UFT research and practical applications.

The structure of this paper is as follows. Section 2 presents the research background and literature review, focusing on the ECs of UFT, MCDM models for CL decision making, and SCBA analysis of UCC concepts. Section 3 outlines the proposed model and research methodology. Section 4 describes the application of the model in a case study, along with the presentation and discussion of the main results. In Section 5, the robustness of the model is tested through sensitivity analysis. Finally, Section 6 provides concluding remarks, discusses limitations, and offers recommendations for future research.

2. Research Background

The most significant negative effects of transportation include traffic congestion, air pollution, climate change, noise, and traffic accidents [21]. In addition to these primary effects, there are other negative impacts, such as water and soil pollution, damage to landscapes and nature, the effects of fuel production and consumption, and visual disturbances [22,23]. Many costs associated with the negative effects of transportation, like healthcare expenses resulting from air pollution-related illnesses, are not solely borne by parties involved in transportation. Third parties also incur costs due to the consequences of these externalities, which are referred to as ECs. These costs are defined as those that arise when the social or economic activities of one group impact another group without full compensation or accountability from the originating group [24,25]. This definition indicates that ECs of transport are the costs borne by "others", which can be neighbors, fellow citizens, the rest of the state, continent, the entire world, or even future generations [26].

The ECs generated by urban freight transportation are typically influenced by variety of factors, including the characteristics of the urban distribution network (e.g., location, distance, and number of nodes), network activities (goods and passenger movements), vehicle type and technology, urban traffic regulations, service levels, and basic costs (e.g., land, fuel, and electricity prices) [26]. Additionally, ECs of freight transport depend on vehicle technology (such as the emission class of the propulsion system), the frequency and severity of accidents, congestion caused by freight vehicles, and other related factors.

UCCs are recognized as a key initiative in CL, with a critical role in mitigating the ECs of UFT [27–29]. The purpose of UCCs is to collect shipments from various senders (i.e., carriers or logistics operators), sort, consolidate, and deliver them using environmentally friendly vehicles in a systematic and organized manner. Allen et al. [30] define UCCs as: "A logistics facility situated in relatively close proximity to the geographic area that it serves (be that a city centre, an entire town or a specific site such as a shopping centre), to which many logistics companies deliver goods destined for the area, from which consolidated deliveries are carried out within that area, in which a range of other value-added logistics and retail services can be provided". This definition underscores the potential of UCCs in reshaping urban freight operations and reduce ECs.

The broader objective of UCCs is not only to consolidate freight flows and reduce the number of vehicles entering the city but also to control the type and structure of the local vehicle fleet and organize local deliveries. This approach enables more effective management of UFT externalities, leading to improved environmental and societal outcomes [31]. Anticipated benefits include reduced traffic congestion, improved air quality, minimized conflicts at loading sites, enhanced safety, heightened service standards for urban recipients, expanded service offerings, increased sales areas for retailers, reduced operational costs, optimized inventory management, improved staff motivation, and mitigation of theft incidents [28,32–34].

Despite their potential benefits, the impacts of UCCs on ECs in UFT remain underexplored in the literature [35]. This gap is notable given their relevance in reducing negative externalities. Dupas et al. [36] emphasized that one of the key limitations in academic studies on UCC implementation is the inadequate assessment of environmental and social economic costs, i.e., ECs. Although some scientific papers address the estimation of ECs within the context of CL, few encompass multiple categories comprehensively. Most studies focus on emission-related ECs, while other categories, such as noise, traffic congestion, and accidents, are often overlooked.

For example, Alessandrini et al. [37] conducted an assessment of the ECs of emissions (CO_2, HC, NOx, PM, and SO_2) and fuel consumption (energy) for three intermodal UCC scenarios. Their findings demonstrated significant savings in ECs, particularly when hybrid vehicles were utilized (82%), highlighting the potential of advanced vehicle technology in reducing ECs. Similarly, Estrada and Roca-Riu [38] assessed the ECs for different distribution strategies (individual distribution and distribution via UCC) and scenarios (electric vehicles, electric cargo bikes, and electric cargo bikes + road freight vehicle restriction zone), concluding that UCCs could achieve daily EC reductions, especially when paired with electric cargo bikes and vehicle restrictions. Katsela et al. [39] provided further evidence of the EC reduction potential of UCCs in scenarios involving micro terminal consolidation, emphasizing a 75% EC reduction for the UCC + micro terminal case. These findings reinforce the importance of systematically including ECs in decision-making processes.

Incorporating ECs as a parameter in decision making allows for the comprehensive expression of all external impacts in monetary terms. The systematic calculation and integration of ECs into decision-making frameworks are pivotal, as they offer an opportunity to holistically evaluate and transparently communicate social and environmental impacts. This approach ultimately fosters greater stakeholder acceptance of investments [40]. Integrating freight flow simulation with urban freight planning is essential for accurately evaluating these impacts. Studies have shown that simulation models can effectively assess the effects of urban consolidation centers and off-hour deliveries on freight dynamics, enabling planners to develop more effective policies to enhance sustainability and reduce congestion [41–43]. To accurately capture vehicle-kilometer data, it is essential to integrate the EC model with a UFT model. Several studies, such as Filippi et al. [44], emphasize this integration as crucial for evaluating the consequences of policy changes. By incorporating UFT models and simulation tools, it becomes possible to predict how different logistics strategies impact transportation activity, thereby enabling a more precise estimation of ECs and supporting informed decision making in urban logistics.

Given the multitude of potential UCC concepts, it is imperative to select initiatives with UCCs within the urban setting under observation. CL literature frequently employs MCDM methods to evaluate UCC concepts due to their capacity to systematically assess and prioritize diverse criteria. Many MCDM models have been developed to address the numerous alternatives and intricate relationships involved in the sustainable CL decision-making process. These include AHP, ANP, MAMCA, DEMATEL, VIKOR, TOPSIS, PROMETHEE, DELPHI, REMBRANDT, WASPAS, CODAS, SWARA, FDMM, FMAGDM, and others. Fuzzy logic is often integrated into these models to address ambiguity in stakeholder preferences. For example, Gallo and Maheut [45] identified AHP hybrid and MAMCA as the most commonly utilized methods in MCDM applications. In addition, Jardas et al. [46] recently used MAMCA to evaluate implementation of UCCs and environmentally friendly vehicles in the city of Rijeka, Croatia. However, a key limitation lies in the lack of correlation between the objectives of these models, resulting in substantial differences in their intended purposes.

MCDM models primarily rely on qualitative criteria and do not directly address ECs. Tadić et al. [47] proposed an MCDM model that addresses factors related to external effects such as natural resources, habitats, and air pollution; however, it does not explicitly account for all external effects or the ECs associated with transportation. Additionally, the criteria outlined in Simić et al. [48], such as air emissions, noise pollution, resource consumption, public health, and public space usage represent the externalities discussed in their paper. These studies do not incorporate a direct estimation of the ECs associated with these externalities. The authors Lasota et al. [49] developed a model for urban delivery planning that integrates the Traveling Salesman Problem (TSP) with MCDM, focusing exclusively on emissions of harmful compounds among all externalities. The most relevant paper on MCDM for this research is presented by Perera and Thompson [50]. In their study, the authors considered ECs as environmental costs (emission and noise costs) and social costs (crash, congestion, and infrastructure costs) among other criteria in the MAMCA evaluation method. However, this study lacks a clear and systematic linkage between ECs and sustainable CL initiatives.

SCBA is used to assess the attractiveness of a given project by obtaining net present value, considering both financial and environmental aspects [51]. Decision makers often employ social cost–benefit analysis but frequently in a non-decisive manner [52]. Recent research has highlighted the importance of integrating stakeholder perspectives and sustainability considerations into SCBA frameworks to enhance decision-making processes in urban freight planning [14,53]. Studies have also suggested that effective SCBA should incorporate comprehensive assessments of environmental externalities and operational efficiencies associated with UCCs to better inform policy and investment decisions [15,54]. This holistic approach can aid in addressing the complexities inherent in urban freight systems and contribute to more sustainable outcomes [55,56].

When applied to the consolidation concept, SCBA should account for both private costs and ECs to provide a balanced evaluation [57]. The literature on the SCBA of UCCs is relatively scarce [7,58]. Kin et al. [7] evaluated ECs related to air pollution, climate change, noise, accidents, and congestion. The findings indicated that UCCs yield positive societal effects when only external effects are considered. The overall cost–benefit trade-off becomes negative when private costs are included. This study primarily assessed the operation of UCCs but did not explore decision making related to other CL initiatives and alternatives. The challenge of creating a business model that effectively aligns environmental, economic, and operational needs for UCC implementation while addressing the diverse interests of stakeholders remains a significant [59].

Despite numerous studies and several EU projects, such as BESTUFS, C-LIEGE, GRASS, NOVELOG, and STRAIGHTSOL, that have addressed decision making on CL initiatives and their externalities [60,61], few have integrated MCDM and SCBA to evaluate various CL concepts comprehensively. The STRAIGHTSOL project [62], for instance, combined three methodologies: SCBA, business model analysis, and MAMCA. While this approach merges MCDM and SCBA, it does not focus primarily on externalities and ECs, only partially addressing these issues without a systematic approach. In contrast, the NOVELOG project utilized a more holistic evaluation framework that incorporated multiple methodologies, including impact assessment, SCBA, transferability and adaptability analysis, and risk analysis. This comprehensive approach integrated behavioral modeling, enhancing the evaluation of diverse urban logistics concepts. The SCBA in the NOVELOG project includes ECs related to congestion, air pollution, climate change, accidents, and noise, as well as impacts on employment and development. However, a notable limitation is that capital and operational costs are not reflected in the SCBA output, highlighting areas for further refinement. Furthermore, recent literature emphasizes the need for integrating stakeholder engagement within these frameworks to ensure that diverse perspectives are considered in the evaluation of urban logistics initiatives [14,63].

3. Methodology and the Model

The structure of the proposed MCDM–SCBA model is illustrated in Figure 1. The first step involves prioritizing additional CL initiatives within UCC concepts. This is achieved by assessing their effectiveness in reducing UFT externalities in the specific urban area under consideration. This component of the model is not intended to identify the optimal UCC concept. Instead, its purpose is to rank UCC concepts based on their potential to reduce externalities of UFT. Second, decision makers set the parameters for the most significant UCC concepts. By utilizing the urban transport model and the recommended methodology, the ECs of UFT are estimated. Finally, an SCBA is performed for each evaluated alternative, aiding and streamlining the final decision making.

The widely used AHP technique [64] provides a straightforward MCDM approach for ranking UCC concepts based on their effectiveness in mitigating UFT's negative impacts. Applying AHP requires systematic selection of UCC concepts suitable for a specific urban context, as the growing number of CL initiatives increases data preparation time, making extensive analysis challenging. To address this, a thorough literature review was conducted using academic databases, municipal websites, and other online resources, focusing on initiatives integrated with UCCs. Keywords such as urban logistics initiatives, urban consolidation centers, city logistics, urban freight transport, and related variations were used. Table 1 summarizes the classification, highlighting five key UCC concepts essential for reducing UFT's adverse effects.

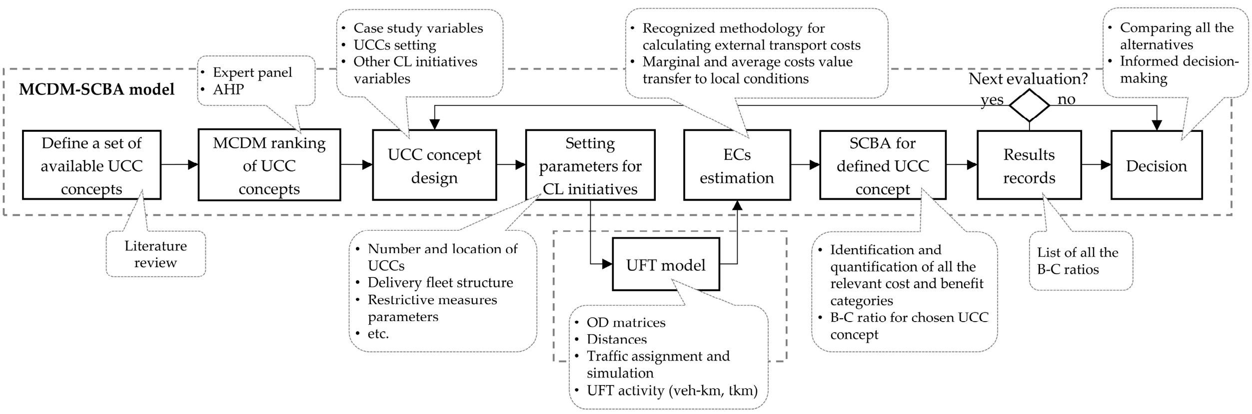

Figure 1. The structure of the proposed model.

Table 1. Key UCC concepts for mitigating the externalities of UFT.

UCC Concept	CL Initiative	Source
UCC + Alternative UFT vehicles	Electric delivery vehicles	[10,33,59,65–68]
	Cargo bikes and tricycles	[67,69–71]
	Transition to smaller trucks	[10,72]
	Drones	[71]
	Cargo trams	[21]
	Other alternative vehicles	[21,73]
UCC + Time windows	Off-peak deliveries	[73–77]
	Night deliveries	[28,72]

Table 1. *Cont.*

UCC Concept	CL Initiative	Source
UCC + Restrictive and regulatory measures	Restrictions of vehicle movements (in a certain part of the city area, for certain types of vehicles, in certain time periods, for vehicles below the defined threshold of the vehicle's load capacity)	[8,15,21,59,72,73,76,78–80]
	Restriction on stopping of trucks for loading/unloading	[21]
	Charge for entering a certain zone	[80]
	Designated areas for off-street (un)loading	[21]
UCC + Incentives	Subsidies for the work of UCC	[7,35,76]
	Subsidies for carriers	[59,80]
	Subsidies for users of UCC services	[76]
UCC + Other CL initiatives	Collection of returns	[34]
	Satellite terminals	[33,81]
	Optimization at the operational level	[82]
	Value-added services	[34,35]
	Application of modern IT solutions	[21]

The input data required for applying the AHP technique were gathered by convening an expert panel comprising professionals from various relevant fields, including urban traffic planning, traffic flow management, urban freight transportation, and logistics, as well as scientific researchers. Expert opinions were collected through a questionnaire survey. The questionnaire was organized into three sections to align with the requirements of the AHP technique:

- Section 1—Collects basic information about the respondent;
- Section 2—Evaluates the relative significance of the adverse impacts of UFT;
- Section 3—Assesses the relative importance of various alternatives, such as different UCC concepts.

Ultimately, it is essential to set the parameters for the UCC concept, calculate the ECs of UFT, and conduct the SCBA analysis. For the ECs calculation, the Handbook on the external costs of transport [83] was consulted. To ensure relevance and accuracy, a transparent value transfer mechanism was employed, using GDP per capita as the adjustment factor to align unit external cost values with the Serbian context. Given that Serbia's GDP per capita is approximately one-third of the EU-27 average, unit costs were proportionally adjusted to the study area. In the SCBA, the costs and benefits categories were defined. UCC concepts involve significant capital expenditures (CAPEX) and operational expenditures (OPEX), which can vary depending on the strategies and technologies employed [7]. CAPEX typically includes investments in infrastructure development (such as UCCs construction or rent costs), technology investments (like IoT, AI, and automation systems for efficient logistics operations), and fleet acquisition (such as purchasing or leasing vehicles for urban deliveries). OPEX primarily covers fuel and energy costs (including fuel for conventional vehicles and electricity for electric delivery vehicles and forklifts), maintenance and operations (such as repairs, utilities, and staffing), and labor costs (wages for drivers, warehouse staff, and logistics coordinators).

Additional initiatives that complement UCC implementation may incur capital expenditures. For example, these could include constructing new loading and unloading zones or installing solar panels to reduce long-term operational expenses. Moreover, operational costs may arise from the maintenance of facilities and infrastructure, as well as IT support and system upgrades. These additional CL initiatives were accounted for in both the CAPEX and OPEX parts of the SCBA. Beyond these, it is crucial to consider external effects in the SCBA analysis, as the primary goal of CL initiatives is to reduce externalities. Including these factors provides decision makers with an essential metric for making informed decisions and effectively communicating the benefits of CL initiatives to stakeholders and other relevant parties.

The main benefits of the UCC concept include UCC revenue (such as fees charged to retailers or logistics companies for using the consolidation services) and UCC subsidies (funds provided by the government or local authorities to incentivize the success of the CL initiative). The structure of the SCBA categories is as follows:

- CAPITAL (infrastructure development, fleet acquisition, and additional CL initiatives CAPEX),
- OPERATIONAL (fuel and energy, labor, UCC revenue, UCC subsidies, additional CL initiatives OPEX), and
- EXTERNALITIES (noise, congestion, road safety, air pollution, climate change, up- and downstream processes, and habitat damage).

The steps of defining the parameters, calculating the ECs, and performing the SCBA must be iterated until all relevant alternatives are considered and all necessary results for decision making are achieved.

4. Results and Discussion

The AHP hierarchy (goal–criteria–alternatives) for ranking additional CL initiatives to form UCC concepts is presented in Figure 2. The criteria for evaluating initiatives are based on the negative effects of UFT, while the considered alternatives are detailed in Table 1. These alternatives represent key UCC concepts identified through an extensive literature review focused on mitigating the externalities of UFT. The literature review provided a foundation for selecting the most relevant initiatives for evaluation and inclusion in the model.

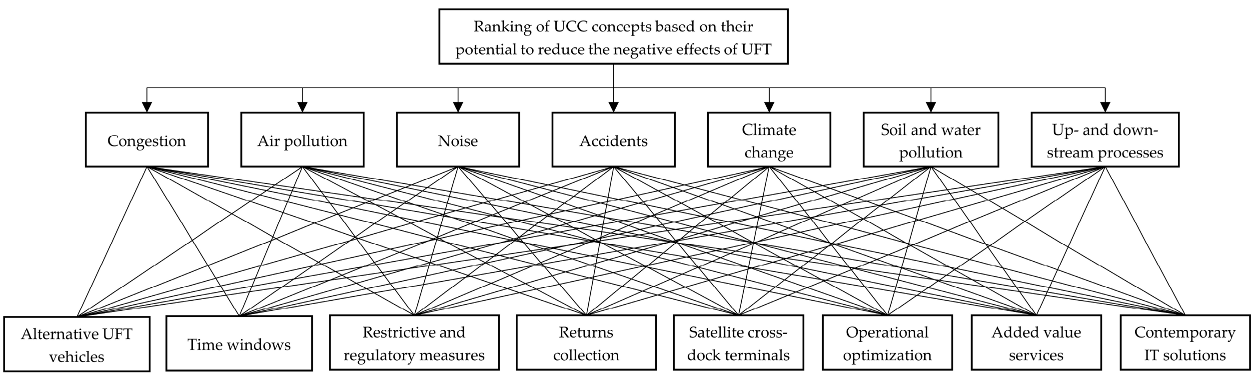

Figure 2. The hierarchy for ranking CL initiatives based on their impact on UFT's external effects.

Novi Sad, Serbia, was chosen as the urban area for the case study. Experts familiar with UFT operations in Novi Sad were grouped into four groups:

- Municipal administration and traffic planners;
- Retail chains, carriers, and courier services;
- Traffic designers;
- Academia.

A total of 22 experts participated in the survey, with an average professional experience exceeding 15 years. The breakdown of respondents by sector is as follows: 36% from academia, 23% from municipal administration, 18% from retail, carrier, and courier services, and 23% from the traffic design sector. The experts conducted pairwise comparisons in the presence of a member of the research team, whose role was to clarify any uncertainties the experts might have had. This approach helps minimize the possibility of misinterpretation regarding specific criteria or alternatives being compared.

For the AHP analysis, we used the Superdecisions tool (version 3.2.0). The overall inconsistency ratio of the model is 0.02333, indicating that the degree of consistency within the AHP is acceptable. It is worth noting that some outliers needed to be corrected to improve the consistency ratio, but the required interventions were minimal and had a negligible impact on final results. The AHP results, outlined in Table 2, shows that experts prioritize certain UCC concepts for mitigating the adverse impacts of UFT in Novi Sad. These primarily include restrictive and regulatory measures, alternative transport modes, and operational optimization.

Table 2. Results of ranking additional initiatives for UCC concepts by their relative importance in reducing the negative effects of UFT.

Alternatives	Normalized Value	Rank
Restrictive and regulatory measures	0.201410	1
Alternative UFT vehicles	0.194143	2
Operational optimization	0.134063	3
Time windows	0.124678	4
Contemporary IT solutions	0.107698	5
Returns collection	0.101050	6
Satellite cross-dock terminals	0.096741	7
Added value services	0.040217	8

According to the presented results, a potential UCC concept for this case should include restrictive and regulatory measures, as well as distribution using alternative UFT vehicles, such as electric delivery vehicles. Additionally, opportunities for optimizing freight flows at the operational level, introducing time windows, and implementing modern IT solutions should be considered.

ECs of UFT are calculated through simulations across various scenarios. These scenarios include different numbers of UCCs, various strategies for attracting goods to UCCs, differing characteristics of restriction zones, varying proportions of EVs for last-mile deliveries, and different levels of night deliveries. The input data for EC calculation, such as OD matrices of vehicle and goods movements, are sourced from the Novi Sad Transport Model (NOSTRAM). The data include 3498 freight vehicles entering the inner city daily, consisting of 69% light commercial vehicles and 31% heavy commercial vehicles. Collectively, these vehicles transport 10,285.12 tons of goods each day, with 38% of deliveries taking place during peak hours. The impact of the UCC concept on key UFT performance indicators, like vehicle-kilometers traveled by vehicle size, type, and fuel, is simulated by an Excel 2019 macro-based tool programmed in VBA. This tool is designed to be user-friendly for decision makers (the user interface is shown in Figure 3). The utilization of the tool is not constrained by computer resources, allowing for smooth operation across various systems. However, the data collection process is a more resource-intensive task, requiring careful planning and allocation of efforts.

Table 3 summarizes the effects of various UCC concepts on UFT ECs, highlighting their potential to decrease or increase external costs.

An SCBA of all considered alternatives is conducted to guide the final decision on sustainable CL projects by providing benefit–cost ratios (B–C ratios). Input data needed for the SCBA analysis are local market prices, such as fuel per liter, electricity per kWh, UCC investment per m^2, delivery vehicle acquisition per vehicle, and unloading space price per m^2 and percentage of subsidies for the UCC. In this paper, we assumed that subsidies would fully cover UCC operational costs during the year of implementation. This is expected to decrease in the future. Table 4 presents SCBA results for one sample UCC scenario.

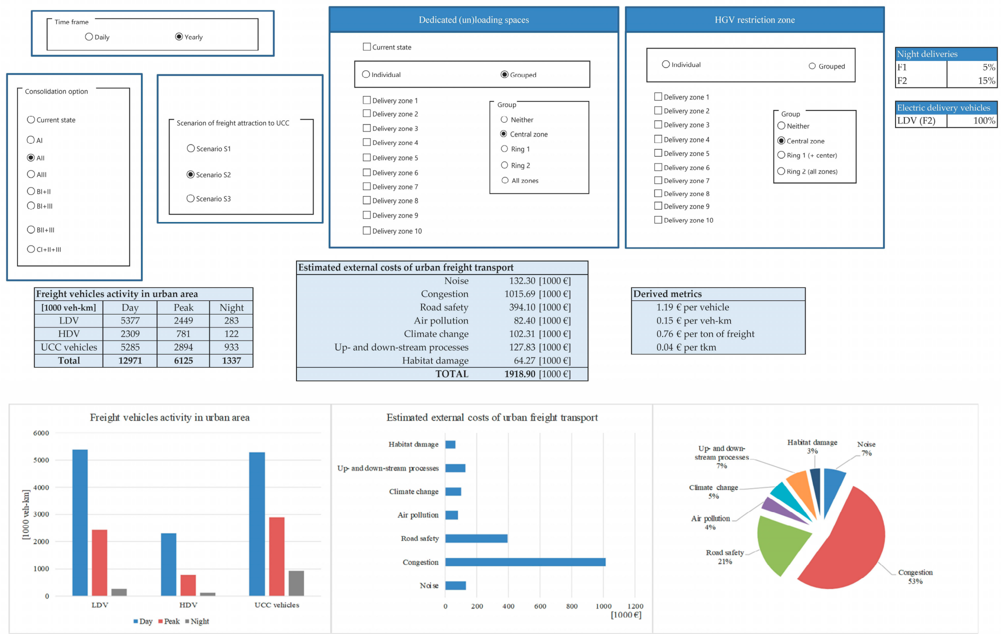

Figure 3. Example of EC estimation for a selected UCC concept (dashboard).

Table 3. Effects of UCC concepts on UFT ECs.

UCC Concept	Major Decrease	Median	Major Increase
UCC + HGV restriction zone	−10.0%	+53.3%	+129.0%
UCC + Dedicated (un)loading spaces	−77.4%	−47.2%	+8.4%
UCC + Electric delivery vehicles	−28.4%	+16.7%	+107.4%
UCC + Night deliveries	−91.9%	−52.1%	+38.9%

Table 4. Sample SCBA results for selected UCC scenario.

CAPITAL	Type	Amount [1000 €]
Infrastructure development	Cost	2018.48
Fleet acquisition	Cost	68.40
Additional CL initiatives CAPEX	Cost	0.00
OPERATIONAL		
Fuel and energy	Cost	2063.34
Labor	Cost	24.54
UCC revenue	Benefit	−102.23
UCC subsidies	Benefit	−2087.88
Additional CL initiatives OPEX	Cost	0.00
EXTERNALITIES		
Noise	Cost	17.47
Congestion	Cost	50.33
Road safety	Benefit	−3.42
Air pollution	Benefit	−89.14
Climate change	Benefit	−100.53
Up- and downstream processes	Cost	29.84
Habitat damage	Benefit	−15.89
	B–C ratio	**0.56**
	B–C ratio (without ECs)	**0.52**

The proposed model is designed for what-if analyses of sustainable CL concepts relative to the current state. It is important to note that some categories in the SCBA may shift from a benefit to a cost depending on the scenario. For example, in a UCC + Night Delivery concept, noise costs may increase, turning it into a project cost. Conversely, in a UCC + electric delivery vehicles concept, low-noise vehicles would turn noise into a project benefit.

For this paper, we calculated the B–C ratio for 243 scenarios by varying the number of UCCs (1, 2, or 3), percentage of electric delivery vehicles (0%, 50%, 100%), size of the restriction zones (center, ring 1, ring 2), coverage of dedicated unloading spaces (without, center, ring 1), and percentage of night deliveries (0%, 20%, 40%). Table 5 presents the SCBA results for 10 example scenarios, highlighting the B–C ratios with and without the inclusion of ECs. This comparison highlights the importance of thoroughly accounting for externalities in SCBA analysis. The case study demonstrates that incorporating ECs can increase the B–C ratio by up to 0.16 in certain scenarios, such as Scenario 10. However, as illustrated in Scenario 1, including ECs may sometimes result in a lower B–C ratio, suggesting that externalities do not always improve project viability.

To contextualize the findings, the results of this study are compared with those from existing evaluations of UCC concepts in the literature. The calculated average B–C ratio for the UCC concepts in the case study is 0.58, indicating that societal returns amount to €0.58 for every €1 invested. This aligns with findings from Kin et al. [7], where a B–C ratio of 0.42 was reported, highlighting that while UCCs demonstrate positive social and environmental impacts, they often struggle to achieve financial self-sufficiency. This consistency across studies underscores the common challenge of balancing the societal benefits of UCCs with their financial viability, reinforcing the importance of targeted policy interventions and innovative funding mechanisms to support their implementation.

Table 5. Results of the SCBA for selected UCC concepts.

Scenario						B–C Ratio	
No.	**Number of UCCs**	**EVs Percent**	**HGV Restriction zone**	**Dedicated Unloading Spaces**	**Night Deliveries**	**With ECs**	**Without ECs**
1	1	0%	C	No	0%	0.58	0.59
2	1	100%	C	No	0%	0.51	0.49
3	1	0%	C + R1 + R2	No	0%	0.60	0.64
4	1	0%	C	C+R1	0%	0.60	0.58
5	2	50%	C + R1	C	20%	0.58	0.55
6	2	100%	C	No	0%	0.51	0.48
7	3	0%	C	C	40%	0.68	0.56
8	3	0%	C + R1 + R2	No	0%	0.63	0.67
9	3	100%	C + R1 + R2	No	0%	0.50	0.51
10	3	100%	C	C	40%	0.62	0.46

Symbols: C—Center; R1—Ring 1; R2—Ring 2.

Overall, low B–C ratio for the year of implementation is mainly due to high initial expenditures, such as infrastructure development and the acquisition of electric vehicles. However, the B–C ratio is expected to improve over time as infrastructure costs decrease and operational expenses decline with economies of scale. Furthermore, the external benefits are likely to grow, enhancing the overall value of the project. While this is outside the scope of this paper, it should be considered when conducting a feasibility study.

5. Sensitivity Analysis

To evaluate the robustness of the proposed model, a comprehensive sensitivity analysis was performed, focusing on key input variables for the SCBA. The analysis examined variations in critical cost factors, including UCC construction costs and the level of subsidies (Table 6), fuel and electricity prices (Table 7), as well as the procurement costs of EVs and land allocation for unloading spaces (Table 8). This approach helps to identify the most sensitive parameters, providing valuable insights into their impact on the overall cost–benefit outcomes of UCC concepts.

Table 6. Sensitivity of the B–C ratio from changes in level of subsidies and UCC construction price (brighter shades indicate a greater change in the variables).

	Change in UCC Construction Price										
	−50%	−40%	−30%	−20%	−10%	0%	10%	20%	30%	40%	50%
0%	0.77	0.72	0.68	0.64	0.60	0.57	0.54	0.52	0.49	0.47	0.45
−10%	0.71	0.67	0.63	0.59	0.56	0.53	0.50	0.48	0.46	0.44	0.42
−20%	0.66	0.61	0.57	0.54	0.51	0.48	0.46	0.44	0.42	0.40	0.38
−30%	0.60	0.56	0.52	0.49	0.47	0.44	0.42	0.40	0.38	0.36	0.35
−40%	0.54	0.50	0.47	0.44	0.42	0.40	0.38	0.36	0.34	0.33	0.32
−50%	0.48	0.45	0.42	0.40	0.37	0.35	0.34	0.32	0.31	0.29	0.28
−60%	0.42	0.39	0.37	0.35	0.33	0.31	0.30	0.28	0.27	0.26	0.25
−70%	0.36	0.34	0.32	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.21
−80%	0.30	0.28	0.27	0.25	0.24	0.23	0.21	0.20	0.19	0.19	0.18
−90%	0.25	0.23	0.22	0.20	0.19	0.18	0.17	0.16	0.16	0.15	0.14
−100%	0.19	0.18	0.16	0.16	0.15	0.14	0.13	0.13	0.12	0.12	0.11

Table 7. Sensitivity of the B–C ratio from changes in fuel and electricity price (brighter shades indicate a greater change in the variables).

	Change in Fuel Price										
	−50%	−40%	−30%	−20%	−10%	0%	10%	20%	30%	40%	50%
−50%	0.46	0.48	0.51	0.53	0.55	0.57	0.58	0.60	0.61	0.63	0.64
−40%	0.46	0.48	0.51	0.53	0.55	0.57	0.58	0.60	0.61	0.63	0.64
−30%	0.46	0.48	0.51	0.53	0.55	0.57	0.58	0.60	0.61	0.63	0.64
−20%	0.46	0.49	0.51	0.53	0.55	0.57	0.59	0.60	0.62	0.63	0.64
−10%	0.46	0.49	0.51	0.53	0.55	0.57	0.59	0.60	0.62	0.63	0.64
0%	0.46	0.49	0.51	0.53	0.55	0.57	0.59	0.60	0.62	0.63	0.64
10%	0.46	0.49	0.51	0.53	0.55	0.57	0.59	0.60	0.62	0.63	0.64
20%	0.47	0.49	0.51	0.54	0.55	0.57	0.59	0.60	0.62	0.63	0.64
30%	0.47	0.49	0.52	0.54	0.56	0.57	0.59	0.60	0.62	0.63	0.64
40%	0.47	0.49	0.52	0.54	0.56	0.57	0.59	0.61	0.62	0.63	0.64
50%	0.47	0.49	0.52	0.54	0.56	0.57	0.59	0.61	0.62	0.63	0.65

Table 8. Sensitivity of the B–C ratio from changes in EVs procurement and unloading space price (brighter shades indicate a greater change in the variables).

	Change in EVs price					
	0%	−10%	−20%	−30%	−40%	50%
−50%	0.571	0.573	0.575	0.577	0.578	0.580
−40%	0.571	0.573	0.575	0.576	0.578	0.580
−30%	0.571	0.573	0.574	0.576	0.578	0.580
−20%	0.571	0.573	0.574	0.576	0.578	0.579
−10%	0.571	0.572	0.574	0.576	0.577	0.579
0%	0.570	0.572	0.574	0.576	0.577	0.579
10%	0.570	0.572	0.574	0.575	0.577	0.579
20%	0.570	0.572	0.573	0.575	0.577	0.579
30%	0.570	0.571	0.573	0.575	0.577	0.578
40%	0.570	0.571	0.573	0.575	0.576	0.578
50%	0.569	0.571	0.573	0.574	0.576	0.578

To illustrate the sensitivity of the B–C ratio to various cost categories, we created a specific type of bar chart known as a "tornado" chart, shown in Figure 4. This type of chart is particularly effective for sensitivity analysis because it visually highlights the impact of each variable on the outcome, making it easier to identify the most influential factors.

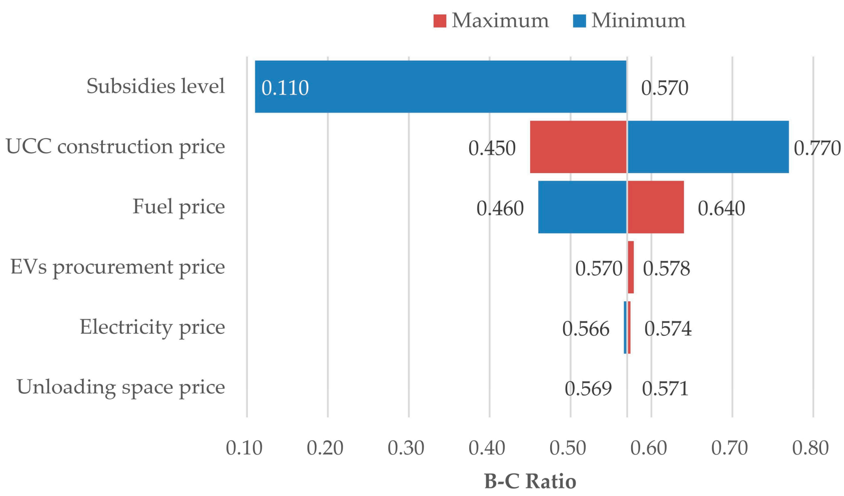

Figure 4. Sensitivity of the model results to changes in load factor.

The SCBA results indicate that variations in subsidy levels and UCC construction costs significantly affect the B–C ratio. Specifically, as subsidies increase or construction costs decrease, the B–C ratio improves, suggesting a more favorable cost–benefit outcome for UCC concepts. Note that subsidies emerge as the most critical factor for UCC success; without these incentives, the B–C ratio can drop to as low as 0.11. Conversely, fluctuations in fuel and electricity prices have a comparatively moderate effect on the B–C ratio. The tornado chart reveals that fuel prices are the primary cause of this sensitivity. This finding supports the decision to procure electric delivery vehicles due to their long-term benefits.

6. Conclusions

In this paper, we presented a novel approach to enhance decision making in sustainable CL planning and development by integrating MCDM, simulation and SCBA. The proposed MCDM–SCBA model addresses the complexities of financially evaluating UCCs concepts and their associated ECs by prioritizing CL initiatives based on their potential to mitigate negative externalities.

To systematically assess and prioritize various UCC concepts, we employed the AHP technique due to its simplicity. This enabled effective ranking of possible UCC concepts. The findings revealed that restrictive and regulatory measures, alternative transport options, and operational optimizations are preferred solutions in the specific case study. However, a well-known limitation of the AHP is its reliance on subjective impact assessments. This reliance makes it difficult to account for the inherent uncertainty in human decision making. To address this, our approach incorporates analytical calculations of ECs for selected UCC concepts, based on simulations of urban freight flows. Calculating ECs alongside capital and operational expenditures within the SCBA component of the model provides quantitative metrics for decision makers. This approach enhances the decision-making process by offering a comprehensive analysis of both private and external costs.

In the case of the city of Novi Sad, the experimental results indicated that initial B–C ratios for the proposed UCC concepts may be below one, signifying current financial inefficiency. However, the long-term benefits associated with reduced ECs and improved operational efficiencies hold promise for enhancing project viability over time. The findings also emphasize the necessity of systematically including ECs in cost–benefit analyses, as they significantly contribute to total net benefits.

The sensitivity analysis conducted in this research reveals the critical parameters influencing the B–C ratio, highlighting the significance of subsidies for UCC operations.

Overall, the proposed MCDM–SCBA model serves as a powerful decision-making tool by providing a quantitative, scenario-based approach to evaluating the effects of CL initiatives. It helps in shaping policies regarding the application of various UCC concepts and managing trade-offs between costs and benefits. Decision makers can use model outputs to strategically implement measures that reduce congestion, emissions, and operational costs while improving overall efficiency and sustainability in CL.

This research has several noteworthy limitations which imply promising paths for future research. Regarding the application of SCBA, the analysis was conducted solely for the year in which city logistics initiatives are potentially implemented. Future work should extend the SCBA over the next five to ten years to account for evolving trends. Such trends may involve a shift toward "servitization" models, where businesses pay for equipment usage rather than ownership, potentially reducing long-term capital expenditures (CAPEX). Further, the adoption of electric vehicles, despite their higher initial costs, could also lead to lower operational expenses over time. Additionally, the current SCBA categories do not encompass all potential costs and benefits but focus on the most significant ones.

While the current approach considers major external costs like noise, congestion, road safety, and air pollution, other potential external effects (such as land use and visual impact) are worth considering. Future studies should include benefits such as cost savings for retailers and improved delivery reliability. This would enhance the analysis and provide a more comprehensive understanding of the economic and environmental implications of UFT. Finally, developing an adaptive decision-making framework that incorporates incremental learning techniques to dynamically refine UCC evaluations as new data become available could significantly enhance the practical applicability of such models. An improvement in uncertainty analysis methods in future research is also desirable to enhance result reliability.

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