Annals of Operations Research
https://doi.org/10.1007/s10479-021-04013-3

ORIGINAL RESEARCH

A game-theoretic multi-stakeholder model for cost allocation in urban consolidation centres

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Accepted: 24 February 2021

Abstract

Recently, many European local authorities have set up Urban Consolidation Centres (UCC) for dealing with challenges arising from the environmental and social impacts of logistical activities in urban contexts through shipment synchronisation and carrier coordination policies. However, the number of successful UCC projects led by local authorities in Europe is low, with most of the UCCs failing to achieve financial sustainability after the initial experimental phase, which is often heavily supported by public funds. In order to propose mechanisms that could favour the economic and financial sustainability of UCC systems, this research develops an adaptation of game-theoretic approaches to the problems of responsibility and cost allocation among stakeholders participating in a UCC delivery network. A solution based on the Shapley Value concept is employed to derive cost allocations; applications of the model to a real-world scenario are evaluated. An extensive sensitivity analysis shows that the proposed cost allocation rules can provide alternative arrangements, based on *extended responsibility* concepts, which can alleviate the burden on local authorities for the set up of UCCs. As such, results provide useful policy and practice implications on how to safeguard UCCs' viability under different scenarios, including the outsourcing of the last-mile deliveries.

Keywords Urban consolidation centres · Urban logistics · Urban freight transport · Cost allocation · Shapley value · Sustainable urban logistics

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1 Introduction

Urban Freight Transportation (UFT) only accounts for 15% of the total vehicle movements in urban areas. However, such a number of movements contributes significantly to city congestion due to the large size of vehicles employed for goods distribution (Paddeu, 2018); indeed, UFT produces 30–40% of transport carbon emission (Browne, 2019). Coherently to the recently introduced Sustainable Development Goals, the European Union requires emissions from the transport industry to be reduced by 60% (compared to 1990 levels) within 2050 (European Comission, 2011). In this context, different categories of measures for sustainable urban logistics (SUL) (including market-based measures; regulatory measures; land use planning; infrastructural solutions; adoption of new technologies) are being implemented in order to achieve objectives linked to sustainable urban development (Stathopoulos et al., 2012; Zhang et al., 2020).

As an infrastructural response to these challenges, many local authorities (LAs), also through the establishment of public–private partnerships, have set up Urban Consolidation Centres (UCCs) for dealing with *last-mile* distribution, as an attempt to deal with negative impacts of logistics in urban contexts through a freight consolidation strategy (Dablanc et al., 2011). UCCs are normally located on the outskirt of urban areas. UCC-based mechanisms encompass coordination among different carriers and shippers, require long haul carriers to deliver their loads of goods at UCCs, where such loads go through unloading, sorting, and cross-docking processes (Miao et al., 2012), before being consolidated and delivered to the final user through the usage of a fleet of smaller and environmentally-friendly (electrical or gas) vehicles (Martinez-Sykora et al., 2020). Complex structures based on multiple tiers of UCCs also emerged, particularly in the case of large metropolitan areas, and related optimisation challenges were tackled in the literature (Crainic & Sgalambro, 2014; Crainic et al., 2009).

It has been shown that UCCs can contribute to the improvement of environmental quality in cities by reducing air pollution and alleviating congestion (Browne et al., 2005, 2011). Furthermore, UCCs can help long-haul carriers to solve the complexity of urban deliveries through value-adding services (e.g. just-in-time); also, customers (e.g. retail stores, catering establishments) in urban areas can save cost by reducing the need for warehouse space (Browne et al., 2005).

Notwithstanding these encouraging premises, the number of successful UCC projects in Europe is very low and most of them have experienced serious difficulties in going beyond the experimental phase (Paddeu, 2018). Indeed, most of the UCCs fail to achieve financial sustainability and to operate autonomously after the initial experimental phase that might be heavily supported by public funds. Local and central governments might invest considerable capital in the start-up process of UCCs in order to alleviate environmental and social issues related to logistics in urban areas (Allen et al., 2012; Browne et al., 2005). However, unless the use of UCC facilities is mandatory for all shipments to and from the considered urban areas, in most cases UCCs cannot attain long-term sustainability due to the relatively low volume of users who typically subscribe to these types of projects (Janjevic & Ndiaye, 2017a). It has to be highlighted, indeed, that the last-mile distribution process suffers from significantly higher costs than other long-haul freight transport activities (Lindholm & Behrends, 2012) due to the impact from resident density, restrictive policies, and inherent spatial constraints which can be found urban environments (Gevaers et al., 2014). As such, last-mile distribution costs can account for up to 75% of the total cost of supply chain logistics (Devari et al., 2017).

Both private and public stakeholders are involved in UCC delivery networks (Anand et al., 2012). Private stakeholders include: (i) long-haul carriers; (ii) local carriers associated with the UCC; (iii) consumers; (iv) goods' suppliers. On the other hand, LAs are the most prominent category of public stakeholders involved in these networks (Taniguchi & Tamagawa, 2005, Browne et al., 2007, Allen et al., 2012, Behrends, 2016, de Oliveira & de Oliveira, 2017). The attributes and interests of different stakeholders cause the heterogeneity of their behaviours and objectives in the functioning of UCC networks (Gatta & Marcucci, 2014; Marcucci et al., 2017; Taniguchi & Tamagawa, 2005); as such, it is not uncommon that different categories of stakeholders in UCC networks will have very different priorities (Kin et al., 2016). When conceiving solutions for freight transport, the main challenge is to satisfy the interests of all stakeholders (Vieira et al., 2015, Sanz, 2018); however, due to lack of resources, it might be extremely challenging for LAs to harmonise different objectives (across the economic, environmental and social dimensions) associated with different categories of private stakeholders (Akgün et al., 2019). Private stakeholders seldom integrate their logistical planning process or daily business operations into the overall sustainable development strategies of LAs (Dablanc, 2007); in other words, there is a distinctive boundary of responsibility and lack of co-operation among stakeholders. Such responsibility issues are likely to work against the promotion of collaborative projects in Urban Logistics and exacerbate financial issues experienced by UCCs.

Sustainable urban logistics should be aimed at reducing the total *social cost* of urban goods movements (Ogden, 1992). As such, all stakeholders should understand that SUL principles are aimed at promoting financial and non-financial benefits for all members in a supply chain (Morana & Gonzalez-Feliu, 2015). In circumstances where financial rewards cannot be achieved in the short term, mechanisms are needed for establishing fair and efficient cost-sharing for stakeholders participating in UCC networks. This is required for UCCs to achieve financial sustainability and promote responsibility sharing schemes aimed at overcoming the initial situation where such facilities are merely depending on subsidies from local and national governments. Within this context, this research aims to develop an adaptation of established game-theoretic approaches to the problem of responsibility and cost allocation among stakeholders participating in a UCC delivery network. The proposed models will allow the establishment of responsibility sharing schemes aimed at promoting the financial sustainability of UCCs.

Proposed approaches are derived from the theory of Unlimited Territorial Integrity (Ambec & Sprumont, 2002), which has been previously applied to the Supply Chain context (Ciardiello et al., 2020). A solution based on the Shapley Value (Shapley, 1953) concept will be employed to calculate the numerical results for cost allocations, under different responsibility scenarios. Applications of the model to a real-world scenario will be then evaluated, in order to draw useful policy and practice implications.

The paper is organized as follows. In Sect. 2, a literature review is provided; after a general introduction to collaborative solutions to urban freight transportation problems, the paper focuses on modelling approaches based on both optimisation and game theory. Some research gaps are identified, related to scenarios in which collaborative solutions (such as UCCs) are set up by Local Authorities. The paper also highlights that, in these contexts, the fairness of cost-sharing rules is a desirable property, given the conflictual nature of stakeholders' preferences. In Sect. 3, we clarify the contribution of the current paper. In Sect. 4, we propose the game-theoretical model for UCC networks, which is an adaptation of the so-called *River Problem* (Dong et al., 2012; Ni & Wang, 2007); we adopt new responsibility concepts; according to them, we present the numerical formulation of the Shapley value. In Sect. 5, we implement our model and we derive cost allocations for a particular case study; an extensive sensitivity analysis is performed, which allows drawing some interesting implications. Finally, conclusions are provided in Sect. 6.

2 Literature review

2.1 Collaborative urban logistics in urban consolidation centres

Collaborative freight transportation involves the creation of partnerships involving two or more actors aiming at achieving specific business goals through the utilisation of shared assets (Lambert et al., 1999; Pomponi et al., 2013). In the field of urban logistics, Cleophas et al. (2019) classify the UCC network as a vertical initiative of collaborative urban freight transportation (CUFT), in which goods flow across partners who are in a multi-tier structural relationship. As a vertical CUFT system, UCC based delivery mechanisms can be regarded as a two-echelon delivery network (Nozick & Turnquist, 2001). Parcels are transhipped to an intermediate facility before being moved to an urban area (Guastaroba et al., 2016). After that, sustainable methods, such as light or electric vehicles are utilised for goods distribution within the urban area (Gonzalez-Feliu, 2008).

A typical UCC system requires the setup of a collaborative network involving upstream and downstream stakeholders, including upstream long-haul carriers (LHCs), suppliers, and downstream customers, in order to intercept and merge goods flows to be delivered in an urban area (Cleophas et al., 2019). Van Heeswijk et al. (2019) identified two different types of UCC business models according to the categories of UCC subscribers. In the first model, LHCs outsource their last-mile delivery business to an UCC, which consolidates goods from multiple LHCs, and deliver them to the customers in the urban area; Brussels UCC operates according to this model (Janjevic & Ndiaye, 2017b). In the second category of UCCs, downstream customers (e.g. retailers, restaurants) designate the UCC facility as a consolidation point in order to activate collaborative delivery mechanisms in the urban area. This model includes the operational UCCs for perishable products in Parma (Italy) (Morganti & Gonzalez-Feliu, 2015) and Nijmegen (The Netherlands) (Duin et al., 2016) and the British UCCs serving the Regent Street area in London (Browne et al., 2011) and the Bristol-Bath conurbation (Duin et al., 2016).

2.2 Financial sustainability of UCCs

While UCCs can provide great environmental and social advantages, their financial sustainability, along with their transition to autonomously-funded projects, which are not heavily relying on governmental support, is a challenging proposition. Even if governments invest considerable capital in the initial stage of the UCC project, this might not achieve long-term sustainability (Allen et al., 2012). Historically, the low volume of users subscribing to UCC facilities has caused financial issues; indeed, most of these schemes have been implemented voluntarily. As such, it is hard for UCCs to achieve financial availability through service fees (Paddeu, 2018). Four main factors can produce such issues:

- Given the extremely fragmented nature of the urban freight transport market (in which a plethora of small companies and self-employed drivers operate) (Paddeu, 2018), it is difficult for UCCs to capture significant market shares in last-mile logistics (Allen et al., 2014; van Duin et al., 2010).

- Due to the need to introduce further sorting and merging processes, UCC schemes might generate extra fees for all the actors involved in the entire supply chain (Van Rooijen & Quak, 2010). In addition, as profit margins in the urban freight market are generally low, shippers are reluctant to join UCC projects and to hand over one of the most lucrative portions of their value chain to an external entity (Van Rooijen & Quak, 2010).
- Many carriers might already autonomously achieve high truck-load rates; as such, they can realise efficient shipments. This will prevent them to subscribe to UCC facilities (Olsson & Woxenius, 2014).
- Many UCC projects are originally built for experimental purposes; such attempts generally exhibit a weak stakeholders' engagement and communication during the planning stage, making the transition to a fully operational project extremely difficult (Tsiulin et al., 2017).

Besides the above-mentioned issues, high fixed costs (typically faced by LAs) represent another financial constraint for UCC projects (Quak & Tavasszy, 2011). LAs might be able to set up UCCs thanks to grants or external funding (Duin et al., 2016, Paddeu, 2018); however, many UCC projects suffer losses from the very initial stage of their operations, failing to reach commercial viability (Janjevic & Ndiaye, 2017a; van Duin et al., 2010). In this context, LAs need to support UCCs, with subsidies which can also cover 40% of the total expenditure of an UCC, as stated by Duin et al. (2016). This might result in UCC operations being discontinued when the original grant (or public subsidy) terminates (Browne et al., 2005; Duin et al., 2016; Kin et al., 2016). Subsidies increase the financial burden for public authorities (Duin et al., 2016; Kin et al., 2016); besides that, under certain regulations, persistent public support to UCCs can violate competition rules (Paddeu, 2018). For the purpose of promoting the adoption of UCCs, LAs might need to use restrictive policies (such as congestion and emission charges), in order to force LHCs to join such schemes, or to penalise them from an economic point of view (Allen et al., 2012; Björklund et al., 2017; Ville et al., 2013); however, imposing such measures could generate legal feuds between LAs and private companies.

2.3 Cost-allocation mechanisms for UCCs

According to both the academic and grey literature, current mechanisms require individual LHCs to join UCC schemes. Therefore, UCC facilities operators, or LAs (which mainly act as sponsors of the project) need to assume the financial responsibility for UCC operations. Such mechanisms might cause low uptake rates (e.g. for LHCs) and exacerbate UCC financial issues (Battaia et al., 2014). As such, the current expectation for local governments is to find ways to promote responsibility sharing for UCC operations, in such a way to produce shared allocations of logistical costs, with the main aim of sustaining the viability of UCCs (Allen et al., 2012; Browne et al., 2005; Marcucci & Danielis, 2008). Specifically, LAs should seek to build *coalitions* aimed at involving more stakeholders in the functioning of UCC facility, through participatory cost-sharing mechanisms.

As such, cost allocation rules should span across individual stakeholders' business boundaries, implementing *extended responsibility* rules capable of providing a comprehensive view of the whole logistics chain. Also, cost allocation mechanisms should provide rules for sharing the overall cost of the logistical activities taking place within the UCC network, involving all stakeholders in a multi-tier position according to fairness and efficiency principles. In practice, complex negotiations are required to enable the distribution of costs and benefits among agents (Kurnia & Johnston, 2001). Considering this, models and methods aimed at performing such allocations could be of help to policy-makers willing to adopt UCC solutions in urban contexts.

Guajardo and Rönnqvist (2016) performed a very detailed review of cost-allocation methods in transportation problems, albeit not restricting their focus to the urban setting (and, therefore, to UCCs). In particular, collaboration or cooperation might be expressed through the willingness of sharing logistical resources or accepting the negative externalities due to freight transportation activities. Cooperation might involve different tangible and intangible assets; how to distribute profits or how to allocate costs is the key problem for setting up such collaborations. According to Guajardo and Rönnqvist (2016), cooperative game-theoretical models are particularly suited for solving this type of problem. Within this context, the most employed game-theoretical approach is the one based on the concept of the *core*. Such a concept (and its ad-hoc developed variations) appears one of the most naturally adaptable ones to the transportation context, given its property of *individual rationality*. Such a property can very naturally describe the desired *tout court* stability of the collaboration among the members of the logistical network (see, for instance: Dai & Chen, 2012; Padilla Tinoco, 2017; Hezarkhani et al., 2019).

Let (N,v) be a pair where N is the set of players and the function v is defined of the superset of N. The function $v(T)$ describes the value of collaboration of players in a given subset $T \subseteq N$. The pair (N,v) is called a Transferable Utility (TU) game. Classical solutions address an aggregation issue, trying to summarise information from TU games into single allocations/payoffs assigned to each of the players. Within this context, the *individual rationality* property of the *core* incorporates the desirable incentive to join a coalition, meaning that each participant is better off with the collaborative allocation than with its initial endowment $v(i)$.

Among the other approaches which have been employed for promoting collaboration among stakeholders engaged in a logistical system, Guajardo and Rönnqvist (2016) also cite the study by Vanovermeire et al. (2014) based on the *Shapley Value* (Shapley, 1953).

Shapley (1953) succeeded in providing the following four conditions on the transformation from a TU-game into an allocation that can be fairly said to be natural:

- The *symmetry* axiom: if two participants equally contribute to the worth of any coalition, i.e. $v(T)$, then they must have the same Shapley value.
- The *efficiency* axiom: the sum of individual Shapley values must be equal to the worth of the whole grand coalition.
- The *dummy-player* axiom: participant who does not contribute to any coalition must have a null value.
- The *additivity* axiom: let us have two TU games on the same set of players. For each TU game, each player has a Shapley value. Let us construct the sum-game of the previous two games. Then, individual Shapley values of the sum game are equal to the sum of the two initial Shapley values.

The Shapley value has been also used for sharing mechanisms in transportation as a form of incentives for companies to join the full collaboration, even if it does not necessarily satisfy individual rationality (Vanovermeire et al., 2014).

Dai and Chen (2012) studied the stability multiple carriers' alliance if carriers share their transportation requests, vehicle capacities in order to increase vehicle utilization rates and reduce empty back hauls; they employ the Shapley value to re-allocate profits among the multiple carriers. This is done as to maintain the stability of the alliance among carriers. Significantly, the authors prove that the Shapley value is in the core. As also shown by Dahlberg et al. (2019), if an allocation mechanism satisfies both fairness and individual rationality properties, then there is good hope to provide strong incentives that can foster stakeholders' collaboration.

Hezarkhani et al. (2019) studied the relationship between a UCC and its suppliers; collaboration here is intended as stakeholders' willingness to process goods through the UCC, in order to reduce the unit costs for UCCs through the achievement of economies of scale. Profits achieved by the UCC profits are shared with participants in order to provide an incentive aimed at fostering collaboration.

2.4 Research gaps

Despite the growing literature on UCCs in urban contexts, little attention has been devoted to the specific development of allocation mechanisms for the start-up phase of UCCs led by local authorities.

In general, the challenges of urban logistics may vary across countries, cities, and projects. The overall aim of allocation schemes is to mitigate negative impacts, without having a negative influence on the functionality of urban logistical systems (e.g., shippers, transport companies, receivers, end customers, public administrations). It must be remarked that, in an urban context, negative externalities associated with freight transportation represent the main reason for which local authorities establish UCCs; as such, the mitigation of these externalities represent the prime objective for local authorities. Consequently, individual rationality should not be seen as the main property to be respected by allocation schemes for the urban context. In other words, allocation rules are not to be solely meant as incentives to form collaboration among stakeholders. Taniguchi (2014) discusses the role of municipalities in promoting sustainable urban logistics solutions. Municipalities provide coordination, advice, and infrastructures, along with investment for the start-up phase of the UCC. However, Taniguchi (2014) also points out that UCCs (and, in general, urban logistics projects) should not depend too heavily on financial support from the municipality in the long run. It is therefore fundamental that municipalities build mechanisms aimed at helping the start-up phase of UCC but seek to recover the initial investment through cost-reduction and economies of scale.

Despite their individual rationality, stakeholders may perceive as *fair* the regulatory role of municipalities (Kiba-Janiak, 2016). Within this context, allocation rules can become a helpful tool for local authorities, willing to adopt UCC solutions for protecting their urban area from the negative externalities of urban freight transport. It must be noticed that there is a dearth of research on these specific aspects. Some initial attempts to study allocation schemes when the municipality is somehow dominant have been provided by Dahlberg et al. (2018). Van Heeswijk et al. (2020) provided an agent-based model for the study of urban logistics systems set up by local authorities; the result of those simulations shows that the implementation of UCCs can considerably reduce negative externalities deriving from urban freight transport; however, a detailed scenario analysis confirms that such policies might not achieve financial viability.

As such, as explained in the previous sections, appropriate cost allocations rules are a stringent need in order for UCCs to achieve financial sustainability and promote responsibility sharing schemes aimed at overcoming the initial situation where such facilities are merely depending on subsidies from local and national governments. Our focus is complementary to the emerging literature on gain sharing mechanisms for UCCs (Hezarkhani et al., 2019), but more devoted to the start-up phase of the facility.

Specifically, this paper considers the opportunity of involving a wider set of stakeholders in a coalition, which could participate to cost-sharing mechanisms associated with the operation of a UCC facility run by a local authority. To the best of our knowledge, no study, to date, has paid attention to cost allocation issues in order to sustain the existence of UCCs and, as a second criterion, to promote the participation of stakeholders according to fairness principles (Dahlberg et al., 2019).

3 Contribution of the study

According to the current literature and state-of-practice, the most widely adopted cost-sharing mechanism requires operators and LAs to assume economic and financial responsibility for UCC operations. Notwithstanding, the pivotal role of cost-sharing policies to share financial burdens among a wider set of different classes of stakeholders (including Suppliers, Long-haul Carriers, Retailers) and successfully implement advanced consolidation-based logistics strategies were widely evidenced in the literature (Schaffer, 2000; Kurnia & Johnston, 2001; Guajardo & Rönnqvist, 2016; Verdonck et al., 2016).

In this paper, we adopt a game-theoretic approach in order to evaluate the impact of different cost-sharing strategies. The approach is aimed at negotiating more sustainable allocations of both economic efforts and practical benefits, to maximise involvement in a UCC network. Indeed, such a strategy seeks to involve more stakeholders in contributing to the total cost of the UCC facility, in order to improve the prospects of financial autonomy and viability of such facilities. Specifically, this paper considers the opportunity to involve Suppliers (which originate the flows of goods through their manufacturing processes), Long-haul Carriers (LHC) (which take care of transporting such flows of goods), and Customers (whose demand for goods can be seen as the ultimate reason for the activation of such logistical flows).

From a theoretical standpoint, the legitimacy of involving suppliers into cost allocation mechanisms in UCC networks can be derived from an Extended Producer Responsibility (EPR) view. EPR requires producers' responsibility to be extended to the life cycle of a product. Specifically, goods producers should take responsibility for all the environmental impacts and externalities associated with the product's service life, also including end-of-life options (Lindhqvist & Lifset, 2003); the usage of EPR schemes represents a policy which can mitigate the negative environmental and social impacts arising from production activities (Spicer & Johnson, 2004). Based on the above-mentioned principles, it is reasonable for producers to take responsibility for logistical activities related to the distribution of their products; logistical processes, indeed, represent a key segment in the life cycle of the products. Coherently, according to such view, suppliers can be required to mitigate the negative environmental and social effects caused by goods transportation; the participation to the functioning of UCC schemes can be seen as a way to implement such logic.

A similar argument can be employed for the involvement of LHCs. Typically, LHCs contribute to UCC operations as such facilities merge goods from different carriers and deliver them to the final customers in the urban area. Again, this participation in costs of UCCs can be seen as a way to ask LHCs to be accountable for the detrimental effects (on the environmental dimension) of their activities. Also, participation in UCCs can be beneficial for intercity shippers, as delivery consolidation can lead to short travel times and efficiency improvements through off-peak deliveries goods into UCCs; also, thanks to UCCs, LHCs can avoid dealing with the intricacies of last-mile deliveries (such as time-windows or traffic restrictions). On this basis, it seems reasonable to ask LHCs to participate in cost-sharing schemes for the functioning of UCCs.

From a theoretical standpoint, the legitimacy of involving customers into cost allocation mechanisms in UCC networks can be derived from an Extended Customer Responsibility (ECR) view (Sheu & Choi, 2019). The idea of ECR is novel and can be described as the need for customers to take responsibility for the "societal harm" caused by the commodities or services they want to obtain. When ECR principles are implemented in the field of SUL, it calls customers to be responsible for the adverse effects, which are caused by the delivery processes of goods, or services they purchase. Extending such an idea to a UCC network, customers can be seen as the receivers of the final goods; their purchasing behaviour generates demand for logistical activities, which leads to environmental and social issues. However, customers have significant potential in improving the overall environmental performances of a supply chain through purchasing aggregation and consolidation (Vachon, 2006). Within such logic, and coherently to an ECR scheme, it can appear reasonable to ask customers to contribute to the functioning costs of UCCs, to alleviate the environmental consequences of logistical activities generated by their demand.

4 A game-theoretic model for cost allocation in UCC networks

The model developed in this paper is an adaptation to the UCC context of the fundamental contribution of (Ni & Wang, 2007). Such an allocation approach was originally developed in the field of environmental economics, for the so-called *polluted river problem*. This problem can be briefly described as follows: there is a river that can be divided into n segments; in each segment, a manufacturing company is generating pollutants, which are contaminating the river into this river. In order to mitigate their environmental impact on the river, each company must contribute to the cost of cleaning activities. Several extensions and variants to this problem have been introduced in the literature (see, for instance: Alcalde-Unzu, et al. 2015; van den Brink et al, 2018; Gudmundsson et al., 2019). However, in general, three principles can be followed for the allocation of the costs of such activities:

- A Local Responsibility principle (LR), according to which each company is strictly responsible for the cleaning costs, related to the production activities strictly happening at its premises (and, therefore, within their river portion).
- An Upstream Responsibility principle (UR), stating that companies located upstream are responsible not only for pollution happening at their premises, but will also pollute portions located downstream, and should be held responsible for this, participating in cleaning costs.
- A Downstream Responsibility principle (DR), stating that downstream companies located along the river should participate in cleaning activities for upstream portions of the river.

Based on the LR, DR, and UR principles mentioned in the above section, three allocation methods can be proposed: Local Responsibility Sharing (LRS), Upstream Equal Sharing (UES), and Downstream Equal Sharing (DES) methods (Dong et al., 2012; Ni & Wang, 2007).

In this paper, an adaptation of this framework will be developed to the cost allocation problem in the context of a UCC delivery network, under the following assumptions (see Fig. 1):

- Different stakeholders are cooperating in a multi-tier delivery chain;
- Parcels will be moved from upstream stakeholders (i.e., suppliers) to downstream ones (i.e., customers).

Under such assumptions, a typical UCC based freight transport chain can be considered. Such a transport chain can be regarded as including a finite set N of n different stakeholders linked together by a set of goods moving processes (GMPs). Such GMPs can be represented as a set of links L, which are connecting stakeholders operating in the network. Therefore, the number of stakeholders is equal to the number of GMPs, that is $|L|=n$. According to this feature, we consider these GMPs in an upstream–downstream structure. Each link L_i is associated with a label (cost), denoted by c_i and representing the cost of the GMP for moving a parcel delivers from stakeholder i to stakeholder $i+1$. We refer to $c=(c_1, c_2, \dots, c_n) \in R^n_+$ as the cost vector. The cost-share of stakeholder i is denoted by x_i. We say that the vector $x=(x_1, x_2, \dots, x_n) \in R^n_+$ is the stakeholders' cost allocation vector. An *efficient* solution to the cost allocation problem should respect the property $\sum_{i=1}^n x_i = \sum_{i=1}^n c_i$. See Fig. 1 for a graphical representation of our model. Cost Allocation rules may be defined in order to define the vector x. Ni and Wang (2007) and Dong et al. (2012) introduce cost allocations for the above-mentioned river problem. In particular, such cost allocation rules become the Shapley Value of specific games in characteristic form, which satisfies the efficiency property. We use such cost allocation rules in our settings. In our context, cost allocations given by the same allocation rule respect the principle of fairness against the above-mentioned principles of responsibility. A similar interpretation for cost allocation in supply chains has been given in (Ciardiello et al., 2020; Granot et al., 2014). According to the Local Responsibility Sharing (LRS) rule, stakeholder i is the only one responsible for the delivery costs c_i. The latter means that $x_i=c_i$.

An upstream equal sharing (UES) is represented by the following cost allocation:

$$
\begin{aligned}
x_1 &= c_1+\frac{c_2}{2}+\cdots+\frac{c_i}{i}+\frac{c_{i+1}}{i+1}+\cdots+\frac{c_n}{n}\\
x_2 &= \frac{c_2}{2}+\cdots+\frac{c_i}{i}+\frac{c_{i+1}}{i+1}+\cdots+\frac{c_n}{n}\\
\cdots &= \cdots\\
x_i &= \frac{c_i}{i}+\frac{c_{i+1}}{i+1}+\cdots+\frac{c_n}{n}\\
\cdots &= \cdots\\
x_n &= \frac{c_n}{n}
\end{aligned}
$$

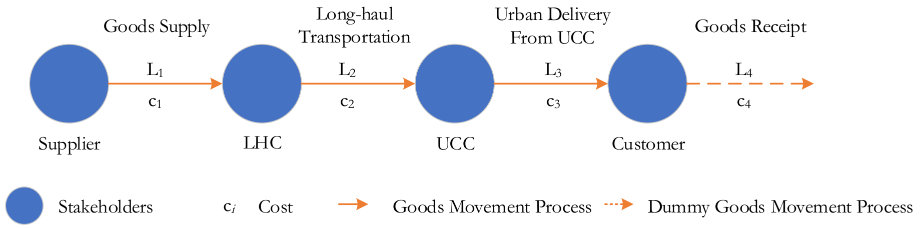

Fig. 1 Typical UCC based Freight Transport Chain

Each stakeholder is responsible for the costs of GMPs which happen downstream of his position in the delivery network (including the cost of GMP at his premises).

A downstream equal sharing (DES) rule is represented by the following cost allocation rule:

$$
\begin{aligned}
x_1 &= \frac{c_1}{n}\\
x_2 &= \frac{c_1}{n} + \frac{c_2}{n-1}\\
\cdots &= \cdots\\
x_i &= \frac{c_1}{n} + \frac{c_2}{n-1} + \cdots + \frac{c_{i-1}}{n+2-i} + \frac{c_i}{n+1-i}\\
\cdots &= \cdots\\
x_n &= \frac{c_1}{n} + \frac{c_2}{n-1} + \cdots + \frac{c_{i-1}}{n+2-i} + \frac{c_i}{n+1-i} + \cdots + c_n
\end{aligned}
$$

Each stakeholder is responsible for the costs of GMPs which happen upstream of his position in the delivery network (including the cost of GMP at his premises).

4.1 Model properties

As described in Ciardiello et al. (2020), the allocation rules introduced in the previous section are characterised by several desirable properties, which become very relevant in the context of UCC delivery networks as described in the following Table 1.

The *no free riding* and *equal sharing of extra costs* are desirable properties since they allow stakeholders in the delivery network to be protected from opportunistic behaviours from remaining participants. Even if stakeholders have a collaborative behaviour, some increases in logistical costs could occur over time. Such a change should be treated *fairly* in terms of further burdens on stakeholders. Interestingly, UES and DES cost allocation rules satisfy the above properties (Ciardiello et al., 2020).

The unilateral disaggregation stability ensures that stakeholders do not have any convenience to *disaggregate* their activities over delivery networks. By disaggregation, we mean the splitting of activities of a stakeholder into two separate entities under the ownership of the same stakeholder itself. Our cost allocations rules satisfy the unilateral disaggregation stability; this means that, for instance, a company participating in the UCC delivery

Table 1 Structure of operational cost in UCC (Janjevic & Ndiaye, 2017a)

Property	Relevance for UCC networks
Equal Sharing of Extra costs	If there is an increase in total operational costs, it is required that companies responsible for this increase should be equally affected by extra burdens
No free riding	This property requires that if the total costs increase, but, at the same time, for some firms, the costs of the processes they are responsible for remains unchanged, the allocation for these firms should remain the same
Unilateral disaggregation stability	If a stakeholder disaggregates its own activities into two different companies (under its ownership; for instance, by creating a subsidiary company being in charge of certain logistical processes), then the sum of cost allocations for these two *new* entities is larger than the cost allocation for the original stakeholder

network might be penalised (through a higher total logistical cost) if it decides to split its logistical activities across two entities characterised by the same ownership.

The following section details the application of the allocation rules to a case study.

5 Case study

The purpose of this section is to measure, assess, and compare the effects deriving from the adoption of different cost-sharing strategies whilst managing a UCC delivery network (as shown in Fig. 1). To this aim, the above-defined and described cost allocation rules (LRS, UES, and DES) are applied here to the experimental framework introduced by Janjevic and Ndiaye (2017a, b), based on a UCC located in the urban area of Brussels (Belgium). Janjevic and Ndiaye (2017a, b) originally adopted this UCC as a testbed for their theoretical framework, aimed at verifying the financial viability of UCC cross-docking and consolidation operations. The accurate characterisation of the logistical costs presented by Janjevic and Ndiaye (2017a, b) allows a realistic evaluation of the impact of the cost allocation mechanisms.

It must be noted that, in this paper, the case study is employed for a slightly different purpose: while Janjevic and Ndiaye (2017a, b) focus their analysis on demonstrating how profitable operations are subject to an efficient use of resources, we are interested here in exploring the impact of different cost allocation policies on individual actors' profitability. To the best of our knowledge, no previous contributions have performed similar analyses in the extant literature. As such, the considered experimental framework went through a careful adaptation process in order to make it suitable for our experiments, as described in the following.

We hypothesise a network composed of the following stakeholders, linked together by respective GMPs: (i) Suppliers; (ii) Long-haul carriers (LHCs); (iii) UCC operators; (iv) Customers.

According to Janjevic and Ndiaye (2017a), the logistical costs which can be attributed to the presence of a UCC include: (1) last-mile delivery costs and (2) in-facility goods handling costs (encompassing goods trans-shipment and handling costs and other general administrative costs related to the UCC). Values for these two types of costs (for typical parcels) have been validated by Janjevic and Ndiaye (2017a) as in Table 2.

Janjevic and Ndiaye (2017b) propose a cost modelling approach aimed at comparing costs faced by LHCs under different scenarios. When an LHC performs a delivery through a direct shipment, costs faced by the LHC include: (i) costs generated by the main freight movement, involving the shipment to the service area and the return to the depot after the completion of the delivery; (ii) costs generated by *ordinary freight movements*, for delivering goods to each customer in the service area (Fig. 2, top). When an LHC decides to utilise a UCC, costs faced include: (i) costs generated by the return trips between the LHC depot and the UCC; (ii) costs generated by dwell time at the UCC; (iii) costs generated by the payment for the UCC service (Fig. 2).

Table 2 Structure of operational cost in UCC (Janjevic & Ndiaye, 2017a)

Types of cost	Values	Percentage
Last-mile delivery costs	€2.08/parcel	67.8%
In-facility goods handling costs	€0.99/parcel	32.2%
Total costs	€3.07/parcel	100.0%

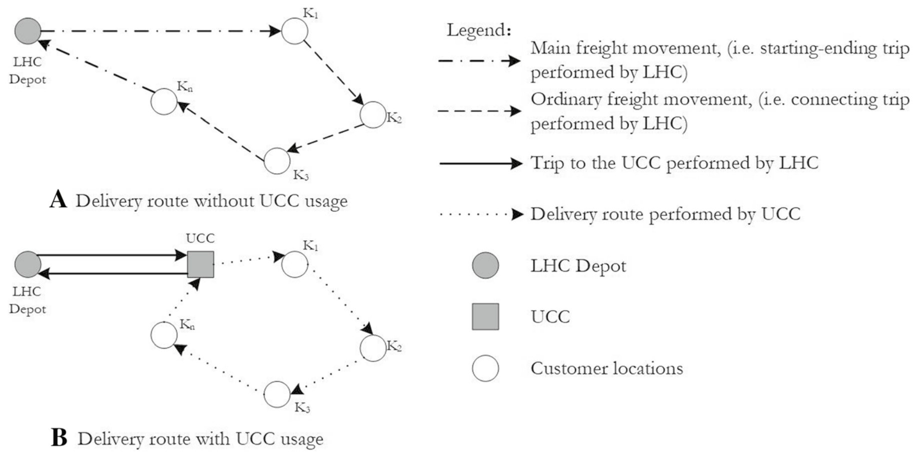

Fig. 2 Typical Delivery Process with (bottom)/without (top) UCC (adapted from Janjevic & Ndiaye, 2017b)

As such, Janjevic and Ndiaye (2017b) assume that the total cost faced by an LHC will be different under the two scenarios. In particular, if the LHC needs to serve a small number of customers (and, as a result, needs to deliver a small number of parcels) in each trip, the strategy of outsourcing the last-mile delivery to a UCC could reduce the costs faced by the LHC. Conversely, using a UCC can increase the costs faced by the LHCs if the LHC is shipping a large number of goods, thus achieving full truckload shipments. This can happen when large LHCs already achieve high consolidation by themselves, thus reducing the average shipping cost per parcel. Under these conditions, service fees charged by UCCs, along with handling and administrative costs and dwell times, might make the UCC option unattractive.

Indeed, if the cost of direct shipping is lower than the one faced using the UCC, LHCs will certainly decide not to outsource urban delivery processes to a UCC, unless LAs are adopting very stringent restrictions on private freight movement. As a result, UCCs might face difficulties in attracting customers, despite the proven environmental and social benefits associated with these facilities. Within this context, the proposed cost allocation rules could be employed, by LAs, to promote cost alleviation mechanisms for LHCs who are already able to achieve high consolidation factors and might then be reluctant to subscribe to UCC facilities.

As such, the considered Case Study is based on the assumption that LHCs cannot get an economic benefit from accessing UCC services (Janjevic & Ndiaye, 2017b). According to the scenario considered by Janjevic and Ndiaye (2017b), this would happen if the LHC is transporting more than 17 parcels in a typical delivery trip. In accordance with their findings, we focus on a setting where the considered LHC is delivering 50 parcels in its service area. According to the formulas and the parameters of the service area (such as the location of the depot and of the UCC, vehicle types, and service charge, information are shown in the Appendix) provided by Janjevic and Ndiaye (2017b), we calculate the cost for an LHC with and without using the UCC (Table 3). Besides the above discussion, we also assume that when LHCs outsource their urban distribution to a UCC, the goods supply, and receipt GMPs generate no extra cost. Under this scenario, LHCs might have no interest in accessing UCC services, as they could face lower costs by implementing a direct delivery policy.

Table 3 Costs for LHCs—direct delivery and UCC delivery (Janjevic & Ndiaye, 2017b)

Total parcels to be delivered in the urban area	Total cost for LHC direct delivery (*€/parcel*)	Total cost for LHC through UCC delivery (*€/parcel*)	Additional cost faced by LHC through UCC delivery (*€/parcel*)
50	2.75	4.26	1.51

As mentioned, LAs could try to incentivise the participation of large LHCs in the UCC by using the mentioned cost allocation rules. According to DES and UES cost-sharing policies, the additional costs faced by LHCs (arising from the outsourcing of last-mile deliveries to an UCC operator) could be shared with the upstream/downstream stakeholders (including suppliers and customers).

Based on the data from these two studies, we propose the cost structure of parcel delivery in a UCC network in Table 4. Here, only additional costs generated by the adoption of UCC services are accounted for and considered for cost-sharing purposes.

According to the principles formulated in the above sections, the results provided by cost-sharing schemes based on the LRS, UES, and DES are illustrated in Table 5.

Under the LRS rule, each participant is only responsible for the immediate GMP they contribute to. In this case, UCCs will benefit from both UES and DES principles. The UES principle reduces UCC's cost to €1.02/parcel, with the percentage of the UCC cost decreasing from 67.06% to 22.35%. The DES principle lowers the contribution of the UCC to €2.04 /parcel (44.51%). In addition, the DES rule also alleviates the extra costs faced by a LHC to €0.50/parcel, with the percentage of the cost for LHC decreasing from 32.94% to 10.98%. Table 4 illustrates that the UES strategy provides the most convenient allocation for the UCC. The DES strategy can be convenient both for UCC and LHC.

Table 4 GMP costs to be shared by Stakeholders (€/parcel)

Types of stakeholders	Types of GMP	Cost of GMPs for allocation (€ per parcel)
Supplier	Goods supply	€0
LHC	Long-haul transportation	€1.51
UCC	Urban delivery from UCC	€3.07
Customer	Goods receipt	€0

Table 5 Cost Allocation According to LRS, UES, and DES rules (€/parcel)

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.78	38.82%	0.00	0.00%
LHC	1.51	32.94%	1.78	38.82%	0.50	10.98%
UCC	3.07	67.06%	1.02	22.35%	2.04	44.51%
Customer	0.00	0.00%	0.00	0.00%	2.04	44.51%
Total	4.58	100.00%	4.58	100.00%	4.58	100.00%

Table 6 Composite Cost Allocation Rules (€/parcel)

Types of stakeholders	50%LRS + 50%UES		50%LRS + 50%DES		80%LRS + 20%UES		80%LRS + 20%DES	
	(€)	%	(€)	%	(€)	%	(€)	%
Supplier	0.89	19.41%	0.00	0.00%	0.36	7.86%	0.00	0.00%
LHC	1.64	35.88%	1.01	21.96%	1.56	34.06%	1.31	28.55%
UCC	2.05	44.71%	2.55	55.79%	2.66	58.08%	2.86	62.55%
Customer	0.00	0.00%	1.02	22.26%	0.00	0.00%	0.41	8.90%
Total	4.58	100.00%	4.58	100.00%	4.58	100.00%	4.58	100.00%

UES and DES rules have a clear cost-sharing mechanism for members across the UCC delivery network. The UES rule significantly helps the UCC that transferring its costs to upstream stakeholders. Such a rule responds to an Extended Producer Responsibility principle. Conversely, the DES rule successfully involves final customers in the cost-sharing system. It emphasizes that customers, as the generator of the city logistics activities, also need to contribute to the functioning of urban logistics activities, through an Extended Consumer Responsibility principle.

It is clear that, while UES and DES schemes can provide an advantage to the authority managing the UCC, other involved stakeholders (e.g., suppliers and customers) might feel penalised from such allocations, which could produce extra costs for them. As such, it is worth noticing that compromise solutions can be adopted, by developing convex combinations of the different rules. For instance, a mixed allocation rule, based on a convex combination of LRS and DES approaches could be developed. This can be seen as a way to partially correct the LRS rule (which is the de-facto approach adopted in most cases).

Table 6 illustrates the result provided by such hybrid rules.

Of course, as the proportion devoted to LRS increases, stakeholders' cost allocations will be closer to the original ones. Weights to be assigned to the different responsibility rules could be then seen as the object of negotiations among different stakeholders in order to achieve a compromise agreement, which could be agreed upon by upstream and downstream stakeholders.

5.1 Sensitivity analysis

In practice, some UCCs might outsource the last mile delivery activities to other companies (e.g., Nijmegen UCC, as reported by Duin et al. (2016)). Under this strategy, the UCC will only be responsible for the cost of in-facility goods handling and sorting. However, such an outsourcing strategy could introduce some changes to the cost of last-mile delivery. In order to assess the feasibility of the cost allocation rules in such cases, we design the following sensitivity analysis, which is based on the following assumptions:

1. The total cost of last-mile delivery in the UCC network without outsourcing is equal to the total cost of last-mile delivery after implementing outsourcing strategy;
2. The total cost of last-mile delivery in UCC network without outsourcing is unequal to the cost of last-mile delivery after implementing outsourcing strategy (the cost of last-mile delivery may be increased due to the expertise of the carrier and to economies of scale; alternatively, the cost of last-mile delivery may be decreased due to additional administrative costs.)

Table 7 Cost allocations under the outsourcing strategy without total cost change (€/parcel)

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.60	35.04%	0.00	0.00%
LHC	1.51	32.93%	1.60	35.04%	0.38	8.23%
UCC	0.99	21.63%	0.85	18.56%	0.70	15.45%
Local Carrier	2.08	45.44%	0.53	11.36%	1.75	38.16%
Customer	0.00	0.00%	0.00	0.00%	1.75	38.16%
Total	4.58	100.00%	4.58	100.00%	4.58	100.00%

5.1.1 Assumption 1: outsourcing without total cost changes

In case the outsourcing of the last-mile delivery GMP does not alter the total cost, the cost structure of the whole delivery network is reported in Table 7. The UCCs' original cost is €0.99/parcel, local carriers' original cost is €2.08/parcel. It can be noticed that, in this case, the final cost share for the UCC,—under LRS (€0.99/parcel), UES (€0.85/parcel), and DES (€0.70/parcel)—are below the best solutions which can be obtained when the last-mile delivery process is conducted in-house (€1.02/parcel). This can be seen as an incentive for UCCs to outsource such activities. Besides this, DES rules also reduce the cost for the LHC to 0.38; such a cost allocation scheme appears to be the best for relieving the cost for both LHCs and UCCs under a last-mile outsourcing strategy.

5.1.2 Assumption 2: outsourcing with total cost changes

The outsourcing of last-mile delivery activities could, however, cause changes in the total cost structure. In this case, several considerations can be developed, based on the cost of the last-mile delivery activities performed by an outsourced carrier. If the local carrier can keep its cost lower than €2.76/parcel (see in Table 8), the outsourcing strategy is convenient, from a UCC perspective, under all the principles (LRS, UES, and DES). Otherwise, cost allocation based on UES principle will be higher than the best solution provided by an in-house strategy (€1.02/parcel). As such, LRS and DES principles need to be preferred by the UCC (see Fig. 3).

The best results of cost allocation will be changed with the variation of the local carrier's cost (details are shown in Fig. 4): if the local carrier can keep its urban delivery cost lower than €1.48/parcel (Table 9), UES will be the most convenient allocation rule for the

Table 8 Cost Allocation of UCC in Outsourcing Strategy with carriers cost in €2.76/parcel

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.78	33.75%	0.00	0.00%
LHC	1.51	28.71%	1.78	33.75%	0.38	7.17%
UCC	0.99	18.82%	1.02	19.38%	0.70	13.45%
Local Carrier	2.76	52.47%	0.68	13.12%	2.09	39.69%
Customer	0.00	0.00%	0.00	0.00%	2.09	39.69%
Total	5.26	100.00%	5.26	100.00%	5.26	100.00%

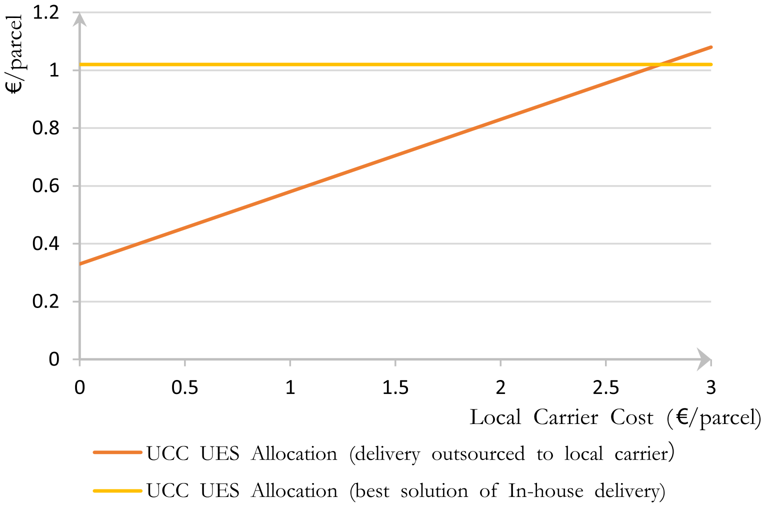

Fig. 3 Variation of UCC cost allocation under UES rule. A comparison of in-house and outsourced delivery options

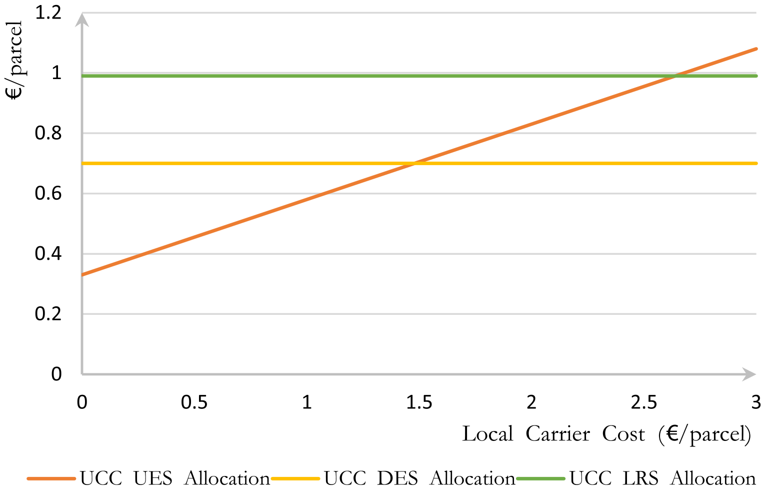

Fig. 4 UCC cost allocations under different responsibility rules based on variations of the carrier's cost

UCC. Such a rule also allows the UCC to subsidise the activities of the LHC and local carriers. If the local carrier keeps its cost between €1.48/parcel and €2.64/parcel (Table 10), a DES rule produces a better-cost allocation. When considering the need to encourage LHCs to use the UCC, DES will always provide the most convenient solution, reducing the LHC's extra cost to €0.38/parcel. When local carriers can keep last-mile costs under €1.70 per parcel (Table 11), a UES allocation can also benefit the LHC (Fig. 5). Therefore, when the local carrier can keep its costs under €1.48/parcel (Table 9), the UES rule can provide the best solution for the UCC, while also providing partial financial relief to the LHC.

Table 9 Cost Allocation of UCC in Outsourcing Strategy with carriers cost in €1.48/parcel

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.46	36.56%	0.00	0.00%
LHC	1.51	37.94%	1.46	36.56%	0.38	9.48%
UCC	0.99	24.87%	0.70	17.59%	0.70	17.78%
Local Carrier	1.48	37.19%	0.36	9.30%	1.45	36.37%
Customer	0.00	0.00%	0.00	0.00%	1.45	36.37%
Total	3.98	100.00%	3.98	100.00%	3.98	100.00%

Table 10 Cost Allocation of UCC in Outsourcing Strategy with carriers cost in €2.64/parcel

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.75	33.95%	0.00	0.00%
LHC	1.51	29.38%	1.75	33.95%	0.38	7.34%
UCC	0.99	19.26%	0.98	19.26%	0.70	13.76%
Local Carrier	2.64	51.36%	0.66	12.84%	2.03	39.45%
Customer	0.00	0.00%	0.00	0.00%	2.03	39.45%
Total	5.14	100.00%	5.14	100.00%	5.14	100.00%

Table 11 Cost Allocation of LHC in Outsourcing Strategy with carriers cost equal to €1.70/parcel

Types of stakeholders	LRS (€)	LRS (%)	UES (€)	UES (%)	DES (€)	DES (%)
Supplier	0.00	0.00%	1.51	35.95%	0.00	0.00%
LHC	1.51	35.95%	1.51	35.95%	0.38	8.99%
UCC	0.99	23.57%	0.75	17.98%	0.70	16.85%
Local Carrier	1.70	40.48%	0.43	10.12%	1.56	37.08%
Customer	0.00	0.00%	0.00	0.00%	1.56	37.08%
Total	4.20	100.00%	4.20	100.00%	4.20	100.00%

5.2 Discussion

According to Taniguchi (2014), municipal UCCs (and, in general, urban logistics projects) should not depend too heavily on public finances. As such, municipalities should build, from the very beginning, mechanisms aimed at helping the start-up phase of UCC and achieving financial sustainability through cost-reduction and economies of scale (Taniguchi, 2014).

Within this context, the illustrated case study has shown that the proposed allocation rules can provide municipalities with useful tools. Indeed, UCCs have the potential to benefit, under certain conditions, from both UES and DES allocations, as these principles enact suppliers' and customers' participation in UCC operating costs. This is aligned with the empirical advice provided by Kiba-Janiak (2016), stating that, despite their individual rationality, stakeholders may perceive as *fair* the regulatory role of municipalities. In

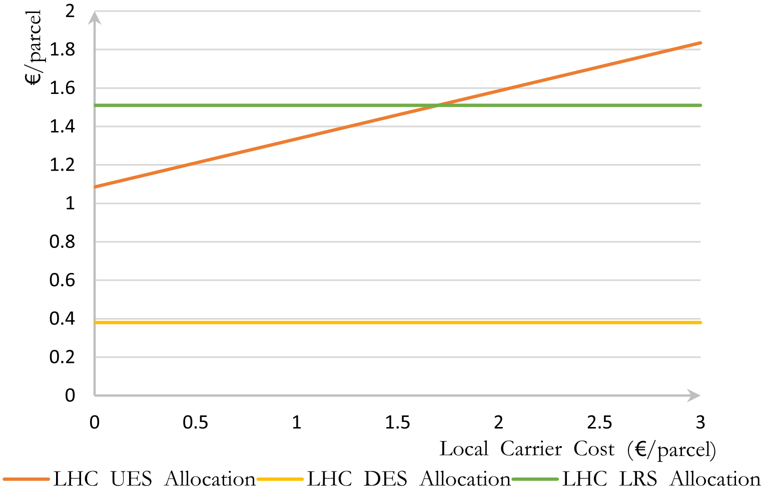

Fig. 5 LHC cost allocations under different responsibility rules based on variations of the carrier's cost

particular, the paper has dealt with a specific UCC delivery network case study. Comparing with the original structure of logistical costs, we find out that a UES rule provides the most convenient solution for the UCC. Also, a DES rule benefits both the LHC and the UCC (see Table 4).

Our analysis is extended to the case of an UCC which is outsourcing its last-mile delivery activities. Interestingly, if the outsourcing process does not modify the cost structure of the logistical network, then outsourcing the last-mile delivery is always beneficial to the UCC. This result is, interestingly, obtained regardless of the cost-allocation policy adopted by the LA.

However, this assumption might be quite ideal. Therefore, our analysis has turned to a more realistic case, involving a change in the cost structure caused by the outsourcing of the last-mile distribution. In this case, results are less straightforward. A DES rule may be set to benefit the UCC, if local carriers' costs are high (see Fig. 4). Moreover, a DES rule might also be convenient for incentivising LHCs participation in UCCs (see Fig. 5). From the UCC perspective, a change in the optimal allocation rule occurs if the costs of the local carrier (who are in charge of last-mile delivery processes) are larger or lesser than some critical values, which have been identified through our analysis. Our method allows for the numerical evaluation of such thresholds and may provide a very practical tool for LAs interested in evaluating the effect of specific cost allocation rules.

As such, if local carriers' costs are larger/smaller than some critical thresholds, LAs may, accordingly, decide to implement the right policy in order to safeguard the financial viability of the UCCs. Undoubtedly, local authorities might choose the policy that safeguards the financial viability of the UCC (and not necessarily the one of other stakeholders). Also, the implementation of composite allocation rules could be adopted, in an attempt to implement lighter mitigation strategies. It has to be remarked, though, that as these schemes might cause the increase in costs to be faced by other stakeholders, such a solution should be implemented in practice through strong political interventions and thorough consultation and engagement.

In terms of comparison with the recent literature, our results are consistent with the recent literature. For instance, Van Heeswijk et al. (2020) highlight the financial unsustainability of UCCs, providing, de facto, the motivation for our analysis, which is aimed at finding optimal cost allocation policies that are capable of mitigating the original structure of logistical costs. This is similar to the work performed by Dahlberg et al. (2018); however, this study assumes that LAs are willing to face some costs in order to ensure a stable collaboration among stakeholders. Such a requirement is a strong one and assumes a financial intervention of LAs in UCC networks. The focus in Dahlberg et al. (2018) is on the stability of cooperation; conversely, our focus is to define policies that promote the fairness of cooperation among stakeholders. In general, stability and fairness are distinct concepts in cooperative game theory.

6 Conclusions

Recently, many local authorities have set up Urban Consolidation Centres (UCC) for dealing with challenges arising from the negative impacts of logistics in urban contexts through a freight consolidation strategy. It has been shown that such facilities can contribute to the improvement of environmental quality in cities by reducing air pollution and alleviating congestion. Notwithstanding these encouraging premises, the number of successful UCC projects in Europe is very low, with most of the UCCs fail to achieve financial sustainability and to operate autonomously after the initial experimental phase that might be heavily supported by public funds.

In order to propose mechanisms that could favour the financial sustainability of UCC systems, this research has developed an adaptation of established game-theoretic approaches to the problem of responsibility and cost allocation among stakeholders participating in a UCC delivery network. Proposed approaches are inspired by extended responsibility principles that have been previously applied to the supply chain context. A solution based on the Shapley Value concept has been employed in order to calculate numerical results of cost allocations, under different responsibility scenarios. Applications of the model to a real-world scenario have been developed, along with a sensitivity analysis which has evaluated the suitability of the approach to different scenarios, and the possibility of applying the developed cost allocation rules in order to incentivise stakeholders' participation in UCC projects.

As the case study has revealed, allocation schemes based on an extended responsibility concept (UES, DES and resulting composite rules) can enhance the viability of UCCs, alleviating the need for public subsidies through suppliers' and customers' participation in UCC operating costs. As these schemes might cause increases in costs faced by other stakeholders, it has also been remarked that these solutions should be implemented through strong political interventions and thorough consultation and engagement.

The proposed rules have been validated on secondary data based on a real-world case study; future researches could be aimed at investigating the practical implementation of the proposed rules through primary data to be collected in collaboration with Local Authorities. Also, the cost allocation scheme could be extended in order to take into account more complex delivery networks and to evaluate the impact of reverse logistics operations.

Appendix

Parameter values for the UCC case – adapted from Janjevic and Ndiaye (2017b)

Parameters	Value
Average distance from the depot to the delivery zone	11.2 km
Average speed of the vehicle from the depot to the delivery zone	30.70Km/hour
Radius of the service area	7.16 km
Average speed of the vehicle within the delivery zone	30.70 km/hour
Vehicle travel distance from the depot to the UCC location	8 km
Average speed of the vehicle between the depot and the UCC	36.84 km/hour
Maximum vehicle capacity	212 parcels
Total expenses for UCC services	€3.75/parcel
Average parcels received per customers	2.5 parcels/customer
Types of vehicle used in the route for direct delivery	Light commercial vehicle (less than 3.5 T)
Types of vehicle used in the route between LHC depot and UCC	
Types of vehicle used by the UCC in the urban delivery route	

Acknowledgements This research was partially supported by the following projects: "Promoting Sustainable Freight Transport in Urban Contexts: Policy and Decision-Making Approaches (ProSFeT)", funded by the European Union H2020-MSCA-RISE-2016 programme (Grant Number: 734909); "Promoting Circular Economy in the Food Supply Chain (ProCEedS)", funded by European Union H2020-MSCA-RISE-2018 programme (Grant Number: 823967).

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