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EVALUATION OF SMART CITY LOGISTICS SOLUTIONS

ABSTRACT

The negative effects of goods flows realisation are most visible in urban areas as the places of the greatest concentration of economic and social activities. The main goals of this article were to identify the applicable Industry 4.0 technologies for performing various city logistics (CL) operations, establish smart sustainable CL solutions (SSCL) and rank them in order to identify those which will serve as the base points for future plans and strategies for the development of smart cities. This kind of problem requires involvement of multiple stakeholders with their opposing goals and interests, and thus multiple criteria. For solving it, this article proposed a novel hybrid multi-criteria decision-making (MCDM) model, based on BWM (Best-Worst Method) and CODAS (COmbinative Distance-based ASsessment) methods in grey environment. The results of the model application imply that the potentially best SSCL solution is based on the combination of the concepts of micro-consolidation centres and autonomous vehicles with the support of artificial intelligence and Internet of Things technologies. The main contributions of the article are the definition of original SSCLs, the creation of a framework and definition of criteria for their evaluation and the development of a novel hybrid MCDM model.

KEYWORDS

city logistics; smart city; Industry 4.0; grey BWM; grey CODAS.

1. INTRODUCTION

Transport accounts for a quarter of the EU's greenhouse gas emissions, which are still growing (The European Green Deal, 2019). This is one of the reasons why the EU established the European Green Deal strategy, one of which goals is to further reduce emissions from transport. The EU strives to achieve climate neutrality, i.e. a 90% reduction in transport emissions by 2050 [1]. Transport should become drastically less polluting, especially in cities. In order to achieve this, the EU transport system and infrastructure should be made fit to support new sustainable mobility services that can reduce congestion and pollution, especially in urban areas [1]. Accordingly, city logistics (CL) is an important planning domain because of its tight bonds with the sustainable development of urban areas. The growth in CL problems, caused by structural changes of goods flows, political and social changes, new business models etc. [2] has attracted the attention of many researchers in this field. Although the importance of CL is recognised in the scientific literature, in practice, the impact of logistics activities, especially transportation, has been unsustainable for decades [3]. Neglect and inadequate approach towards the problems of logistics in urban areas results in great traffic congestions, air pollution, time losses, the inefficiency of logistics processes, generating of vibrations and noise etc., which can be mitigated only through comprehensive and long-term planning of CL [4].

City administration in most cases has a negative attitude towards logistics activities and tries to constrain them by implementing different restrictive measures [5]. City administration should, instead, play the role of integrators and stimulate other stakeholders to cooperate in order to achieve sustainable CL solutions. Attempts to implement individual initiatives and measures in practice have shown that the traditional approach for CL planning is unsustainable [6]. Aside from the understanding of city characteristics, identification of participants, their demands, goals and interactions, successful implementation of CL solutions requires integrated planning, cooperation of stakeholders, removing of all barriers and defining of measures that would support the realisation of plans [7]. The application of modern Industry 4.0 technologies makes the definition of creative and sustainable CL solutions possible.

The technologies of Industry 4.0 are already the topic of scientific discussion. However, aside from the analysis of individual technologies and their expected influence on logistics, the analysis of smart solutions of CL (SSCL) does not exist. Accordingly, this article proposes SSCLs combining the existing initiatives, concepts and measures with the technologies of Industry 4.0. The diversity of CL problems inspired the analysis of a broad set of initiatives, concepts and measures [8, 9]. Some of the most analysed in the literature, and thus the ones that make the basis for the establishment of the SSCLs in this article, are cooperation and flow consolidation (e.g. [10–14]), eco-vehicles (e.g. [15] and small delivery vehicles (e.g. [16]), alternative transportation modes (e.g. [17–19]), crowdsourcing (e.g. [20, 21]), cargo hitching (e.g. [22]), etc. On the other side, the technologies of Industry 4.0 provide an entirely new spectrum of possibilities in the planning and realisation of logistics activities and processes [23]. Some of the most analysed Industry 4.0 technologies that have the greatest potential to reshape existing logistics systems, especially in the field of CL, are Internet of Things (IoT) (e.g. [24, 25]), Artificial Intelligence (AI) (e.g. [26]), Cloud Computing (CC) (e.g. [27]), Blockchain (e.g. [28]), Augmented Reality (AR) (e.g. [29]), Autonomous Vehicles (AV) (e.g. [30, 31]), Advanced Robotics (e.g. [32]) etc.

There are only a limited number of articles in the literature that focus on the selection of the most appropriate CL solution/initiative. Some of the articles focus on the evaluation of initiatives from specific categories [4, 33]. Some articles focus on the selection of the most appropriate CL solution from a set of solutions that are based on different combinations of initiatives, technologies and ideas, for the whole urban area [e.g. 34, 20], or the central business district [35]. Some articles also analyse different configurations of consolidation centres in the combination with other initiatives [36] and various forms of horizontal cooperation [12]. On the other hand, there are no research articles that focus on the definition and selection of CL solutions that lead towards smart cities. This article is trying to fill the research gap by defining different SSCLs, based on existing CL initiatives and concepts, in the combination with the innovative smart technologies of Industry 4.0. At the same time, this is one of the main contributions of the article.

CL problems require finding compromise solutions that will be in line with the very often conflicting attitudes and goals of different stakeholders, from which a large number of criteria for evaluating the solutions arise. Accordingly, for solving the problem of ranking and selecting the most favourable CL solution, an appropriate multi-criteria decision-making (MCDM) method or the combination of the methods (hybrid models) needs to be applied. The main motive for using a hybrid model is to make use of the individual advantages of each method while minimising their disadvantages [37]. There are no methods that are better or worse, but only those that more or less correspond to the defined problem structure [15]. Accordingly, there are MCDMs in the literature that are mostly used to determine the weights of criteria, among which pair wise comparison methods dominate, and those that are used to rank the alternatives, among which distance-based methods dominate. In this paper, the BWM method was used for obtaining the criteria weights. The main advantages, and thus the reasons for selecting the BWM instead some other pair wise comparison methods, such as AHP and ANP, are that it has a significant better consistency while forming comparison matrices, which leads to more reliable results, has a greater degree of conformity with other MCDM methods, and minimises the required data for element comparison. To rank the alternatives in this article, the CODAS method is used for the following reasons. In comparison with other distance-based methods, such as TOPSIS, VIKOR, EDAS, COPRAS etc., the advantage of CODAS is the possibility of considering several distance metrics when evaluating the problem elements, which improves the result accuracy significantly and makes a fine differentiation between closely ranked alternatives [38]. The methods that make up the model have some shortcomings that can arise due to the inaccurate, incomplete or ambiguous evaluations by the decision makers. Most of these shortcomings can be eliminated by applying intuitive or interval sets (e.g. fuzzy, rough, grey), which is exactly why the model is developed in the grey environment.

Another contribution of the article is that it proposes an innovative framework for the selection of the most appropriate SSCLs from the aspect of all CL stakeholders, whose attitudes are expressed through 10 criteria. For the ranking of the defined SSCLs, a novel hybrid multi-criteria decision-making (MCDM) model, based on BWM (Best-Worst Method) and CODAS (COmbinative Distance-based ASsessment) methods in grey environment, is developed. BWM [39] is based on defining the best and worst element (criterion or alternative) for decision-makers and their comparison with other criteria. The extraction of element importance (weight) requires the formulation and solving of a maximin problem. In the last few years, the BWM method has, individually or in combination with other methods, found its application for solving various problems from different areas (e.g. [40–43]). The CODAS method [38] is based on the ranking of decision-making elements (alternatives in most cases) by considering Euclidean and Taxicab distance from the negative ideal point (solution, alternative). CODAS is a relatively new method, but in a short time, individually or in the combination with other methods, it has already been used for solving various problems (e.g. [44–47]). The problem with conventional BWM and CODAS methods could be the uncertainties of decision-makers during the definition of preferences, which could be avoided by the application of intuitive or interval sets (for example fuzzy, rough, grey). Fuzzy, rough and grey sets represent different ways of uncertainty representation in datasets [48]. This article develops the described MCDM method in grey environment which enables better processing of partial data and the combination of ambiguous and incomplete data into one model [48]. The CODAS method was developed in grey environment in the article [44] while the grey BWM was developed in the article [49]. However, there are no examples of the combination of these two methods in any form (conventional or in the environment of intuitive/interval sets). This research gap is covered in this article, which represents another of its contributions.

The article is organised as follows. The next section defines and describes the SSCLs that are analysed, as well as the criteria for their evaluation. The novel MCDM model is described in Section 3, while its application for the defined problem, as well as the sensitivity analysis of the obtained results, are presented in Section 4. Section 5 provides a discussion, while the last section presents concluding remarks and the direction of future research.

2. PROBLEM DEFINITION

This section defines the SSCLs that are analysed in this article. The solutions are defined according to typical CL solutions and their combination with the technologies of Industry 4.0. The ongoing phenomenon in CL is the increase of small delivery frequencies [50], which cause most of the problems in the planning and realisation of logistics activities [6, 7]. This trend tends to continue in the future, therefore the focus of this article is set on such categories of goods flows. The assumption is that all solutions are based on the concept of consolidation and cooperation through urban consolidation centres (UCC) at the outskirts of urban areas. UCCs have been thoroughly analysed in the literature and they stand out as exceptional CL solution elements for systems with low collaboration degree and utilisation rate of resources caused by the increasing trend of small delivery frequencies [4, 6, 11, 12, 15]. UCCs represent a potential domain for the application of advanced robotics in goods handling processes, order picking, marking, sorting etc., therefore it will not be explicitly repeated in the description of SSCLs. Since the ongoing trend is also reducing human labour and increasing the participation of automated technologies in everyday life (therefore in logistics activities as well), it is obvious that such technologies would represent elements of future smart CL solutions. Having in mind the great expansion of information technologies in the last decades and the abundance of data which are generated, collected and analysed on a daily basis in logistics systems, it is assumed that decision support systems, as well as blockchain technology, are an integral part of every SSCL. The integration of blockchain technology into SSCLs is mandatory since data safety becomes more and more important in modern businesses.

The first solution (SSCL1) refers to the combination of the ideas of parcel lockers and crowdsourcing (*Figure 1a*). The delivery of goods from the UCC to parcel lockers is realised with road delivery vehicles. Flow generators can collect the goods from parcel lockers. The registered crowd agents can take over the delivery on the relation parcel lockers-generators or UCC-parcel lockers. The application of crowdsourcing in delivery requires the implementation of a CC platform that would provide system access for crowd agents, the information about deliveries that are available for taking over, and the communication with logistics providers and flow generators. With the application of AR, it is possible to visualise the possibilities for package storage in parcel lockers, as well as to inform the crowd agents about potential delivery routes, traffic conditions etc. In this case, AR would represent an integral part of the CC platform, while being available to all crowd agents with appropriate hardware (tablets and mobile phones). The application of IoT is apparent because it is required to set up adequate communication between UCC, delivery vehicles, crowd agents, flow generators, parcel lockers etc. The application of IoT would enable the tracking of deliveries (and goods) at the CC platform in real-time which would make delivery planning easier for providers and crowd agents. The application of parcel lockers reduces the uncertainties which exist in classical crowdsourcing models because it makes sure the goods are delivered to the close proximity of flow generators. Furthermore, the providers are relieved from the responsibility in the last phase of the delivery. This solution requires the installation of parcel lockers in the urban area and the development of a CC platform. The development of SSCL1 requires relatively small investments, but its main disadvantage is delivery reliability which is problematic because of the crowd agents' autonomy.

The solution SSCL2 is based on the concepts of flow micro-consolidation and the application of autonomous vehicles (*Figure 1b*). The development of micro-consolidation centres (MCCs) in the delivery zone aims to shift the transportation work to autonomous vehicles. The delivery at the relation UCC-MCCs is realised with road delivery vehicles, while on the relation MCCs-flow generators, autonomous vehicles are utilised – autonomous road vehicles and

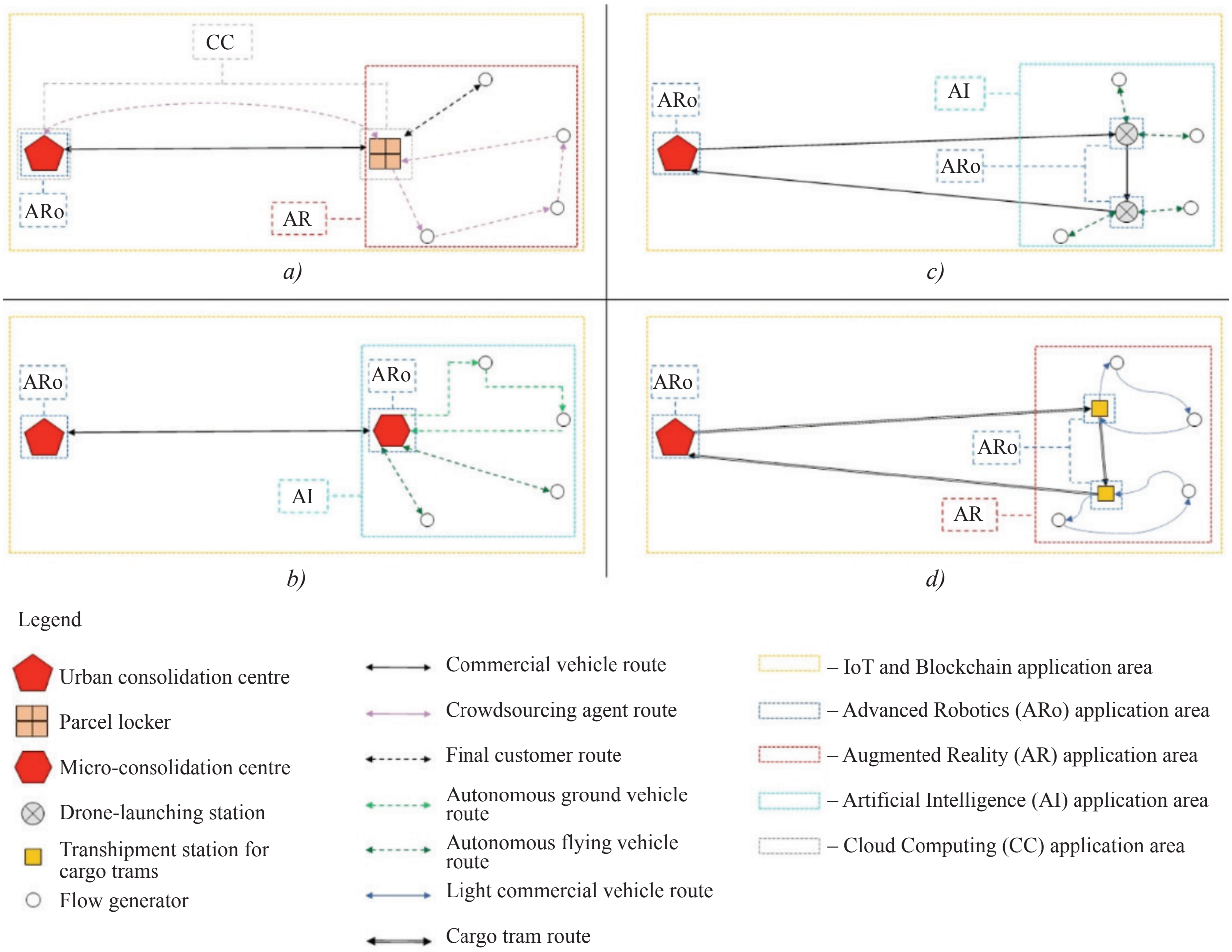

Figure 1 – The proposed SSCLs

drones. AI makes it possible for autonomous vehicles to independently plan and realise their deliveries, and to adapt to the conditions in the environment. Aside from UCCs, advanced robotics could be applied at MCCs for all activities that refer to the handling of goods. IoT makes the communication between system echelons, autonomous vehicles, logistics providers etc. more efficient. The transformation of the system into a two-echelon system, such as in this solution, makes the delivery process more efficient, but also requires the development of additional infrastructure – MCCs. The application of autonomous vehicles could have positive effects on sustainability because it replaces the traditional delivery approach (road delivery vehicles), but opens a wide variety of questions regarding the regulatory framework of the application.

In the third solution (SSCL3), the delivery is realised through the combination of road delivery vehicles and drones (*Figure 1c*). Road delivery vehicles play the role of moving depots that visit the locations reserved for launching drones for the realisation of the last delivery phase. Aside from the drones, the road vehicles are equipped with advanced robotics which is responsible for the automation of goods handling and its loading at drones. As in the previous solution, the application of drones is automated through AI and does not require the involvement of humans, while the synchronisation is made possible with IoT and real-time tracking. This solution does not require the development of new infrastructure, which is its main advantage but requires the synchronisation of road vehicles and drones. The main disadvantage of the solution is still the dominance of road delivery vehicles in the city, while the regulations that refer to the usage of drones for urban deliveries are still absent.

The fourth solution (SSCL4) refers to the application of cargo trams for goods transportation to loading stations in the delivery zone, where the modal shift to light delivery vehicles – bicycles, cycles and scooters takes place (*Figure 1d*). The application of AR is possible in the last phase of the delivery as a support for the drivers of light delivery vehicles, and in combination with IoT, it ensures on-time information about the incoming goods at loading stations. At the loading stations, it is possible to apply advanced robotics to automate the goods handling activities. The disadvantage of this solution is the need for establishing regular tram lines on the relation UCC-loading stations, the development of those stations, and general low flexibility of rail transportation mode. The advantages of the solution are a high degree of road transportation vehicle elimination from the city and the flexibility in the last phase of delivery where the light delivery vehicles are utilised.

When solving CL problems, it is necessary to define the criteria in a way to encompass the attitudes, demands and goals of all stakeholders – local administration, logistics providers, service users and residents [6], and to cover all three sustainability aspects – social, economic and environmental [51]. The existing literature considered a broad set of criteria with regard to the nature and the observation level of problems [4, 15, 35, 52]. The following text describes the criteria used for SSCL evaluation in this article.

Efficiency (C1) describes the rationalisation level of logistics activities of solutions and refers to the loading space utilisation of delivery vehicles, the average travelled distance per delivery, energy and fuel consumption, average delivery time etc. *The modal shift of transport work* (C2) refers to the stimulation for the application of alternative transportation modes as a replacement for road delivery vehicles in urban areas. *Reengineering level* (C3) describes the reorganisation complexity of the existing logistics system to transform it into the desired one. The complexity is reflected by the need for structural and organisational changes in logistics systems, the development and improvement of new information systems, the adaptation of business politics to incoming technological and business trends, the procurement and studying of modern Industry 4.0 technologies, personnel training etc. *The development of additional infrastructure* (C4) refers to the need for developing adequate logistics infrastructure – MCCs, parcel lockers, loading stations, etc. *System reliability* (C5) refers to the availability of services and goods in acceptable time intervals. *Flexibility* (C6) refers to the ability to adapt the system to unexpected disturbances and changes in environmental characteristics and requirements. *The complexity of regulatory framework defining* (C7) refers to all procedures, measures and laws that have to be defined and executed to make the application and exploitation of solutions possible. *Effects on mobility* (C8) refers to the improvement of conditions that ensure the undisturbed realisation of goods and people flows in urban areas which succeeds the application of the observed solution

– the improvement of traffic conditions and safety. *Environmental impact* (C9) describes at which level the observed solution contributes to the reduction of negative environmental impacts of logistics activities – the emission of air pollutants, noise and vibrations. *Operational complexity of delivery* (C10) depends on the transformation degree of goods flows and the applied technologies. It refers to the complexity of activities that must be realised in the delivery process. *Acceptability* (C11) refers to the willingness of stakeholders, especially logistics providers and residents, to accept the observed solution.

3. A HYBRID GREY BWM-CODAS MODEL

For solving the defined problem, a novel hybrid MCDM model that combines BWM and CODAS methods in *grey* environment is developed. The *grey* BWM method is used for criteria weight extraction while *grey* CODAS is used for alternative ranking. The application steps of the model are explained in the following text.

Step 1: Define the problem structure – form the set of alternatives, the criteria for their evaluation and identify the stakeholder groups.

Step 2: Define the *grey* scale for criteria and alternative evaluation by the decision-makers. Linguistic terms and their corresponding *grey* values are shown in *Table 1*.

Step 3: Extract the criteria weights by using the *grey* BWM method. The procedure requires the realisation of several steps (3.1–3.3) that are explained in the following text.

Table 1 – Grey scale used for evaluation

Linguistic term	Abbreviation	Grey scale
None	N	[0, 2]
Very Low	VL	[1, 3]
Low	L	[2, 4]
Fairly Low	FL	[3, 5]
Moderate	M	[4, 6]
Fairly High	FH	[5, 7]
High	H	[6, 8]
Very High	VH	[7, 9]
Extremely High	EH	[8, 10]

Step 3.1: In general, every stakeholder group d (d=1,...,f), where f represents the number of stakeholder groups, chooses the best and the worst element (the most and least important criterion) j_B and j_W respectively (j=1,...,m), where m stands for the number of criteria. Every stakeholder group evaluates other elements (criteria) in comparison with the best and worst elements by using the linguistic terms that can be transformed into *grey* values through the relations from *Table 1*. In such a way, *grey* vectors are extracted: „the best compared to others" - $\otimes A_B=(\otimes a_{B1},\otimes a_{B2},...,\otimes a_{Bm})$, and „others compared to the worst" - $\otimes A_W=(\otimes a_{1W},a_{2W},...,a_{mW})$.

Step 3.2: Regarding every stakeholder group d, optimal *grey* criteria values (weights) $\otimes w_{d1},\otimes w_{d2},...,\otimes w_{dm}$, $\forall d$=1,...,f are determined by solving the following nonlinear problem (*Equation 1*):

$$\min \otimes \xi$$
$$s.t.\begin{cases} \left| \frac{\otimes w_B}{\otimes w_{dj}} - \otimes a_{Bj} \right| \leq \otimes \xi \\ \left| \frac{\otimes w_{dj}}{\otimes w_W} - \otimes a_{jW} \right| \leq \otimes \xi \\ \sum_{j=1}^{m} W(\otimes w_{dj}) = 1 \\ \underline{w}_{dj} \leq \overline{w}_{dj} \\ \underline{w}_{dj} \geq 0 \\ j = 1,...,m \end{cases} \tag{1}$$

where $\otimes\xi = [\underline{\xi},\overline{\xi}]$ is a *grey* number whose lower and upper values are $\underline{\xi}$ and $\overline{\xi}$, respectively, $\otimes w_B = |\underline{w}_B,\overline{w}_B|$ is the optimal *grey* number (weight) of the best element (the most significant criterion), $\underline{w}_B$ and $\overline{w}_B$ are the lower and upper values of the *grey* number $\otimes w_B$, $\otimes w_W = [\underline{w}_W,\overline{w}_W]$ is the optimal *grey* number (weight) of the worst element (least significant criterion) with $\underline{w}_W$ and $\overline{w}_W$ as its lower and upper values, $\otimes w_{dj} = [\underline{w}_{dj},\overline{w}_{dj}]$ is the optimal *grey* number (weight) of the element (criterion) j, j=1,...,m, $j \neq j_b, j_W$, $\otimes a_{Bj} = [\underline{a}_{Bj},\overline{a}_{Bj}]$ is the *grey* number that describes how much the best element (most significant) criterion is better than the element (criterion) j, $\otimes a_{jW} = [\underline{a}_{Bj},\overline{a}_{jW}]$ describes how much the element j is better (more significant) from the worst element (criterion). $W(\otimes w_j)$ is the *white* value of the *grey* number $\otimes w_j$ which is determined by *Equation 2* [53]:

$$W(\otimes w_{dj}) = (\underline{w}_{dj} + \overline{w}_{dj})/2 \tag{2}$$

As the optimisation problem in *Equation 1* requires the comparison of *grey* numbers, the model must include the principles of *grey* possibility degrees (GDPs) [54]. Now, the problem from *Equation 1* could be transformed in the following way:

$$\min \otimes\xi$$
$$s.t.\begin{cases} P\left\{\left|\frac{\otimes w_B}{\otimes w_{d_j}} - \otimes a_{B_j}\right| \le \otimes\xi\right\} < 0.5 \\ P\left\{\left|\frac{\otimes w_{d_j}}{\otimes w_W} - \otimes a_{jW}\right| \le \otimes\xi\right\} < 0.5 \\ \sum_{j=1}^{m} W(\otimes w_{d_j}) = 1 \\ \underline{w}_{d_j} \le \overline{w}_{d_j} \\ \underline{w}_{d_j} \ge 0 \\ j = 1,...,m \end{cases} \tag{3}$$

where P represents the GPD value which can be calculated for any two *grey* values (for example $\otimes p$ and $\otimes q$) in the following way [54]:

$$P[\otimes p \le \otimes q] = \frac{\max(0.L(\otimes p) + L(\otimes q) - \max 0.\overline{p} - \underline{q})}{L(\otimes p) + L(\otimes q)} \tag{4}$$

where $L(\otimes p) = |\overline{p} - \underline{p}|$ and $L(\otimes q) = |\overline{q} - \underline{q}|$ are valid. To ensure that $\otimes p$ is lower than $\otimes q$ the inequality $P\{\otimes p \le \otimes q\} < 0.5$ must be valid.

By solving Equation 3, the optimal *grey* numbers (weights) of elements (criteria) ($\otimes wd_1, \otimes w_{d_2}, ..., \otimes w_{d_m}$) are extracted, and the procedure is repeated for every stakeholder group d.

Step 3.3: Check the comparison consistency. To control the results of the method, it is necessary to calculate the consistency ratio (CR) with Equation 5:

$$CR = R(\otimes\xi)/CI \tag{5}$$

where $R(\otimes\xi)$ represents the white value of the *grey* number $\otimes\xi$, calculated by the Equation 2, and CI represents the consistency index which is derived as the largest solution value for the following quadratic equation:

$$CI^2 - (1 + 2\overline{a}_{BW})CI + +(\overline{a}_{BW}^2 - \overline{a}_{BW}) = 0 \tag{6}$$

where $\overline{a}_{BW}$ is the upper value of the *grey* number $\otimes a_{BW} = [\underline{a}_{BW}, \overline{a}_{BW}]$ which represents the greatest *grey* number from the comparisons of the best (most significant) element (criterion) with other elements (criteria), and the comparison of other elements (criteria) with the worst (least significant) element:

$$\otimes a_{BW} = \max_j \{\otimes a_{Bj}, \otimes a_{jW}\} \tag{7}$$

The comparison is considered consistent if the CR value is close to 0 [39].

Step 3.4: The final element (criteria) weights are extracted with Equations 8–10 [44]:

$$\otimes w_j = [\underline{w}_j, \overline{w}_j], \quad \forall j = 1,...,m \tag{8}$$

$$\underline{w}_j = \left(\prod_{d=1}^{l} \underline{w}_{dj}\right)^{1/d} \tag{9}$$

$$\underline{w}_j = \left(\prod_{d=1}^{l} \underline{w}_{dj}\right)^{1/d} \otimes a_{BW} = \max_j \{\otimes a_{Bj}, \otimes a_{jW}\} \tag{10}$$

Step 4: Evaluate the alternatives by applying the extension of the conventional CODAS in *grey* environment [38].

Step 4.1: Form the *grey* decision matrix ($\otimes X$) in the following way:

$$\otimes X = [\otimes x_{ij}]_{n \times m} = \begin{bmatrix} \otimes x_{11} & \otimes x_{12} & \cdots & \otimes x_{1m} \\ \otimes x_{21} & \otimes x_{22} & \cdots & \otimes x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes x_{n1} & \otimes x_{n2} & \cdots & \otimes x_{nm} \end{bmatrix} \tag{11}$$

where $\otimes x_{ij} = [\underline{x}_{ij}, \overline{x}_{ij},]$ represents the *grey* evaluation of alternative i (i=1,2,...,n) with regard to criterion j (j=1,2,...,m), where $\underline{x}_{ij}$ and $\overline{x}_{ij}$ represent the lower and upper values of the *grey* number $\otimes x$.

Step 4.2: Form the weighted decision matrix ($\otimes R$) in the following way:

$$\otimes R = [\otimes r_{ij}]_{n \times m} \tag{12}$$

$$\otimes r_{ij} = [\underline{r}_{ij}, \overline{r}_{ij}] = \otimes w_i \cdot \otimes x_{ij} \tag{13}$$

where $\otimes w_i$ represents the *grey* value that refers to the weight of criterion i.

Step 4.3: Define the negative ideal solution in the following way:

$$\otimes ns = [\otimes ns_j]_{1 \times m} \tag{14}$$

$$\otimes ns_j = [\underline{ns}_j, \overline{ns}_j] = [\min_i \underline{r}_{ij}, \min_i \overline{r}_{ij}] \tag{15}$$

Step 4.4: Calculate the Euclidean distances of alternatives from the negative ideal solution:

$$\otimes E_i = [\underline{E}_i, \overline{E}_i] \tag{16}$$

$$\underline{E}_i = \sqrt{\sum_{j=1}^{m} \max(0, \min(\underline{e}_{ij} \cdot \underline{e}_{ij}, \underline{e}_{ij} \cdot \overline{e}_{ij}, \overline{e}_{ij} \cdot \underline{e}_{ij}, \overline{e}_{ij} \cdot \overline{e}_{ij}))} \tag{17}$$

$$\overline{E}_i = \sqrt{\sum_{j=1}^{m} \max(\underline{e}_{ij} \cdot \underline{e}_{ij}, \underline{e}_{ij} \cdot \overline{e}_{ij}, \overline{e}_{ij} \cdot \underline{e}_{ij}, \overline{e}_{ij} \cdot \overline{e}_{ij})} \tag{18}$$

where $\underline{e}_{ij}$ and $\overline{e}_{ij}$ refer to the lower and upper values of the *grey* number $\otimes e_{ij}$ derived from the following equations:

$$\otimes e_{ij} = [\underline{e}_{ij}, \overline{e}_{ij}] = \otimes r_{ij} - \otimes ns_j \tag{19}$$

$$\underline{e}_{ij} = \underline{r}_{ij} - \overline{ns}_j \tag{20}$$

$$\overline{e}_{ij} = \overline{r}_{ij} - \underline{ns}_j \tag{21}$$

Step 4.5: Calculate the *grey* Taxicab distances of alternatives from the negative ideal solution in the following way:

$$\otimes T_i = [\underline{T}_i, \overline{T}_i] \tag{22}$$

$$\underline{T}_i = \sum_{j=1}^{m} |\underline{e}_{ij}| \tag{23}$$

$$\overline{T}_i = \sum_{j=1}^{m} |\overline{e}_{ij}| \tag{24}$$

Step 4.6: Form the *grey* matrix of relative values in the following way:

$$\otimes Ra = [\otimes h_{ik}]_{n\times n} \tag{25}$$

$$\otimes h_{ik} = [\underline{h}_{ik}, \overline{h}_{ik}] \tag{26}$$

$$\underline{h}_{ik} = (\underline{E}_i - \overline{E}_k) + (\psi(\underline{E}_i - \overline{E}_k)\cdot(\underline{T}_i - \overline{T}_k)) \tag{27}$$

$$\overline{h}_{ik} = (\overline{E}_i - \underline{E}_k) + (\psi(\overline{E}_i - \underline{E}_k)\cdot(\overline{T}_i - \underline{T}_k)) \tag{28}$$

where k=1,2,...,n represents the index of the alternative that is compared with all other alternatives i (all alternative pairs are compared), and ψ represents the function which determines the equality threshold of Euclidean distances of two alternatives, determined in the following way:

$$\psi = \begin{cases} 1\, if\, |W(\otimes E_i) - W(\otimes E_k)| \geq \tau \\ 0\, if\, |W(\otimes E_i) - W(\otimes E_k)| < \tau \end{cases} \tag{29}$$

where $W(\otimes E)$ is determined with *Equation 2*.

In *Equation 29*, τ represents the threshold parameter defined by the decision-maker. The recommended values for this parameter are between 0.1 and 0.5. If the difference of Euclidean distances of two alternatives is greater than τ, then the alternative comparison should also include the Taxicab distance values.

Step 4.7: Calculate the GPD values for all alternative pairs ($P\{\otimes h_i \leq \otimes h_k\}$, $\forall i,_k$=1,...,n) by applying *Equation 4*.

Step 4.8: Perform the final alternative ranking according to the values P. The alternative that has the value P<0.5 in the most number of comparisons is considered the best.

4. RESULTS OF THE HYBRID MODEL APPLICATION

This section presents the application of the developed model for solving the observed problem and the results of its application. In the second part, a sensitivity analysis is conducted to determine the stability of the model. In the last part, the discussion of results, their implications and the analysis of the model are presented.

4.1 Hybrid model application

The first application step of the proposed hybrid MCDM model refers to the definition of alternatives and criteria for their evaluation, as well as the identification of stakeholder groups that are interested in solving the observed problem. The considered alternatives and criteria used for their evaluation are described in Section 3, while the evaluation is performed by four stakeholder groups: logistics service providers (Pro.), users (Use.), city administration (Adm.) and residents (Res.). The providers want to minimise the costs of collection and delivery of goods to the customers and maximise their profit. Service users are the senders/receivers of goods that require the maximisation of service level in terms of shorter times of goods collecting/delivering, greater reliability and flexibility, better information availability etc. with lower service price. Administration as a goal has the economic development of the city and improving the employment possibilities while reducing traffic congestions, improving living conditions and improving traffic safety in cities. Residents are the people that live, work and buy goods in cities, and their goal is the minimisation of traffic congestions, noise, air pollution and traffic accidents in their surrounding [55].

For the purpose of criteria evaluation, several meetings and discussion panels were held with the representatives of each stakeholder group – experts in the field, university researchers, sector managers from logistics companies, logistics employees and workers, residents, local administration officers, business owners etc. The participants were presented with a survey composed of questionaries whose results were processed and transformed into criteria evaluation terms. Stakeholder group representatives have chosen the best and worst criteria and evaluated all the remaining criteria according to the linguistic terms from *Table 1*. Stakeholder representative criteria evaluation is shown in *Table 2*. This way, the vectors "the best compared to others" and "others compared to the worst" are derived.

For the derived vectors, the optimisation problem from *Equation 3* is solved, considering the GDP values derived by *Equation 4* and white values derived by *Equation 2*. As explained in Section 4, the optimisation problem from *Equation 3* is derived by transforming the problem from *Equation 1*. This way, optimal grey criteria weights for every stakeholder group are derived. *Equations 5–7* are applied to check the evaluation consistency. Having in mind that all CR values are close to 0, the evaluation is considered consistent. The final criteria weights are determined by

Table 2 – Criteria evaluation by stakeholder groups

	Pro.		Use.		Adm.		Res.	
C_1	best	EH	best	EH	M	M	FL	FH
C_2	FL	FH	VH	VL	FL	FH	L	H
C_3	L	H	FH	FL	L	H	EH	worst
C_4	VL	VH	EH	worst	best	EH	M	M
C_5	FH	FL	VL	VH	H	L	EH	N
C_6	FL	FH	L	H	VH	VL	EH	N
C_7	L	H	EH	N	N	EH	FH	FL
C_8	EH	worst	VH	VL	L	H	VL	VH
C_9	VH	VL	H	L	VL	VH	best	EH
C_{10}	VL	VH	FL	FH	EH	worst	EH	N
C_{11}	N	EH	M	M	VL	VH	H	L

applying *Equations 8–10*. Optimal grey criteria weights for every stakeholder group, as well as final grey criteria weights, are presented in *Table 3*.

In the next step of model application, the evaluation of alternatives (SSCLs) according to the defined criteria and linguistic terms is performed (*Table 4*).

By transforming these evaluations into grey values (according to the relations from *Table 1*), the *grey* decision matrix is formed (*Equation 11*). For the extracted criteria weights, by applying *Equations 12 and 13*, the weighted *grey* decision matrix is formed. The negative ideal solution is determined by applying *Equations 14 and 15*, while the Euclidean and Taxicab alternative distances from the negative ideal solutions are determined by *Equations 16–21* and *Equations 22–24*, respectively. The grey matrix of relative values is formed by applying *Equations 25–29*, for which the GDP values are determined by applying *Equation 4* for all alternative pairs. The final ranking

Table 3 – Optimal and final grey criteria weights

Criterion	Optimal weights				Final weights
	Pro.	Use.	Adm.	Res.	
C_1	[0.082, 0.249]	[0.242, 0.33]	[0.042, 0.053]	[0.093, 0.305]	[0.094, 0.191]
C_2	[0.054, 0.063]	[0.04, 0.047]	[0.055, 0.064]	[0.091, 0.14]	[0.057, 0.072]
C_3	[0.079, 0.082]	[0.056, 0.06]	[0.08, 0.083]	[0.026, 0.114]	[0.055, 0.082]
C_4	[0.105, 0.163]	[0.024, 0.026]	[0.083, 0.253]	[0.046, 0.07]	[0.056, 0.093]
C_5	[0.033, 0.045]	[0.14, 0.216]	[0.028, 0.04]	[0.035, 0.076]	[0.046, 0.074]
C_6	[0.054, 0.063]	[0.105, 0.139]	[0.024, 0.036]	[0.035, 0.046]	[0.047, 0.061]
C_7	[0.079, 0.082]	[0.035, 0.042]	[0.16, 0.249]	[0.046, 0.056]	[0.067, 0.083]
C_8	[0.018, 0.02]	[0.04, 0.047]	[0.08, 0.083]	[0.022, 0.218]	[0.034, 0.064]
C_9	[0.023, 0.035]	[0.046, 0.052]	[0.107, 0.166]	[0.152, 0.244]	[0.065, 0.093]
C_{10}	[0.105, 0.163]	[0.084, 0.093]	[0.019, 0.021]	[0.035, 0.046]	[0.049, 0.061]
C_{11}	[0.158, 0.245]	[0.069, 0.07]	[0.107, 0.166]	[0.047, 0.057]	[0.086, 0.113]

Table 4 – Alternative evaluation according to the criteria

SSCL	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
SSCL1	L	VL	FL	EH	L	VH	VH	FL	L	VH	M
SSCL2	FH	FH	EH	H	VH	H	H	H	H	EH	EH
SSCL3	VL	L	H	VH	M	EH	L	VL	VL	H	FH
SSCL4	H	H	VH	M	H	FH	VH	M	FH	M	VH

Table 5 – The final ranking of alternatives

$P\{\otimes h_i \leq \otimes h_k\}$	SSCL1	SSCL2	SSCL3	SSCL4	Rank
SSCL1	/	0.5159	0.3797	0.5124	3
SSCL2	0.4841	/	0.3746	0.4957	1
SSCL3	0.6203	0.6254	/	0.6292	4
SSCL4	0.4876	0.5043	0.3708	/	2

of alternatives regarding the GDP values, as an output result of the grey CODAS method, is shown in *Table 5*.

4.2 Sensitivity analysis

To check the stability of the derived solution, a sensitivity analysis is performed. The solution from the previous part is adopted as the base scenario (Sc.0) and, by varying different model parameters, another 10 scenarios are defined. The first four scenarios refer to the ranking of alternatives according to the criteria weights of individual stakeholder groups: Pro. (Sc.1), Use. (Sc.2), Adm. (Sc.3) and Res. (Sc.4). In the fifth scenario (Sc.5), all criteria are considered to be equally significant. In all the remaining scenarios, one of the five most important criteria (criteria with largest weight coefficients) is excluded from the analysis: C1 (Sc.6), C11 (Sc.7), C9 (Sc.8), C7 (Sc.9) and C4 (Sc.10). Sensitivity analysis results (the change in alternative rankings) are presented in *Figure 2*.

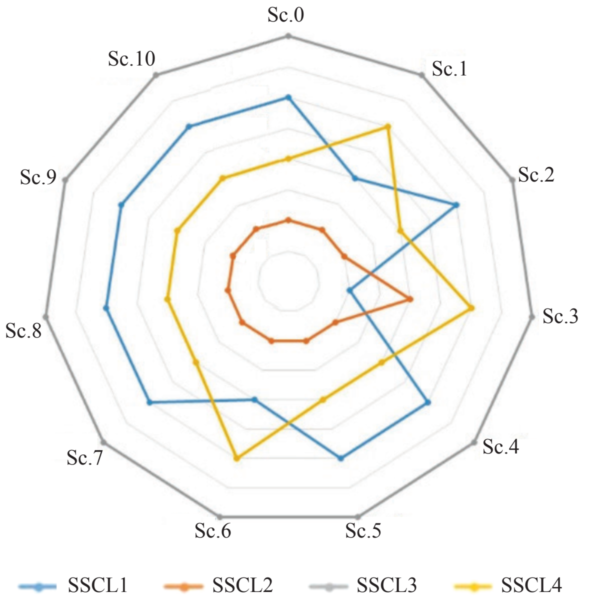

Figure 2 – Sensitivity analysis

SSCL2 is the best-ranked alternative in all scenarios except in Sc.3, where it was ranked as the second-best. SSCL4 and SSCL1 are in more scenarios ranked as the second-best and third-best alternative, respectively. SSCL3 is ranked as the worst alternative in all scenarios. As there is no significant deviation in alternative rankings, the obtained solution is considered stable and suitable for adopting as the final solution. For the analysed problem in this article, the alternative SSCL2 stands out as the best sustainable smart solution of CL.

5. DISCUSSION

SSCL2, which represents the combination of the micro-consolidation concept and autonomous vehicles with the application of AI and IoT technologies, is selected as the best smart solution for CL. MCCs are located in the close proximity of flow generators, which compensates for the technical limitation of autonomous vehicles. The application of AI and IoT enables better connectivity of all participants, real-time information sharing and appropriate decision-making in crisis situations, which leads to significant improvement in flow realisation efficiency. The application of this solution would have significant positive effects on the sustainability of logistics activities in urban areas: efficient process realisation, reduction in air pollutant emissions, noise and vibrations, reduction of traffic congestions caused by delivery vehicles, improving the attractiveness of the city, promoting the application of smart technologies etc. On the other hand, the application of this solution would be possible only if all relevant problems on strategic and tactical decision-making level are solved (defining the required number of MCCs, their location and capacity, the number and type of autonomous vehicles, regulatory frameworks and ethical norms for their wide application, characteristics of the system that would enable the application of AI and IoT technologies etc.), as well as on the operational level (vehicle routing, synchronisation of activities etc.).

SSCL4, which refers to the application of cargo trams for goods transportation to loading stations in the delivery zone, where the modal shift to light delivery vehicles takes place, is the second-ranked solution. Its main downside, which prevented it from being the first-ranked, is the inflexibility of the rail transportation mode and the requirement for developing additional rail infrastructure (which is not always possible due to technical and spatial limitations). Still, SSCL4 stands for a sustainable solution for CL and its application should be considered in urban areas with dense rail infrastructure. SSCL1 is the third-ranked solution. It refers to the application of parcel lockers and the idea of crowdsourcing in parcel delivery. The main issue with this solution is the unreliability of the crowdsourcing idea which could not entirely replace the traditional delivery models. In order to make crowdsourcing-based CL solutions more sustainable and reliable, they should be combined with other sustainable CL solutions in cases where their application would be feasible. SSCL3, which refers to the delivery through the combination of road delivery vehicles and drones, is ranked as the worst solution. The main reasons for this are the technical limitations of autonomous vehicles (especially drones) and their current state of development which is not yet sufficient for a wider application. Further technological improvements, integration with other sustainable CL solutions, and more intensive engagement in regulatory issues would potentially lead to justified and wider application of such solutions.

For the purpose of solution evaluation and selection, a novel hybrid MCDM model, that combines the BWM and CODAS methods in *grey* environment, is developed in this article. Its applicability is successfully demonstrated by solving the observed problem. The BWM method ensured consistency in forming comparison matrices and retrieving reliable results by minimising the "violation" and "total deviation" parameters. The CODAS method provided an efficient ranking of alternatives with a minimal number of comparisons and obtained precise results through a fine differentiation of closely-ranked alternatives by considering two types of distances. As the evaluations were performed by stakeholder representatives, with often incomplete or ambiguous evaluations, the methods are combined in *grey* environment to reduce the ambiguity in datasets, to ensure more efficient processing of incomplete data, and to combine ambiguous and incomplete information into one model.

The theoretical implications of the article are multiple. The article contributes to the field of logistics in general through the analysis of the possibilities of application of Industry 4.0 technologies for the improvement of various logistics activities. A special contribution was made in the field of city logistics because the existing initiatives, solutions and concepts have been upgraded and improved with technologies of Industry 4.0, with the aim of achieving more efficient realisation of goods and transport flows within the urban areas. The article contributes to the field of smart cities through the analysis of smart logistics solutions and their significance and impact they have on the formation of smart cities. The article contributes to the area of Industry 4.0 by finding new possibilities, i.e. expanding the areas of application of technological solutions that are an integral part of the Industry 4.0 framework. The article of contributes to the MCDM theory through the definition of a new universal hybrid model that can, after minor adjustments, be applied to solve problems in this or any other area.

Practical implications of the problem-solving in this article are in providing guidelines/base points for policy creators and decision-makers in cities when defining smart solutions for logistics. However, it is recommendable for them to not only use the results obtained in this study, but also to investigate some additional applications of the existing, and especially new technological solutions which emerge rapidly, and use the provided framework for the definition, evaluation and selection of new solutions. Additional practical implication is the developed model which provides a simple but efficient tool for decision-makers in solving all sorts of practical multi-criteria problems.

The article defines only four smart solutions for city logistics. In reality, almost countless different solutions could be defined, which would be insignificantly different from each other. This could be one of the limitations of the proposed approach. However, the solutions defined in this article differ significantly in terms of applied initiatives, measures and technological solutions, which is why it is justified to adopt them as typical solutions that deserve more detailed analysis. An additional limitation of the defined approach could be a set of criteria, which could be broader, but again, the proposed approach encompassed the most important criteria which cover the attitudes, demands and goals of main stakeholders and main sustainability aspects.

6. CONCLUSION

This article focused on the problem of defining and ranking sustainable SSCLs. The goal was to find a sustainable solution that would meet all modern challenges of goods distribution in urban areas with the application of advanced Industry 4.0 technologies. Four feasible solutions are defined and, after their evaluation, the solution that combines the concept of micro-consolidation and autonomous vehicles with the support of AI and IoT technologies, is selected as the best. For solution evaluation and selection, a novel hybrid MCDM model, which combines the BWM and CODAS methods in *grey* environment, is developed.

The main contributions of the article are the definition of original SSCLs as a combination of modern initiatives and concepts of CL with the technologies of Industry 4.0, the creation of a framework and definition of criteria for their evaluation, as well as the development of a novel hybrid MCDM model for ranking and selection of the best solution. Having this in mind, this article contributes significantly to the research areas of logistics, smart cities, Industry 4.0 and MCDM.

One direction of future research would be in further development of the defined solutions and the identification of new application possibilities for the existing and those in development, technologies of Industry 4.0. A significant future research direction would be the development of completely new solutions from the ones that are defined in this article, as well as the analysis of their practical feasibility in different cities across the world. As the developed MCDM model is universally applicable, with certain adjustments, it could be used for problem-solving in future research in the area of logistics, Industry 4.0 and other areas as well. The developed model, or some of its components, could serve as the base for the development of new models.

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OCENA PAMETNIH REŠENJA CITY LOGISTIKE

SAŽETAK

Negativni efekti realizacije robnih tokova su najvidljiviji u urbanim sredinama – mestima najveće koncentracije ekonomskih i društvenih aktivnosti. Glavni cilj istraživanja je identifikacija primenjivih tehnologija Industrije 4.0 u realizaciji različitih operacija city logistike (CL), definisanje pametnih održivih rešenja CL (SSCL) i njihovo rangiranje sa ciljem identifikacije onih koji mogu predstavljati osnovu razvoja i planiranja pametnih gradova u budućnosti. Ovakav tip problema uključuje različite zainteresovane strane sa konfliktnim ciljevima i interesima što dovodi do prisustva više različitih kriterijuma. Za rešavanje problema, predložen je novi hibridni model višekriterijumskog odlučivanja (VKO), zasnovan na BWM (Best-Worst Method) i CODAS (COmbinative Distance-based ASsessment) metodama u grey okruženju. Rezultati primene modela ukazuju da je potencijalno najbolje SSCL ono koje se zasniva na kombinaciji koncepta mikro-konsolidacionih centara i autonomnih vozila, sa podrškom tehnologija veštačke inteligencije i Internet-of-Things. Glavni doprinosi rada su definisanje originalnih SSCL, formiranje metodologije i definisanje kriterijuma njihove ocene, kao i razvoj novog hibridnog modela VKO.

KLJUČNE REČI

city logistika; pametan grad; Industrija 4.0; grey BWM; grey CODAS.

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