Solution approaches for the Smart Waste Collection Routing Problem

Gustavo Souza Marques
DEG, Instituto Superior Técnico, Av. Prof. Dr. Cavaco Silva, Porto Salvo, 2744-016, Portugal
souzamarques014@gmail.com

Abstract: Waste collection companies often face inefficiency in their operations, mostly associated with the highly difficulty in predicting the bins waste accumulation. These fluctuations are linked with the presence of uncertainty in the system, which leads to an excessive travelling kilometer usually to collect a small amount of waste. One way to reduce the uncertainty is to explore electronic devices to access real-time information on the bins fill-level and, thus, optimize the collection routes. This problem is known in the literature as the Smart Waste Collection Routing Problem (SWCRP) and some approaches were already proposed to deal with it (Aguiar et al., in press; Ramos et al., 2018). The SWCRP was approached in both works as a Vehicle Routing Problem with Profits (VRPP) and therefore, the present dissertation aims to improve those works addressing some issues that were not considered beforehand, such as the route balance. Three operational management approaches are introduced to define dynamic routes considering real-time information about the bins fill-levels. In addition to the route balance, another branch is investigated to study how to select the bins to be considered by the model. Besides the option that complies all bins, a pre-selection procedure is explored combining the VRPP model with a heuristic method. The solution method is applied in a real-world case study where a potential increase in the operational profit is achieved by up to 450%. Moreover, it is concluded that the solution method can also allow an improvement of up to 69% in the operations efficiency.

Keywords: Smart Waste Collection Routing Problem, Sensors, Real-Time Information, Optimization, Recycling.

1 INTRODUCTION

Over the decades, the dramatic population growth and expansion of cities has been constantly observed, influencing the waste production generated by citizens. Waste is an environmental problem that can be considered as a consequence of the human activity, which daily generates more and more waste due to the embedded nature of consumption (Beliën et al., 2014; Gutberlet, 2018). However, the management of this waste is a complex task that compels the absorption of a large amount of resources and causes an important and substantial impact on the environment (Ghiani et al., 2014). The demand of exploring solutions for the waste management optimization rises not only to provide access to environmental benefits but as well as in terms of economic benefits and improvement of the associated procedures (Beliën et al., 2014; Ghiani et al., 2014; Gilardino et al., 2017).

According to the Portuguese Environment Agency (APA), when considering mainland Portugal, it is possible to observe that the total waste production has reached approximately 4.94 million tons in 2018 (an increase of 4.2% compared to 2017). It is indicated that Portugal presents a growing trend n waste generation occurring since 2014 (Agência Portuguesa do Ambiente, 2019). However, the collection of this waste is associated with high transportation costs and inefficiency in the use of resources. This because it is common to have uncertainty in the system caused by the highly variation of the amount of municipal solid waste, often leading the vehicles to visit only partially full bins (Nuortio et al., 2006; Ramos et al., 2018). To deal with this uncertainty and the increase production of waste, it is important to design of an efficient waste collection system which, despite its difficult accomplishment and numerous decisions involved, different methods have been developed using Operational Research techniques along with advances in Information and Communication Technologies (ICT). The new era of Web and Internet of Things introduces the proliferation of smart devices to monitor, collect and transmit real-time information, since its constant change leads to great uncertainty in terms of operations. In this way, the increase availability of devices that provide real-time information is responsible for a new paradigm of logistics and transportation systems, enabling operational researchers to focus on the development of optimal planning models (Anagnostopoulos et al., 2017; Powell & Jaillet, 1995).

2 CASE STUDY

The present work analyses a real-world case study that describes the activity of the company ERSUC - Resíduos Sólidos do Centro, S.A., responsible for the collection of recyclable waste in 36 municipalities across Portugal. ERSUC assumes the following collection methods adapted to the needs of each geographical area and target group: eco-points, door-to-door, or voluntary deliveries. The selective collection of disposed waste at the eco-points is organised by static circuits that are performed according to a pre-established frequency, considering the number of bins in each circuit and their waste production. Currently, the company presents potential margins for improvement considering the inefficiency observed in its performance. Through the direct contact with ERSUC, the following issues have been identified:

- Uncertainty regarding the eco-points fill-levels.
- Eco-points filling behaviour affected by seasonality.
- Very extensive collection area.
- Existence of collection zones at long distances from the plants.
- Difficulty in creating new circuits.
- Variability in the duration of the routes.
- Work schedules conjugation.

As we can see, most of the issues identified are related to the uncertainty regarding the bins fill-levels status and to the fact that the operations are carried out statically, through predefined routes. Without access to additional information into the system, the company is unable to optimize its routes as a function of the bins fill-level variation, which represents an extreme challenge to simply base its operations on prediction (since it is subject to many variables including dealing with seasonality and the waste producers' unpredictable behaviour). Moreover, regardless of any occurrence, its large action area needs to be covered, implying an inefficient usage of the company's resources as well as the influence on factors related to the creation of new and improved routes, considered by ERSUC as a complex and slow process. In addition, the company highlights the fact that there is variability in terms of the routes' duration, which affects the fulfilment of the daily workload per employee (7 hours/day) and consequently hampers the work scheduling process.

To enable the analysis of ERSUC's operations efficiency, a data collection process was performed in order to monitor the bins waste accumulation. The process consisted in a manual recording conducted by ERSUC's collection team upon arrival to the bin, classifying the bins fill-level through visual inspection (Table 1). Six classes were defined to describe the bins possible status based on their percentage of filling. Since ERSUC's operating area is deemed extensive, the data collection process was applied only to part of the company's operation, as it is considered to be a representative area. Thus, ERSUC decided to analyse the following municipalities: Soure, Condeixa and Coimbra. One type of recyclable material was selected for study, the paper/cardboard.

Table 1 – Fill-levels recorded per class

Class (%)	Soure	Condeixa	Coimbra	Total (%)
0	0	55	529	10%
0 – 25	203	286	1 681	38%
25 – 50	138	129	898	20%
50 – 75	65	145	936	20%
75 – 100	36	53	595	12%
> 100	0	0	0	0%

It is possible to verify that 48% of the visited/collected bins showed an empty or considerably low fill-level, being represented respectively by the classes 0% and between 0% and 25%. In addition, only 12% of the bins were collected with a fill-level higher or equal to 75%. These are conclusive to state that ERSUC faces a particular problem regarding its operations' performance whereby almost the majority of the bins collected by them are basically empty.

As a possible solution, ERSUC is willing to proceed with the implementation of volumetric sensors in the bins to, thereby, allow the company to access the bins fill status on a real-time basis. It is expected that the introduction of the device in the system will reduce the operation uncertainty since it intends to eliminate the doubt related with the bins waste accumulation and, therefore, improve the collection operation by using resources more efficiently. ERSUC intends to know the impact of such implementation which is defined by the access evaluation to potential benefits, namely in terms of minimizing the distance travelled and maximizing the weight collected, so that its service level is improved or maintained. For that purpose, ERSUC established that the most important key performance indicators (KPIs) for assessment are related to the efficiency, productivity and profitability of the operation, namely the vehicles usage rate, the kg per km ratio and the total profit. Since the company does not operate directly with its customers, the service level mentioned here refers to the prevention of the bins overflow which, if unsuccessful, can be considered as disturbing or in some cases even dangerous for the population. Also, ERSUC is interested in exploring the possibility of merging two municipalities in order to assess the benefits of considering them simultaneously instead of operating separately.

3 LITERATURE REVIEW

3.1 Modelling the Municipal Solid Waste Collection

Waste management practices range from separation and collection operations to recovery and recycling operations (Jatinkumar et al., 2018). However, lately an increasing number of studies have focused on waste collection as this operation is characterized by high transportation costs and inefficient usage of resources since vehicles often visit empty bins that are only partially full. If waste collection efficiency increases, gains in both economic and environmental perspectives can be achieved (McLeod & Cherrett, 2008; Ramos et al., 2018). Operational research techniques can serve as support tool to evaluate complex tasks and systems that cannot be analytically performed or experimented in the real-world, thus, using these techniques to improve the efficiency of waste collection (Bing et al., 2016; Law, 2007).

Yousefloo & Babazadeh, 2019 characterizes the main works developed in the municipal solid waste (MSW) management modeling field, classifying in two types of problems: (1) network design; and (2) collection operations. To perform a more in-depth literature review, focused on waste collection modeling, it will first be reviewed the work of Johansson, 2006 that address the benefits of practicing a traditional collection, i.e. static, versus the concept application of dynamism.

3.2 Static vs Dynamic Waste Collection Planning

The planning approach considered traditionally refers to the design of a static operation, where fixed routes are performed according to a predetermined collection frequency (Johansson, 2006). However, it is possible to observe a significant interest for dynamic planning approaches since transportation and logistics environment are associated with uncertainty and dynamic characteristics. Also, static approaches cannot deal with such characteristics, especially due to the dynamic nature of Internet of Things (IoT) potentiality (Anagnostopoulos et al., 2015; Powell & Jaillet, 1995). In order to evaluate the different policies regarding the effects of static versus dynamic scheduling and routing performance, Johansson, 2006 studied the waste management system through analytical modelling and discrete-event simulation. The author concluded that the association of collection operations with dynamism enables the achievement of economic benefits and the operation's improvement. This because the uncertainty associated to demand is reduced.

The dynamic collection planning is usually associated with data acquisition technologies, which makes it possible to assess real-time information about waste bins fill-levels, enabling the reduction of the uncertainty associated to waste accumulation (Anagnostopoulos et al., 2015; Ramos et al., 2018). As Powell & Jaillet, 1995 stated, dynamic modeling practices place tremendous demands on access to real-time data. The provision of such information is only allowed by the exploitation of devices called "smart" that, when used in waste collection systems, enable tracking procedures, route optimization and, in some cases, even for service provisioning (Hong et al., 2014).

3.3 Smart Waste Collection

The addition of a smart concept applied in waste management is defined by the use of smart enabling technologies to improve monitoring, collection, separation and transport operations in order to perform more efficiently, effectively and sustainably (Zhang et al., 2019). This kind of additional capability is offered by the exploitation of Information and Communication Technologies (ICT) that allow the development of dynamic solutions through the production of sensors, actuators and IoT technologies, which can be installed in bins in order to reduce the associated uncertainty (Jatinkumar et al., 2018). Therefore, a literature review on these components is presented, particularly focusing data acquisition technologies and their applications in collection/routing optimization.

3.3.1 Smart Enabling Technologies

The use of smart devices as a key enabling technology is addressed by Anagnostopoulos et al., 2017 through the development of a comprehensive survey on the utilization of ICT generally applied in waste management models. Hannan et al., 2015 developed a review within the smart waste management context in which the available ICT and their use is explored for problem solving. Through the respective categorization of planning, monitoring, collection and management operations for solid waste, the author divides the ICT into four classes: (1) Spatial technologies, (2) Identification technologies, (3) Data Acquisition technologies, and (4) Data Communication technologies. Esmaeilian et al., 2018 addresses the future of waste management in smart and sustainable cities and conducts a literature review focused on the last three classes recognized by Hannan et al., 2015. According to the author, these classes has received more attention in waste management literature. In addition, four categories are recognized for technologies applied in smart waste management systems: the development of data acquisition and sensor-based technologies; communication and data transmission technologies, field experiment technology and technologies for setting and scheduling truck routes. It is concluded that the studies reviewed by the author have focused primarily on making monitoring, separation, and collection more efficient with the help of sensor-enabled solutions. Finally, the work of Zhang et al., 2019 is pointed out where the barriers of smart waste management to the circular economy in China are identified and, according to the work of Esmaeilian et al., 2018, the author provides an overview of the principles and strategies in waste management based on the main smart enabling technologies used. Focusing on detailing data acquisition technologies, Zhang et al., 2019 states that there has been an increased interest in supporting the waste management system through dynamic planning models, and the development of data acquisition and sensor-based technologies is eventually used to guarantee access to bin fill levels.

It is possible to conclude that modelling dynamic collection operations is explored in conjunction with smart enabling technologies, especially to gain access to real-time information. As already mentioned, this is justified due to the high uncertainty associated with bins filling levels (Ramos et al., 2018). Thus, the next section will address the concept of smart waste routing problem, aimed at modelling routing problems when real-time data is accessible.

3.3.2 Smart Waste Routing Problem

When considering the dynamic collection coupled with real-time information the following studies are highlighted: Mes, 2012 uses the discrete event simulation to evaluate the opportunities of dynamic waste collection with sensors that describe the bins fill-levels. It is concluded that major improvements can be achieved in terms of logistical cost efficiency and customer satisfaction. Anagnostopoulos et al., 2015 studies dynamic waste collection architecture based on data retrieved by sensors. Through the management of the trade-off between cost and performance of immediate collection, the author proposes a system that responds to the demand identified by sensor observations and alerts in high priority areas by forcing vehicles to deviate from the regular collection path and prioritize the bin collection alerted by the sensor. Thus, the author seeks to provide efficient solutions to the dynamic waste collection problem by responding in high priority areas with an optimum reaction, minimizing the time required while maintaining the expected average performance level. Gutierrez et al., 2015 addresses the benefits and drawbacks of providing intelligence to trashcans through sensors that enable the reading, collection, and transmission of waste volume for the waste collection strategies management in a dynamic and efficient way. The benefits of the dynamic system proposed by the author are investigated through simulation, optimizing the selection of which bins should be daily collected and comparing such system with approaches to waste collection by sectors considered traditional. In this way, route optimization algorithms allow the best route design considering the bins previously selected and the minimization of the distance traveled. However, Anagnostopoulos et al., 2015; Gutierrez et al., 2015; Mes, 2012; only explore a minimization of the distance travelled during collection, not considering the profit that may be attained.

Recently, Ramos et al., 2018 explored the profit maximization (maximizing the amount of waste to be collected while minimizing the distance travelled). It is introduced the Smart Waste Collection Routing Problem (SWCRP) as a proposal for the optimization of recyclable waste collection operations. The hypothesis of coupling volumetric sensors to the system is investigated in order to enable the transmission of real-time information regarding the bins' filling level and to introduce the attractiveness concept for choosing which bins are worth to collect it. Based on the information available, different approaches are proposed to define dynamic routes through a Vehicle Routing Problem with Profits (VRPP) mathematical model that, as mentioned above, maximizes the profit associated with the collection of recyclable waste. As a result, the authors achieved an significant operational improvement and proves to reduce the uncertainty present in the system. However, high computational time and the presence of gaps between the integer solution and the lower bound found by CPLEX after the total computational time, providing opportunities for future work developments.

Later, Aguiar et al., in press addressed the limitations of SWCRP and proposed the decomposition of the problem through an optimization-based heuristic. The purpose was to reduce computational time and improve the quality of solutions through the Cluster First-Route Second methodology. Two phases were defined: (1) a heuristic is applied in order to dynamically reduce the numbers of bins; That is, a construction set is formed considering only bins with fill-levels above a predetermined threshold (M) as input for the second phase. (2) The subproblem previously defined is modeled as a VRPP and then solved; The results were compared with real data from a case study and demonstrated the achievement of optimal solutions in a reasonable time, enhancing the proposed method in economic and environmental terms. However, it was noted that in both works the workload is not considered. For instance, the approach found to be the most efficient in Ramos et al., 2018 provides two routes with widely differing lengths in a given day. Ramos & Oliveira, 2011, introduces a heuristic approach to design routes considering two objectives: (1) minimizing variable costs and (2) balancing the workload on depots in an equitable manner. Kim et al., 2006 applies a pre-routing phase through a clustering-based procedure to improve the route compactness and workload balancing. Ramos et al., 2014 presents a multi-objective procedure to obtain a set of solutions considering economic, environmental, and social objectives. One objective is to balance the workload by minimizing the maximum duration of the routes. Matl et al., 2019 investigates the workload equity in vehicle routing and states that minimizing the maximum route duration, or the route length are the two most commonly used measures of equity. When considering the route duration length, the minimization of the difference between the minimum and maximum route duration is taken into account, thus reflecting a more comprehensive view of equity.

Based on the works above described, it can be concluded that Ramos et al., 2018 work is the most appropriate methodology to approach the problem under analysis. Furthermore, it is also concluded that the most appropriate route balance measure would be considering the routes' duration length.

4 SOLUTION METHOD

For the solution method, three operational management approaches are considered: The first approach will run the VRPP model every day and just visualize the current day, respecting the conditions to prevent any bin overflow and maximizing the profit for each day – this approach is called “Everyday”; The second approach will run the model only for those days when there is risk of overflow by visualizing the current day plus the following day, respecting the same conditions mentioned above – this approach is called "Myopic". The third approach can visualize ahead within the planning horizon period. Just as the second approach, the model will be run only for those days when it is expected that some bin from the initial set shows a risk of overflowing and the same conditions previously mentioned are applied – this approach is called "Look Ahead".

In addition, two branches are going to be explored which will be combined with the base approaches, namely the Route Balance and the Bins Selection Rules. As previously mentioned, the Route Balance concept is used to allow the VRPP model to be restricted in terms of duration of the routes, introducing the time element to be considered by the model. Meanwhile, the Bins Selection Rules is explored to distinguish the input methods regarding the bins from the initial set. Besides the base option of inputting the model with all bins (which it is expected to provide the optimal solution or nearst optimal, but do not ensure efficient computational times), the Cluster First-Route Second is here applied based on the work of Aguiar et al., in press and a new type of rule is introduced.

4.1 Operational management approaches

4.1.1 The Everyday approach

The Everyday Approach works by receiving the real-time information from the sensors about the fill level of each bin i on the morning of each day t. Then, the approach will primarily takes into account the prevention of overflows by considering the initial fill-level and an estimated daily filling rate calculated to describe the bins filling rate based on historical data. Secondly, the model optimizes the bin's collection sequence maximizing the profit to perform the collection, given the transportation cost associated to picking up each bin and restricted to collect all the bins expected to overflow. The model will be run every day performing a collection route on those days when it is verified that some bin is at risk of overflowing.

4.1.2 The Myopic approach

The Myopic Approach operates like the Everyday Approach except for two differences: (1) Adopting a conservative stance, the model relies not only on the estimated filling rate of the day but also on an additional estimation for the following day. Thereby, it is verified if there is at least one bin expected to overflow either on day t and day $t + 1$; and (2) The other difference consists of the condition that the model does not run every day but only for those days on which it is estimated to occur an overflow considering the addition of the following day filling rate.

4.1.3 The Look Ahead approach

Considering the Myopic Approach that visualizes the expected filling rates for the following day $t + 1$, an alternative approach is introduced, predefining the next day of collection based on the bins that will be collected on the current day t.

Initially this alternative approach works exactly like the Myopic Approach but differs in the case of being verified there are bins required to be collected. Here, an auxiliary filling value is simulated on the current day t to describe the bins expected fill level for the next days (t'). For the bins that are verified to violate the capacity condition on the current day t, the model will hypothetically collect and a value equal to zero is then considered as their new initial fill level, simulating that they have been collected on day t.

Thus, the model estimates what would be the next day which the bins that violates the capacity condition on day t will present a risk of overflow again, considering that they were hypothetically collected. From those bins, the one verified to overflow sooner defines the next day of collection and, therefore, a subset F is formed encompassing all the bins that are mandatory to be collected between the current day and the next predefined day of collection. Then, the model is forced to collect all bins contained on subset F so that, supposedly, no collections will be required in the estimated time between the two collections. As in the Everyday and Myopic approaches, it is also possible for the model to consider visit bins that are not mandatory to be collected, taking into account, as mentioned before, the profitability and the route required to collect the ones contained in subset F.

4.2 Bins selection rules

In order to establish the possibilities for dealing with the computational time issue, a bins selection rules were developed taking advantage of the fact that the computational time varies significantly as a function of the number of bins considered by the model. Three types of selection rules were analyzed: (1) Considering all bins: No restrictions or pre-selection methods are applied in this case, therefore, all bins contained in the initial set in inputted every day to the model; (2) Considering only some bins by fill-level: In addition to the bins that present a risk of overflow, the model is inputted with other bins from the initial set that satisfies the condition of having the fill-level above a predetermined threshold (M); and (3) Considering only some bins by the relation between distance and fill-level: A dynamic set is initially constructed exactly as described in the the second rule (by fill-level). Then, a second procedure is performed only for those bins contained in the dynamic set and determines according to a second predetermined threshold (R), the distance between these bins with the other bins that are not contained in the dynamic set initially constructed.

4.3 Route balance

To apply the Route Balance concept, it was necessary to establish a maximum and minimum values as a limitation for the route's duration. Then, some additional parameters were included to allow the model to simulate the time required to perform the collection routes, such as the speed of the vehicle fleet and the time to collect the bins (on average). A new way of penalty has been introduced in the objective function which penalizes for violating the duration limit values. Thus, since the VRPP model maximizes profit, the model is influenced to avoid performing routes that exceed the established values.

5 RESULTS AND DISCUSSION

By combining the operational management approaches with the branches introduced in this work, 24 scenarios were created. Thus, a type of triage phase was initially applied to select the most promising scenarios worth to explore. Such phase was performed for the first analyzed instance (Soure) since it had the smallest size considering the number of bins in the initial set. This because larger instances tend to amplify the performance behavior of smaller instances. First, a subset called base scenarios was defined for initial analysis, composed by three scenarios that are potentially the optimum situation of each approach (since they do not consider constraints when it comes to the selection of bins or the routes' duration). Figure 1 displays the base scenarios results for the main KPIs. Figure 2 displays the base scenarios results for the KPIs related to the solution method.

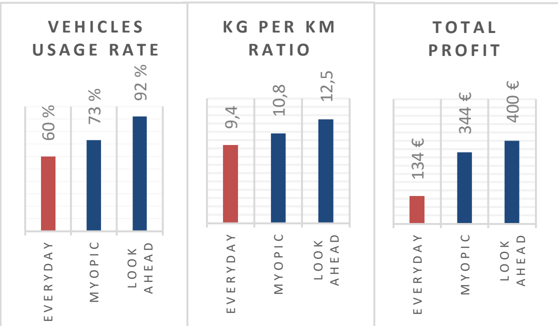

Figure 1 - Main KPIs comparison for Soure

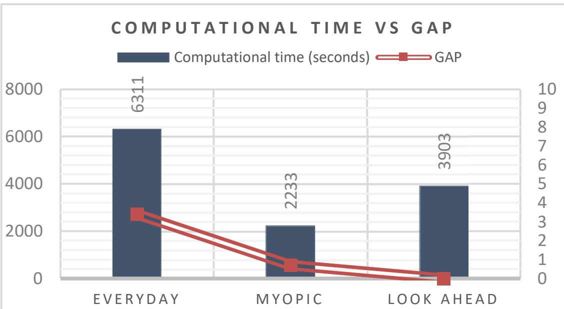

Figure 2 - Computational time vs Gap for Soure

For the KPIs analysed, the base scenario representing the Everyday approach unanimously performed the worst when compared to the other approaches. In fact, its operational profit was considerably low and the approach demonstrated a poor computational performance, with significant gap values in its solutions. These factors are conclusive to state that the Everyday approach is not worth exploring for future development.

The same analysis was applied to the remaining scenarios. Figure 3 shows a scenario tree classified according to the following color scale: Blue represents the base scenarios; Green represents the scenarios that were considered worth exploring; and Red represents those that were eliminated for future development.

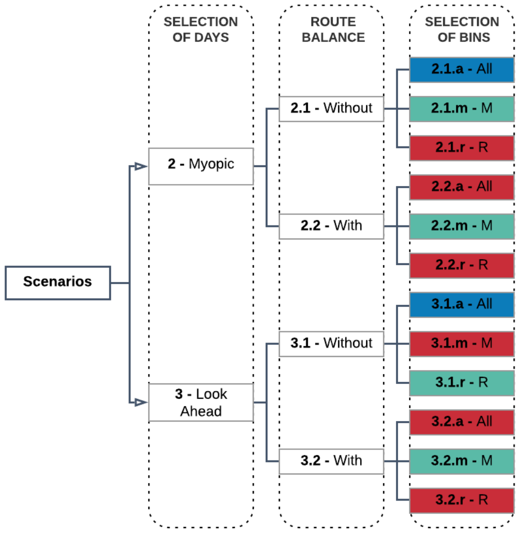

Figure 3 - Scenario tree

In total, six scenarios were considered worth exploring and tested for the three instances defined in this work, namely Soure, Condeixa and Soure together with Condeixa. As previously mentioned, the instances differ in size, i.e. number of bins in the initial set, being respectively considered as small, medium and large instances. However, the application of the solution method demonstrated that the most attractive scenario for each instance is the same, scenario 2.1.M, which follows the Myopic approach methodology without route balance and considering the second bins selection rule (see Figure 3). When looking only at the route-balanced scenarios, the same was observed where for the three instances analysed was verified that scenario 2.2.M is the most attractive one. Therefore, the current situation (CS) faced by ERSUC is compared with the most attractive scenarios for the main KPIs (Figure 4 for Soure and Figure 5 for Condeixa).

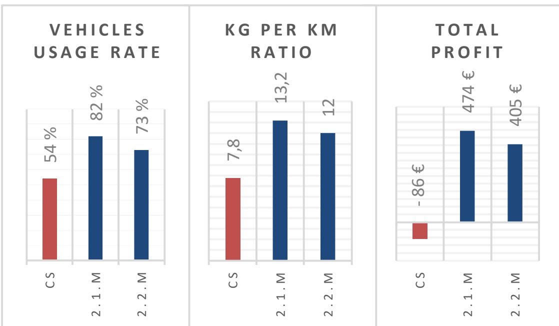

Figure 4 - Main KPIs comparison for Soure

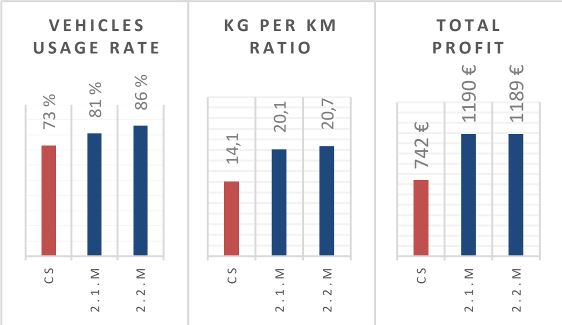

Figure 5 - Main KPIs comparison for Condeixa

For both instances, it was possible to see a significant improvement in the main KPIs when compared to the current situation operated by ERSUC. The results show that for Soure the solution method can achieve a 451% improvement in the operational profitability. In addition, it was observed the possibility to improve efficiency in the capacity utilisation of vehicles and in the kg per km ratio, which can reach an increase of 52% and 69%, respectively. For Condeixa, the solution method presents the possibility of a 60% improvement in the operational profitability, while for the vehicles usage rate and the kg per km ratio, it can be verified a potential increase of 18% and 47%, respectively.

Lastly, four key factors are explored in the analysis of the results: (1) whether the bins have reached an overflow; (2) the effectiveness of the route balance; (3) the assessment of Soure and Condeixa being operated together; and (4) the status of the bins' fill-levels at the moment of collection.

Regarding the first key factor, all the simulated scenarios in this work had no overflow bins observed when considering the difference between the estimated weight and the actual weight being collected, proving the good formulation of the model in terms of preventing overflows.

About the second key factor, the application of the route balance has proved to be quite effective. Scenarios that apply the concept satisfy the two conditions set by its formulation, which are (1) restricts the solutions in terms of maximum and minimum collection time allowed, 7 and 4 hours, respectively; and (2) whenever using two or more vehicles for a collection day, the routes must be designed as balanced as possible. For the medium-sized instance, it can be seen that scenarios that include the route balance concept (2.2.M and 3.2.M) provide greater precision regarding the routes' average duration (Figure 6).

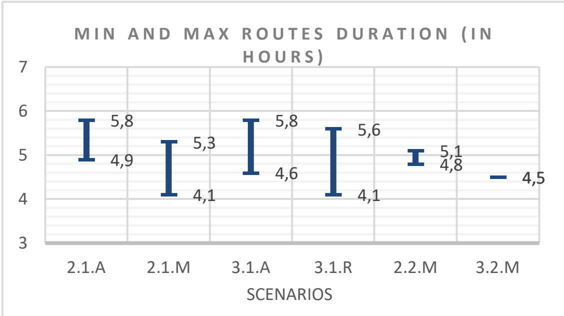

Figure 6 - Variation of the routes' average duration for Condeixa

For the third key factor, it was compared the performance of Soure and Condeixa being operated separately versus together. It was expected that operating Soure and Condeixa simultaneously would be result in a more profitable outcome. However, the results showed that the separate operation provides not only a higher profit, but also a higher kg per km ratio. It is noteworthy that due to the larger size by considering the two municipalities as a whole, the solutions of Soure and Condeixa togheter presented a higher gap values to which the maximum computational time was reached for most of the days, affecting the accuracy of the comparison.

The fourth and last key factor introduces the study of the bins' fill-level at the moment of collection. As previously mentioned, waste collection operations often visit empty or nearly empty bins. For the medium-sized instance, Figure 7 introduces the difference between the bins fill-levels in the current situation versus in the best scenarios simulated (2.1.M and 2.2M).

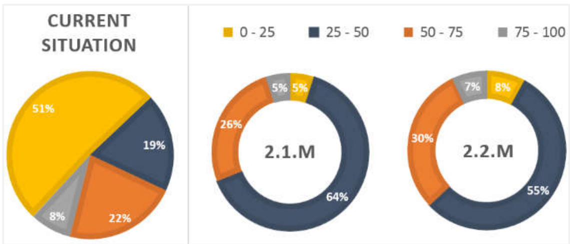

Figure 7 - Bins fill-levels at the moment of collection for Condeixa

With the application of the solution method, it was possible to drastically minimize the collection of bins with a fill-level between 0 and 25%. It is also observed that the majority of the collections performed are now between 25 and 50%. This result is reasonable since the approaches' methodology is based on the condition of preventing overflow by performing a collection when any bin is at risk of overflow. For the collection of these bins and to improve the operation profitability, the model chooses to visit partially full bins that become attractive considering the ones mandatory to collect. As a result, it is expected that the scenarios' outcome will not be majority for higher fill-levels.

6 CONCLUSION

The study of the different types of operational management approaches showed that the Myopic approach was considered the most attractive approach in terms of performance while the Look Ahead approach demonstrated an intermediate performance. The Myopic approach presented in general the best results for the vehicles usage rate, kg per km ratio, total profit, computational time, and gap. However, the Look Ahead approach had compatible results with the Myopic approach and in some cases provided a higher operational profit. Still, its worse computational performance influenced the choice of the most attractive approach. Thus, due to the complexity and demanding methodology, the Look Ahead approach requires a longer computational time and consequently presents higher gaps, decreasing the quality of its solutions.

Different ways of choosing which bins should be inputted into the model have been studied through three selection rules. As expected, the first rule that considers all bins in the initial set showed poor results in the computational time performance, influencing the gap values in its solutions, and thus decreasing their quality. The second selection rule that considers the bins by fill-level demonstrated an effective applicability whereby a significant reduction in the computational time required to reach a solution was observed. The third and final rule did not generally stand out in any of the analyzed instances, consistently providing an average performance when compared to the other selection rules.

The route balance concept was applied restricting the solutions in terms of duration through a predefined minimum and maximum limit. As expected, due to the higher complexity of the route-balanced scenarios, their performance was affected in the KPIs analyzed. The presence of such a concept led to higher gap values in the solutions and thus, justifies the slightly lower performance of the scenarios in the KPIs. However, the two conditions set by the route balance were successfully achieved by the model. Therefore, the conclusion that the route balance concept was generally well formulated in this work is supported.

Summarizing the main findings, under no circumstances was observed bins in overflow and the solution method showed an improvement regarding the status of the bins fill-levels collected by the model. It was observed the eradication in visiting empty bins and moreover, the upgrade in the majority category of the collected bins (from 0-25% to 25-50%). When comparing the current situation faced by the company with the best scenarios, the solution method estimates an improvement potential of 451% and 60% in terms of operational profitability for Soure and Condeixa, respectively. Regarding the productivity and efficiency of the operations, a potential increase in the vehicle's capacity utilization and the kg per km ratio was also achieved for both municipalities. For Soure, the results showed a 52% increase in the vehicles usage rate and 69% in the kg per km ratio. For Condeixa, the increase was of 18% and 47%, respectively. These factors support the conclusion that the implementation of volumetric sensors in the bins offers great potential for ERSUC, both in terms of profitability, productivity and operational efficiency. When considering the route balance option, it is expected that the operational profit will be lower due to the additional constraints on the collection routes. For Soure, such expectation was verified which estimates that the route balance implies a 15% decrease in the operational profit. However, this was not verified for Condeixa where the income was pretty much the same as the option without route balance.

For future work, it is suggested to investigate other methods to solve larger problems (such as the Soure + Condeixa instance), namely metaheuristics. Regarding the VRPP model developed, it should be noted that its formulation does not consider traffic and street conditions.

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